RESOURCE USE AND CONSERVATION AND ENVIRONMENTAL IMPACTS IN THE TRANSITION FROM CONFINEMENT TO PASTURE-BASED DAIRIES

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ABSTRACT

RESOURCE USE AND CONSERVATION AND ENVIRONMENTAL IMPACTS IN THE TRANSITION FROM CONFINEMENT TO PASTURE-BASED DAIRIES

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In recent years, many farms have transitioned from total confinement housing to a pasture-based system in an effort to reduce labor and production costs and improve profitability. There is a growing interest in biogas recovery among livestock producers to reduce energy costs and manure odors but the economic benefits of anaerobic digestion (AD) on small farms is not well known. A comprehensive analysis was conducted using the Integrated Farm System Model, to describe, evaluate and compare the economics, farm performance and environmental impacts of representative dairy farms in Michigan transitioning from conventional confinement to a seasonal- and pasture-based systems, and evaluate the potential for integration of an AD in the confinement and seasonal pasture systems. In the economic analysis the annual pasture-based system had the greatest net return to management and unpaid factors followed by the seasonal pasture and confinement systems. The addition of an AD on a 100-cow, total confinement dairy decreased the net return to management and unpaid factors by 15%. Cycling manure nutrients led to an annual depletion of soil P and K on the confinement dairy and a build-up of P and K on the seasonal- and pasture-based dairies. There was little change in N, P and K or carbon loss to the environment due to AD. In the seasonal and annual pasture-based systems, ammonia emissions increased by more than 100%. The water and reactive nitrogen footprint increased and energy footprint decreased compared to the confinement dairy.

My dedication is to my husband who with all his love, support, sacrifice, encouragement and faith made the accomplishment of this thesis possible. With all my love this is for you.

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KEY TO SYMBOLS AND ABBREVIATIONS

A	Annual pasture-based farm
Ac	Acres
AD	Anaerobic Digester
ADIAC	Anaerobic Digester Initiative Advisory Committee
ADIP	Acid Detergent Insoluble Nitrogen
AEWR	Adverse Effect Wage Rate
ALFALFA	Integrative physiological model of alfalfa growth and development
ARS	Agricultural Research Service- US Department of Agriculture
ASABE	American Society of Agricultural and Biological Engineers
Avg.	Average
BIOCOST	Bioenergy crop costs
BOD	Biologic Oxygen Demand
Btu	British thermal unit
°C	Celsius degrees
C	Carbon
CAFOs	Concentrated Animal Feeding Operations
CC	Cash crop
CERES-Maize	Crop Environment Resource Synthesis for corn

CFR	Code of Federal Regulations
CH_4	Methane
CO	Carbon monoxide
CO_2	Carbon dioxide
CO_{2e}	Carbon dioxide equivalent
COD	Chemical Oxygen Demand
CP	Crude protein
CS	Cool season grass
ctw	Hundredweight
CWT-EQ	Hundredweight equivalent
DAFOSYM	Dairy Forage System Model
DairyGem	Dairy Gas Emissions Model
DGAS	Dairy Greenhouse Gas Abatement Calculator
DHIA	Dairy Herd Information Association
Dif.	Difference
DM	Dry matter
DNDC	Denitrification-Decomposition model
em.	Emission
EPA	Environmental Protection Agency

EPIC	Erosion-Productivity Impact Calculator
Ext.	Extension
F	Farm
FAO	Food and Agricultural Organization
FARMSIM	Farm Income Simulator
FPCM	Fat and Protein Corrected Milk
ft	Feet
gal	Gallons
GHG	Greenhouse Gas Emissions
GLYCIM	Soybean Crop Simulator
Gov.	Government
h	Hours
H_2	Hydrogen
H_2O	Water
H_2S	Hydrogen Sulfide
ha	Hectares
hp	Horse power
HRT	Hydraulic Retention Time
IEA	International Energy Agency

I-FARM	Integrated crop and livestock production and biomass planning tool
IFSM	Integrated Farm System Model
in	Inches
IPCC	Intergovernmental Panel on Climate Change
IRS	Internal Revenue Service
K	Potassium
kg	Kilogram
kJ	Kilojoule
km	Kilometer
kW	Kilowatt
L	Legume
LAM	Livestock Analysis Model
lb	Pound
m^3	Cubic meter
MBtu	One thousand British thermal unit
Mcal	Megacalorie
MDEQ	Michigan Department of Environmental Quality
MI	Michigan
min	Minutes
MJ	Megajule

MMBtu	Million British thermal unit
MSU	Michigan State University
MUSLE	Modified Universal Soil Loss Equation
MWh	Megawatt hour
N	Nitrogen
N_2	Dinitrogen
NAASQS	National Ambient Air Quality Standards
NASS	National Agricultural Statistics Service
NDF	Neutral Detergent Fiber
NFIFO	Net Farm Income from Operations
NH_3	Ammonia
NH_3-N	Ammoniacal Nitrogen
NH_4^+	Ammonium
NLEAP	Nitrate Leaching and Economic Analysis Package
NMPs	Nutrient Management Plans
NO_x	Nitrogen oxides
NPDES	National Pollutant Discharge Elimination System
NRC	National Research Council
NRCS	Natural Resources Conservation Service - US Department of Agriculture

P	Phosphorous
PM	Particulate Matter
ppm	Parts per million
S	Seasonal pasture farm
SRT	Solids Retention Time
SWAT	Solid and Water Assessment tool
t	Metric tonne
TAN	Total Ammoniacal Nitrogen
TS	Total solids
U	University
UDIM	United Dairy Industry of Michigan
USDA	United States Department of Agriculture
USDOE	United States Department of Energy
VS	Volatile solids
w	With
yr	Year

CHAPTER 1: INTRODUCTION

The United States has 51,481 dairy farms (Hoard's Dairyman, 2012) and is the primary milk producer in the world (Dairy Co, 2013). The U.S dairy industry is concentrated in the Great Lakes region with 72% of the United States dairy farms in 2012 (Hoard's Dairyman, 2012). This region is well suited for dairying because forage is abundant and can be stored as winter feed (EPA, 2012a). The Great Lakes region includes five of the top 10 milk producing states in 2012: Wisconsin, New York, Pennsylvania, Minnesota and Michigan (NASS, 2013). The Michigan dairy industry contributes $14.7 billion to the state economy (UDIM, 2013). According to the USDA, 98% of United States dairy farms are family owned and operated, often by multiple generations (UDIM, 2013).

In 2007 there were 9,158 million milk cows on 71,510 operations in the U.S. (Betts and Ling, 2009). These cows produced 84.2 billion kilograms (185.6 billion pounds) of milk along with an estimated 226.8 billion kilograms (500 billion pounds) of manure (Betts and Ling, 2009). Manure processing is routinely handled by collecting, storing and spreading it over the land. Manure contains several essential plant nutrients, such as nitrogen, phosphorous and potassium, which, when is apply correctly, can replace commercial fertilizer applications and increase crop yields. The type of manure and method of application (e.g. broadcast, injected) determine the quantity of nutrient available to the plant (Pennington and VanDevender, undated).

There have been frequent complaints related to manure management, odor, and water quality concerns, primarily directed at large livestock operations (Hadrich and Wolf, 2010). Manure-related problems typically occur when liquid manure is spread during the late winter and early spring when manure cannot be tilled in or adequately absorbed by the soil (EPA, 2011). These environmental concerns along with other factors such as the reduction of land base on which to apply manure, the increase in energy costs and growing interest in renewable energy has encouraged farmers to search for alternative manure handling methods (Betts and Ling, 2009).

One of the alternatives that produce renewable energy in cost-effective ways is biogas recovery system (U.S Department of Energy, 2012). The use of this technology has been increasingly attractive for manure management with around 30 million anaerobic digesters operating worldwide with manure (Chen et al., 2010). The Michigan Department of Labor and Economic Growth states that this technology is gaining interest because of Michigan new laws regulating odor, potential to reduce groundwater contamination and greenhouse gas production in various parts of the United States (Simpkins, 2005). EPA estimated that there were 188 anaerobic digester operating at commercial livestock farms for biogas recovery in the United States in 2012, and 158 were dairy digester projects (EPA, 2013).

The U.S. Environmental Protection Agency (EPA) in 2010 estimated 8,200 U.S. dairy and swine operations produce more than 13 million MWh of electricity with biogas recovery systems. Vanhorn et al. (1994) reported that dairy operations with less than 500 cows produce 3.4 million MWh annually. Anaerobic digesters allow compost and nutrient recovery. A byproduct of biodigesters is a high quality organic fertilizer that can be used in cropping systems. Odors associated with the land application of livestock waste are greatly reduced compared to raw manure (Simpkins, 2005; Zhao et al., 2008). Most dairies that own or contribute manure to biodigesters use the liquid effluent on their own fields (Lake-Brown, 2012). Anaerobic digestion kills several pathogens and effectively reduces biological oxygen demand (BOD) and chemical oxygen demand (COD) in waste, which protects surface waters when the effluent is land applied (EPA, 2005).

The emission of CO_2 and other greenhouse gases (GHG) has become an important issue. Governments and industries are interested in technologies that will allow more efficient and cost-effective waste treatment approaches which will minimize GHG production. Carbon credits will promote the need for CO_2 -neutral technologies (IEA Bioenergy, 2006). Anaerobic digestion also impacts farm economics. EPA-AgSTAR (2010b) evaluated the capital costs of dairy farms larger than 500 cows and compared common types of AD systems such as complete mix, plug flow, and covered lagoon. The smallest farm was 500 cows and used a covered lagoon as an anaerobic digester, with a capital cost of about $1600/per cow. A farm with 2,000 cows and a covered lagoon had a capital cost of about $700/per cow and a farm with 4,000 cows and a plug flow digester had a capital cost of about $750/per cow. One of the important factors that influence the feasibility of setting up an anaerobic digester on a dairy production system is how the managers utilize the byproducts (biogas and digestate) (Betts and Ling, 2009).

Perhaps the greatest operational challenge in integrating anaerobic digestion and pasture-based dairies is the variable and seasonal supply of feedstock, and the lack of knowledge of how to manage diverse feedstocks in the AD process. There is also a need for further research to make anaerobic digestion byproducts more readily available, cost effective, and manageable to small dairy facilities in the United States.

Researchers have created computer models that simulate crop growth, environment and farming systems. Computer models allow the analyst to predict the effect of changes in complex systems (Maria, 1997). Models can help stakeholders understand potential benefits, tradeoffs, costs and impacts associated with management, environmental and other factors (Loucks and Beek, 2005). A model should accurately represent the system and not be too difficult to understand (Maria, 1997). The decision to include or assume information in the model requires judgment, experience, and knowledge about the issues, the system being modeled and the decision-making environment (Loucks and Beek, 2005).

The Integrated Farm System Model (IFSM) is a whole-farm simulation model that uses historic weather data to determine long-term farm performance, environmental, and economic impacts of dairy operations. The simulation includes all of the major processes involved in the farming system including crop establishment, crop production, harvest, storage, feeding, milk production, manure handling and the return of manure nutrients back to the land (Rotz et al, 2011a). Recently, a sub-model was added to include on-farm anaerobic digestion.

IFSM has been used to compare pasture-based with confinement system dairies. Rotz et al. (2009) used IFSM to compare the predicted environmental impacts of four different dairy operations in Pennsylvania where two of them were confinement dairies and two were rotational grazing systems. They reported that the use of a grazing system could reduce erosion of sediment, runoff of soluble P, the volatilization of ammonia, the net emission of greenhouse gases and the C footprint. However, there is lack of information for evaluating the transition from a confinement system to a pasture-based system, and the feasibility of anaerobic digestion in such systems.

Rotz and Hafner (2011b) evaluated the addition of an anaerobic digester on a New York state large confinement dairy farm (1,100 cows) over 25 years of weather. They used farm records to validate simulated feed production and use, milk production, biogas production, and electric generation and use. The digester reduced the net greenhouse gas emissions and farm gate carbon footprint by 25 to 30% with a small increase in ammonia emission. There is a need to evaluate the environmental and economic impact of the integration of an anaerobic digester on a pasture-based system dairy farm with fewer than 500 cows.

Belflower et al (2012) evaluated the environmental impact of a management intensive rotational grazing dairy and a confinement dairy in southeastern of United States. They reported that ammonia emissions were higher on the confinement dairy due to manure handling. Greenhouse gas emissions per cow were also higher on the confinement dairy, but the carbon footprint from milk production on the pasture-based dairy was similar to the confinement system which had greater milk production per cow. They concluded that well-managed pasture-based dairy systems have environmental benefits due to reduced erosion and phosphorous runoff, and reduced gas emissions from manure.

1.1. Objectives

A comprehensive analysis was conducted using Integrated Farming System Model (IFSM) to evaluate resource use, economics and environmental impacts in the transition from a 100-cow, conventional confinement dairy to an annual pasture-based dairy. Specific objectives were to:

1. Evaluate the operating costs and labor requirements of representative confinement-based and seasonal-and pasture-based systems, including all major interactions from harvest and feeding through manure application, tillage and planting.
2. Compare the economics and performance of an anaerobic digester on representative confinement and seasonal pasture dairies.
3. Compare the environmental impacts of representative confinement, seasonal and annual pasture-based dairies.

CHAPTER 2: LITERATURE REVIEW

In recent decades many U.S. dairy farms have increased their net income by expanding herd size (Nott, 2003; USDA-NRCS, 2007). This increased the demand for feed and forage and encouraged the use of confinement systems. Large confined herds required larger structures for housing and feed storage and larger handling equipment and waste management systems (USDA-NRCS, 2007).

A transition from confinement dairy to pasture-based dairy has been adopted due to the profitability in the dairy industry in the Great Lakes Region (Nott, 2003). Pasture-based dairies can reduce feed, labor, equipment and fuel costs. It provides a lower-cost option for small farmers without expanding their dairy farm, or they can start dairying with less debt (USDA-NRCS, 2007). Economic studies show that grazing farms can provide satisfactory profits compared with confinement operations. Pasture-based systems generated $887 net farm income from operations (NFIFO) per cow and $4.22 per hundredweight equivalent (CWT EQ), compared to $640 NFIFO per cow and a negative $10 per CWT EQ (Kriegl and McNair, 2005).

From an environmental perspective, well-managed pasture-based dairies can reduce erosion and protect water, air, plant and animal resources by maintaining vegetation over the bare soil, increasing soil organic matter, improving water quality (because growing forages trap sediments, fertilizer nutrients, pesticides, animal drugs and pathogens), improving the distribution of nutrients on fields (because waste is more evenly spread) and reducing possible odors, spills, or runoff from animal waste storage areas (USDA-NRCS, 2007; Purdue Extension, undated extension bulletin).

2.1. Confinement Dairy Farms

USDA-NRCS (2007) defines a confinement-based dairy as one where land use and feed management systems optimize milk production with confined cows consuming harvested forages. In U.S. confinement dairies operations such as manure collection, storage, and land application vary with farm size and cattle housing system (Gourley et al., 2011). Almost all the herd is housed in a free stall or structure system with restricted or no access to pasture. Maternity stalls and calf pens are typically housed in a shed, barn or hutch (Powell et al., 2005).

Confinement operations have more control of feed quantity and nutrient concentration during the year which helps to stabilize milk production and nutrient concentrations in manure (Wattiaux and Karg, 2004). Confinement farms tend to import more nutrients than needed by the crops, and nutrient imbalance can result mainly when manure is applied in addition to fertilizer applications in the absence of a regular soil testing program (USDA-NRCS, 2007).

2.2. Pasture-based Dairy Farms

USDA-NRCS (2007) defined a pasture-based dairy as a land use and feed management system that optimizes the intake of forages consumed by grazing cows. USDA-NRCS (2007) stated that pasture-based systems are based on two primary resources: pasture, which is a low-cost feed (Soder and Rotz, 2001), and the dairy farmers management skills. Mechanical feed harvesting and storage are reduced because the cow harvests the crop directly from the field.

Pasture-based dairies have several benefits. Less purchased feed is required; therefore, fewer acres need to be harvested as stored forage. Producers can also extend the grazing season to fall, winter or spring by using different forage crops (USDA-NRCS, 2007).

Typically, in a pasture-based system, forage reaches the rumen as high quality feed (USDA-NRCS, 2007). Vegetative forage is higher in available protein, energy, and essential nutrients than stored forage. Vegetative forage is better than mature grass because grasses tend to build up thicker cell walls once they mature, meaning there are fewer nutrients available for the livestock (Purdue Extension, undated extension bulletin).

Seventy to eighty percent of nutrients of consumed feed and forage is returned to land (Whitehead, 1995). The dairy cattle diet, such as supplemental forages and concentrates, needs to maintain a balance of nutrients going out through milk production to reduce fertilizer applications. This maintains fertility levels in the cropland by replacing, with manure or inorganic fertilizer, the nutrients that leave the field in the harvested crop. Between 70 and 90 percent of the phosphorus, potassium, calcium and magnesium consumed by dairy cattle are excreted back onto the pasture (Mott, 1974).

Healthier cows with longer productive lives are common on pasture-based dairies. Grazing reduces foot and hoof problems, increases calving percentage, reduces parasite problems, and reduces fly problems (Purdue Extension, undated extension bulletin). Because cows tend to live longer less money is spent on replacement animals and more income is realized from selling heifers (Kriegl and McNair, 2005).

Grazing reduces manure handling and odors produced by concentrated manure areas because animals tend to herd less. In pastures, decomposition of manure and undigested feed occurs faster due to the aerobic conditions. In confinement systems, accumulated wet waste can increase the odor problem and ammonia volatilization (Tyrell, 2002).

There are many ways to graze, but some of the basic methods include continuous grazing, rotational grazing and management-intensive grazing. In continuous grazing, animals graze in a single large area for the entire season. This is the simplest form of grazing for the farmer in terms of costs and labor. However, this management practice is associated with low forage quality and yield, lower stocking rate, overgrazing and uneven manure distribution (Purdue Extension, undated extension bulletin).

Rotational grazing uses more than one pasture so grazing animals can be moved from one pasture to another based on their feed requirements and forage growth. This allows pastures to rest and re-grow, distributes manure more evenly, and increases forage production. The costs of this system are higher than continuous grazing because of the need for water distribution and fencing (Purdue Extension, undated extension bulletin).

Management-intensive grazing divides large fields into smaller paddocks so animals can be moved frequently at high stocking rates thereby providing as much of the needed forage as possible from pasture. This type of grazing systems provides the greatest forage production per area, controls weeds and brush naturally, provides the most even manure distribution, gives more forage options, and allows paddocks to rest and regrow completely. The disadvantages are that it requires careful monitoring and greater startup cost for water distribution and fencing (Purdue Extension, undated extension bulletin).

2.2.1. Characteristics of pasture-based dairy systems

USDA-NRCS (2007) described the characteristics for an efficient and productive pasture-based dairy system based on practices that optimize livestock performance, pasture quality and dry matter yield and the efficiency of forage utilization.

In pasture-based systems, lactating animals are pastured in a way that the entire herd grazes a fresh paddock on alternating days leaving sufficient forage. The animals are on pasture at least 75% of the grazing season and dry cows and heifers are 90%. Lactating animals obtain around 50% of their forage intake during the grazing season and dry cows and heifers obtain around 90%.

Every rotation cycle paddocks will vary in size to provide sufficient forage for adequate livestock intake and forage residual to maintain pasture growth. A back fence limits access to the paddocks that where recently grazed by the cows, while a front fence limits the availability of fresh and ungrazed grass. Lanes allow movement between the milk parlor and paddock. Cattle will have available water inside the paddock or in the lane near the paddock in which they are grazing. On average, a cow requires 2 to 2.3 kilograms (4.5 to 5 pounds) of water per day per pound of milk produced (Purdue Extension, undated extension bulletin).

A usual rule of thumb is that at least 0.40 ha (one acre) of pasture is necessary for each lactating cow and this area should be within 1.6 km of the milking facility during warm weather. Usually, forage yield will limit herd size (USDA-NRCS, 2007).

There are several indicators for assessing the economic success of various systems, but the best indicator is net farm income from operations (NFIFO) per cow or net cost of production per hundred-weight (CWT) of milk produced (USDA-NRCS, 2007). There are some cases where dairy herds exceed 9,072 kilograms (20,000 pounds) of milk per cow per year, and some producers have reported herd averages of 10,866 to 11,784 kilograms (24,000 to 26,000 pounds) of milk per cow per year. However, some pasture-based dairy herds are cost-effective producing 6,804 kilograms (15,000 pounds) of milk per cow per year (USDA-NRCS, 2007). Some obstacles are the types or characteristics of the climate or land base (rough, fragmented terrain, wet soils, heat and humidity or cold weather), which can prevent efficient grazing of dairy cows.

2.3. Transition from confinement to a pasture-based dairy

In the transition period from a confinement to pasture-based dairy it is important to take into account all aspects of the major shifts in production and operations. Some of the changes needed to increase efficiency are to improve the milking facilities to reduce milking time;

improve pasture fertilization by soil testing and applying recommended fertilizer rates; reduce expensive farm machinery investments; and during the grazing season feed pasture forage based on cattle dry matter intake, amount of standing forage within the paddock, and on forage nutrients (USDA-NRCS, 2007).

During the transition from confinement to pasture system there will be a temporary loss of milk production (Kriegl and McNair, 2005) because cows that have never grazed before expect feed that is provided in the barn and they may not know that they will need to graze to obtain feed. However, milk production will increase and meet or exceed their level of production when the cows have learned to graze and maximize dry matter intake from pasture (Purdue Extension, undated extension bulletin).

The onset of cold temperatures decreases the forage available for grazing; therefore, more feed needs to be supplemented in the barn and cows need to adjust to eat these feeds again. In general, cows are kept in the barn when nighttime temperatures consistently fall below 4.4 degrees Celsius (40 Fahrenheit). However, if there is forage available, the cows can graze during the day. There are also some farmers that are experimenting with “outwintering” their cattle. In this case, cows would be left out at night to adapt to the colder temperatures and the feed is brought to them (Purdue Extension, undated extension bulletin).

2.4. Anaerobic Digestion

Anaerobic digestion (AD) is a process where anaerobic bacteria degrade organic materials in an oxygen free environment to create biogas (mix of methane and carbon dioxide), which can be used to produce electricity and heat (Burke, 2001). The use of anaerobic digesters in the U.S started during 1970’s energy crisis. In 1972, a farm near the town Mt. Pleasant, Iowa, was one of the first farms of U.S. to install an anaerobic digester (Mattocks and Wilson, 2005).

Because of federal incentives, by the 1980's there were already 120 agricultural digesters (Center for Climate and Energy Solutions, 2011), but economic issues and technical problems led to a 60% failure rate of those digesters (Bishop and Shumway, 2009). In recent years, new incentives (grants and loan guarantees) and policies (in the form of renewable electricity standards) have helped increase the use of agricultural anaerobic digesters. EPA-AgSTAR (2011b) estimated 176 digesters were in operation in the United States for livestock manure and many of them were new. The number of digesters in use has been increasing gradually for more than a decade with an average of 16 new digesters each year (AgSTAR, 2011b).

2.4.1. Feedstocks for anaerobic digestion

The input for an anaerobic digester is biomass, such as manure, agricultural waste, and urban waste, though they are not similarly degraded or converted to gas (Burke, 2001). Co-digestion uses a mix of different feedstocks. The use of animal manure as a feedstock for AD is widespread because it produces a valuable fertilizer as well as biogas (IEA Bioenergy, 2006). Flowing, uniform manure slurry collected daily on a regular schedule is ideal, but pre-treatment may be required to adjust the amount of solids in the manure to meet the requirements of the digester (Betts and Ling, 2009).

Digestion transforms the content of manure. There are small reductions in the total of volume of manure due to saturation of the biogas leaving the reactor with water vapor, but this reduction is negligible (EPA-AgSTAR, 2011a). What make digesters helpful are the changes in manure properties and solids separation (Simpkins, 2005). This reduces undesirable odors (Simpkins, 2005) and most nutrients are transformed from an organic form to an inorganic form. The nutrients in manure improve crop yields by converting nitrogen to ammonium, a more readily available form for plant uptake (Betts and Ling, 2009; Lansing et al., 2008). Some studies have shown that crop yields are equivalent to but not greater than those with non-digested manure (Allan et al., 2003; Möller and Müller, 2012).

Instead of using only one type of biomass a mix of different types of biomass can be used. An advantage of co-digestion is an increase in different types of feedstocks that can be used for stakeholders that want to increase their biogas yield (The Minnesota Project, 2010). Although animal manure is a very well-known feedstock for anaerobic digesters, it produces a small amount of biogas per kilogram of biomass compared to other type of feedstocks (Biogas Energy Inc, 2008). The main problem with co-digestion is creating the right mix of feedstock based on availability and location so that the cost of transport of the feedstock is not higher that the profits due to the co-digestion (The Minnesota Project, 2010).

Typical dairy waste biogas is 55 to 65% methane and 35 to 45% carbon dioxide with some trace quantities of hydrogen sulfide and nitrogen (Burke, 2001). If animal waste and other organic feedstock are combined in the right way biogas production may increase anywhere from 200 to 500% (El-Mashad and Zhang, 2007). Figure 1 shows the estimated potential of biogas production from manure co-digested with three different percentages of feedstocks.

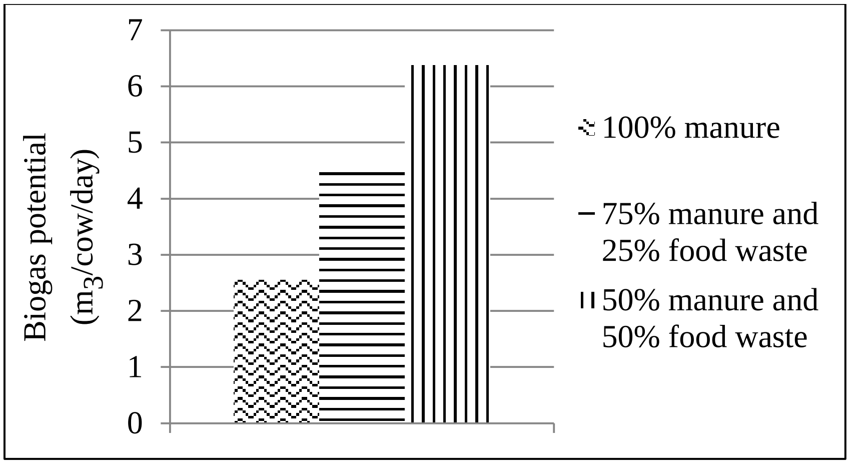


Figure 1. Estimated potential of biogas production from manure co-digested with three different percentages of feedstocks (Norman and Jianguo, 2004).

An additional benefit of co-digestion of organic wastes is that with the right combination of different organic wastes the amount of nutrients in the digestate can be optimized to create an effective fertilizer (EPA, 2005).

2.4.2. Byproducts

Outputs of anaerobic digestion are biogas and digestate. Biogas is available to heat the digester and potentially satisfy other farm energy needs and sometimes provide energy for export. Another byproduct is the digestate which can be divided into solid and liquid components using a separator and can be used as a fertilizer (Burke, 2001).

2.4.2.1. Biogas

The environment in the digester and the feedstock characteristics will affect the rate of conversion of biomass to biogas (Betts and Ling, 2009). Several factors can affect the rate of digestion and biogas production including temperature, pH, retention time, solids concentration, nutrient levels and carbon/nitrogen ratio, food to microorganism ratio, mixing of the digesting material and the particle size of the material being digested (Burke, 2001).

2.4.2.1.1. Temperature

In terms of overall system cost and reliability, medium-high temperatures are best (mesophilic temperature range 35°C- 40.5°C) (Simpkins, 2005). The mesophilic process is more tolerant to changes in feed materials or temperature. In the thermophilic range (50°C - 60°C) decomposition and biogas production occurs faster than in the mesophilic range but the process is less tolerant of changes. Biodigester temperature must be kept constant to optimize the digestion process (U.S Department of Energy, 2012).

The U.S Department of Energy (2012) reported that anaerobic bacteria can tolerate temperatures from below freezing to more than 57.2°C. Because methane bacteria are naturally widespread in the environment, anaerobic degradation can be achieved at moisture contents from around 50% to more than 99% but they operate best at temperatures of about 36.7°C (mesophilic) and 54.4°C (thermophilic) (IEA Bioenergy, 2006).

2.4.2.1.2. pH

The importance of pH in a digester is that it maintains the production and balance of methanogenic and acetogenic, or acetate-producing organisms. Chynoweth and Isaacson (1987) reported that the optimal pH for anaerobic digestion was between 7.0 and 8.0. The pH of manure is at 7.0 or slightly above (USDA, 2003). Methanogenic microorganisms require a pH between 6.8 and 8.5 to produce methane (Burke, 2001).

Acid forming bacteria typically grow more rapidly than methane forming bacteria, creating an excess of acid (low pH) in the system and inhibiting the activity of methane forming bacteria. Methane production may stop completely, but if it is maintained a large amount of methane producing bacteria these pH instability could be prevented (Burke, 2001).

2.4.2.1.3. Retention Time

Retention time determines reactor volume and maintenance of biological reactions. Hydraulic retention time (HRT) is the time a volume of influent remains in a digester. Solids retention time (SRT) is the length of time solids spend inside a digester and is the most important factor regulating the conversion of solids to gas and maintenance of digester stability (Burke, 2001).

Volatile solids (VS) are the basis for estimating organic composition and determining retention times. The degradation of VS in manure increases logarithmically with SRTs greater than approximately 10 days. After approximately 30 days, VS destruction increases linearly until a maximum of 65 percent VS conversion to gas is achieved (Burke, 2001).

The SRT and HRT are equal when the digesters do not have digestate solid/liquid separation, followed by recirculation (Burke, 2001). If the SRT is too low, the rate of microbial loss exceeds the rate of growth, causing a “wash out” and a low level of biogas production (Burke, 2001). If the SRT is high the AD must have a larger digester volume, increasing the ability to dilute toxic compounds and allowing more time for microbes to adapt to toxic compounds (Gerardi, 2003).

2.4.2.1.4. Solids concentration

Biogas production depends on the solids concentration of the feedstock when the digester is operating close to the optimum retention time (Wheatley, 1990). Lower VS concentrations require a longer SRT for effective biogas production (Chynoweth and Isaacson, 1987). Water content of raw biomass must be measured constantly because digestion of material with total solid content lower than 5% is usually not feasible (EPA, 2005) but some dilution can have positive effects. Water can dilute the concentration of some components such as nitrogen and sulfur from which ammonia and hydrogen sulfide can be produced and inhibit the anaerobic digestion process (Burke, 2001).

2.4.2.1.5. Nutrient requirements and carbon/nitrogen ratio

Carbon (C), nitrogen (N), and phosphorus (P) are macronutrients present in dairy cattle manure needed for production of methanogens. ASABE (2008) presents typical macronutrient values for as-excreted dairy lactating cow manure (Table 1). Chen and Hashimoto (1978) reported an optimal C to N ratio of 23:1 for methane forming microorganisms and Archer (1985) reported an optimal C to P ratio of 100-150:1. Iron, nickel, and sulfur, used in the reaction of acetate to methane, are the most important micronutrients required for production of methanogenic microorganisms. Other nutrients of importance needed in limited quantities, are selenium, barium, calcium, magnesium and sodium (Gerardi, 2003).

Table 1. Estimated manure characteristics as excreted (ASABE, 2008)

Characteristic	**Dairy Lactating Cow**	**Units**
Total solids	8.9	kg / day
Volatile solids	7.5	kg / day
COD	8.1	kg / day
BOD	1.3	kg / day
Nitrogen	0.45	kg / day
P	0.078	kg / day
K	0.103	kg / day
Total Manure	68	kg / day
Total Manure	68	liter / day
Moisture	87	% w.b.

2.4.2.1.6. Mixing of the digesting material

Mixing of the biomass during the digestion process can aid biogas production (U.S Department of Energy, 2012). Bedding mixed with manure can inhibit anaerobic digestion by reducing biogas production potential. Bedding increases bulk densities within digesters with materials that do not digest very well. The mass transfer within the digester will decrease and required mixing energies will increase, both of which reduce the overall performance of the digester (Arora, 2011). Sands and silts cause problems by clogging pipes, damaging equipment, and accumulating in anaerobic digestion tanks (Burke, 2001). The exception is at low concentrations in a well-mixed digester where the mixing keeps sand in suspension (Burke, 2001), even though the mixer takes up space and increases energy cost (Safferman, personal communication, 2013).

2.4.2.1.7. Food to microorganism ratio

Food-to-microorganism ratio (F: M) is important because it controls anaerobic digestion. The food-to-microorganism ratio (F: M) is the ratio of kilograms of waste supplied to the kilograms of bacteria available to consume the waste. Depending on temperature, bacteria will consume a limited amount of food per day, so one must supply the proper amount of bacteria to consume the required amount of waste. A lower F: M ratio will convert more quantity of waste to gas (Burke, 2001).

2.4.2.1.8. Biogas use

Biogas can be used as a high quality natural gas or as an alternative fuel in engines to generate electricity, boilers to produce hot water and steam, and gas fired absorption chillers used for refrigeration (USDOE, 1996).

Gas collected from anaerobic digestion is a combination of methane (CH_4), carbon dioxide (CO_2), and trace amounts of other gases such as water vapor and hydrogen sulfide (H_2S) (Walsh et al., 1988). The typical combination of biogas from a digester with dairy manure is listed in Table 2. Biogas properties influence the choice of technologies for cleaning and utilizing biogas (Yadav et al., 2013).

Table 2. Composition of Biogas from the Anaerobic Digestion of Dairy Manure

	Typical (Percent by volume)
Methane CH_4	60-70
Carbon Dioxide CO_2	30-40
Hydrogen Sulfide H_2S	300-4,500 ppm
Ammonia NH_3	Trace
Hydrogen (H_2)	Trace
Nitrogen gas (N_2)	Trace
Carbon Monoxide (CO)	Trace
Moisture (H_2O)	Trace
Other*	Trace

* Particles, Halogenated hydrocarbons, Nitrogen, Oxygen, Organic silicon compounds, and others (USADA-NCRS, 2009)

Each liter of waste processed will produce a quantity of energy depending on the percent conversion of volatile solids to gas. Volatile solids destruction results in methane generation. Each kilogram of volatile solids produces 0.36 cubic meter of methane. Each 0.03 cubic meter (one cubic foot) of methane can produce1055 KJ (1000 Btu) of energy. Therefore, 0.45 kilograms (one pound) of volatile solids will produce 5929 KJ (5620 Btu) of energy. At 35 percent conversion efficiency, the 0.45 kilograms (one pound) of volatile solids will produce 0.58 kWh of energy (Burke, 2001). Biogas can also be used for producing electricity through an internal combustion engine or gas turbine. The engine used produces waste heat (more than 60%) which can be used for heating the facilities, hot water and the digester (EPA, 2005). This generation of heat and power is known as “cogeneration”, which is created from biogas (Betts and Ling, 2009).

The biogas can be flared or burned off, but the only advantage is that it breaks down the methane through combustion, reducing methane emissions (Betts and Ling, 2009). However, this option for biogas does not produce revenue for the farm (Binkley, 2010).

2.4.2.2. Digestate

The non-gaseous material remaining after digestion is referred to as digestate (USDOE, 1996) and can be separated into solid and liquid fractions. Benefits of separating the solids and liquids from digestate include the recovery of bedding, decrease in volume of liquid manure storage, and the ability to sell solid digestate as fertilizer (Sheffield, 2008). The increase in temperature during the digestion process reduces pathogens that are found in waste that accumulates in waste storage facilities (The Minnesota Project, 2010).

Solid and liquid components of the digestate can be used as a fertilizer. In the solid portion of digestate most of the P remains and is sold as bulk fertilizer. The liquid portion retains much of the N that is largely converted to ammonium, which is the main component in commercial based fertilizers (The Minnesota Project, 2010). Both can be land applied, thereby offsetting commercial fertilizer purchases.

Manure from AD seems to reduce phosphorus and micronutrients that are available for plants, but there is no apparent effect on the short-term crop availability under field conditions. Möller and Müller (2012) showed that adding crop and cover crops residues to the anaerobic digestion process increased the total amounts of mobile organic nutrients within the farming system while nitrogen use efficiency was also higher.

It is common to use post-digestion solid waste as bedding for animals on the farm because it eliminates most, if not all, of the bedding costs. Most farmers that had used solid digestate as bedding report that is great for cow well-being and is also known to be less vulnerable to disease spreading bacteria, because the digestion process removes most of the digestible organic matter (EPA, 2005).

Another benefit of the digestate is odor reduction. Anaerobic digesters can reduce manure odors by 70% to 80% compared to untreated manure (Zhao et al., 2008). Two of the three stages of biogas production are related to odor. During the first stage there can be some undigested materials because some fibrous material cannot be liquefied and other inorganic materials can either accumulate or pass through the digester intact. Undigested materials make up the low-odor in the digestate (Legget et al., undated).

In typical liquid manure storage more acid forming bacteria can survive than methane forming bacteria (because of their sensitiveness to the environment), producing more acids that are not converted to biogas. This excess of volatile acids produces a putrid odor (Legget et al., undated). In contrast, during the second stage of the anaerobic digestion process more acids are converted to biogas thereby reducing odor.

Digestate can have some changes in composition during the digestion process. One of them is a reduction in solids content, which for manure slurry could be up to 25% with an increase in ash content, because of mineral conservation, decrease of slurry carbon and decrease of organic matter content. However, due to variability in feedstock and digester conditions, the changes can be inconsistent (Scottish Executive Environment and Rural Affairs Department, 2007). There is also an increase in slurry pH (up to 0.5) and ammonium nitrogen content (up to 25%) (Scottish Executive Environment and Rural Affairs Department, 2007).

The increase in slurry ammonium-N content could have some environmental impact by increasing emissions of ammonia during post-digestion storage, which could be controlled with storage covers and following application of the digestate on the land. The reduced solids content could improve surface infiltration of the digestate, which could help to conserve nitrogen (Scottish Executive Environment and Rural Affairs Department, 2007).

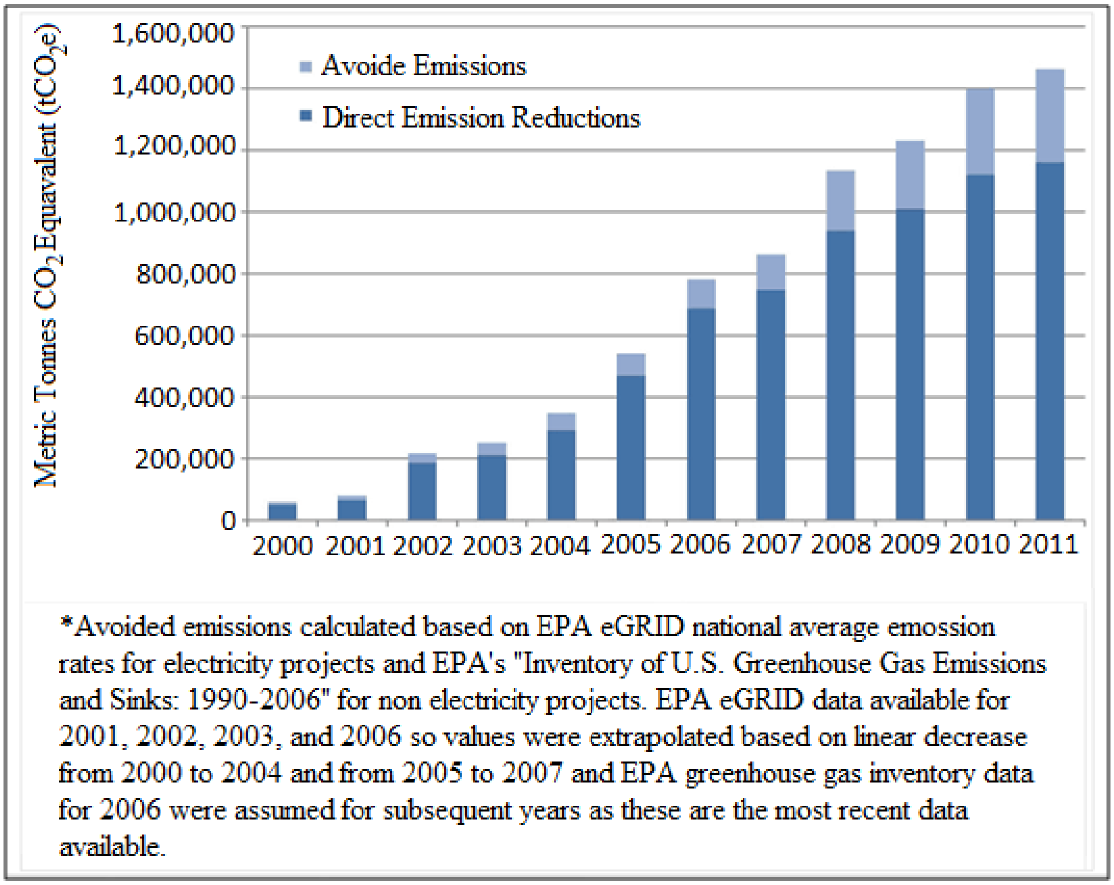
2.4.2.3. Reduce greenhouse gas emission

Anaerobic digesters reduce greenhouse gas emission reductions in two ways:

1. The capture and burning of biogas reduces methane emission which else would be released into the atmosphere from the waste management system (ADIAC, 2009).
2. Fossil fuels are displaced due to the use of biogas to generate energy, therefore greenhouse gases emissions (CO_2, methane, and nitrous oxide) and other pollutants are avoided (ADIAC, 2009).

The overall impact of converting CH_4 to CO_2 is beneficial. Methane from a digester is destroyed through combustion, and combustion produces CO_2 and H_2O. Methane is around 25 times more damaging than CO_2 in its effect on global warming (IPCC, 2007).

EPA (2012b) presents a graph (Figure 2), which shows the annual emission reductions, including both direct reductions and avoided emissions, due to anaerobic digesters since 2000. In total, the combustion of biogas at the digesters prevents the direct emission of about 61,000 metric tons of methane annually (1,278,000 metric tons of CO_2 equivalent) (EPA, 2012b).



*Avoided emissions calculated based on EPA eGRID national average emossion rates for electricity projects and EPA's "Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2006" for non electricity projects. EPA eGRID data available for 2001, 2002, 2003, and 2006 so values were extrapolated based on linear decrease from 2000 to 2004 and from 2005 to 2007 and EPA greenhouse gas inventory data for 2006 were assumed for subsequent years as these are the most recent data available.

Figure 2. Estimated Annual Emission Reductions from Anaerobic Digestion (EPA, 2012b). For interpretation of the references to color in this and all other figures, the reader is referred to the electronic version of this thesis.

2.4.3. Overall benefits and disadvantages of anaerobic digestion

Anaerobic digestion is a natural waste treatment process. It reduces disposed waste volume to be landfilled and it requires less land than aerobic composting (IEA Bioenergy, 2006). EPA (2012b) made a comparison of organic food scrap recycling technologies for a facility processing 40,000 tons per year of organic materials. Anaerobic composting required between 2.4 to 5.3 ha of land area and anaerobic digestion required 1.2 to 2.4 ha.

Anaerobic digestion is an energized process. Biogas is used for heat or electrical generation. Waste heat can be used for heating and cooling dairy facilities. The power generated is “distributed power”, which reduces the need to transform the power grid; therefore, the impact of new power on the power grid is decreased (Burke, 2001).

The time devoted to handling processed digested manure is reduced compared to raw manure. Nutrients are concentrated into a smaller volume reducing land required for liquid waste application (Burke, 2001). Anaerobic digestion also has an environmental impact by reducing greenhouse gas emissions and odors (IEA Bioenergy, 2006). From each ton of carbon recycled it can be obtained carbon credits (greenhouse gas credits). Revenues can be obtained from the treating imported wastes (tipping fees), the sale of nutrient-rich fertilizer and sanitized bedding, greenhouse gas credits, and the sale of power (Burke, 2001).

Anaerobic digestion has some disadvantages such as the need for a high level of capital investment in structures and facilities. Technical knowledge is also required because digesters require proper care, feeding, and good management. At least one person should be in charge of the digester for preventive and unscheduled maintenance, weekly maintenance for oil changes, engine overhauls and periodic digester clean-out. It is important to realize that anaerobic digesters can be a farm safety hazard because of confined space, lack of oxygen and exposure to toxic gas (Legget et al., undated).

2.4.4. Types of Anaerobic Digester

Although there are several types of anaerobic digesters, the most common are plug flow systems, complete mix digesters and covered lagoons. The systems are typically well adapted to the individual dairy operation where they are installed. By 2012, EPA had identified 153 anaerobic digester projects utilizing dairy manure in the United States: 79 were plug flow systems, 46 were complete mix digesters and 4 were covered lagoons (EPA, 2012b). Table 3 shows a summary of characteristics of digester technologies; Table 4 shows a summary of process attributes and Table 5 shows an expected percentage of volatile solids conversion to gas.

Table 3. Summary of Characteristics of Digester Technologies (EPA, 2004)

Characteristics	Covered Lagoon	Complete Mix Digester	Plug Flow Digester	Fixed Film
Digestion vessel	Deep lagoon	Round/Square In/Above-ground tank	Rectangular In-ground tank	Above ground tank
Level of technology	Low	Medium	Low	Medium
Supplemental heat	No	Yes	Yes	No
Total Solids	0.5-3%	3-10%	11-13%	3%
Solids characteristics	Fine	Coarse	Coarse	Very fine
HRT* (days)	40-60	15+	15+	2-3
Farm type	Dairy, Hog	Dairy, Hog	Dairy only	Dairy, Hog
Optimum location	Temperature and warm climates	All Climates	All Climates	Temperature and warm climates

*Hydraulic Retention Time (HRT) is the average number of days a volume of manure remains in the digester

Table 4. Summary of process attributes (Burke, 2001)

Attribute	Complete mix-mesophilic	Complete mix-thermo	Plug Flow Mesophilic	Covered Lagoon
Not limited by solids concentration	X	X		
Not limited by foreign material	X	X		
Digest entire dairy waste stream	X	X		
Sand and floating solids processing	X	X		
Best at odor control	X			
Treat additional substrate	X	X		
Stability			X	X
Simplicity			X	X
Flexibility				
Net energy production		X		

Table 5. Expected percentage VS conversion to gas (Burke, 2001)

Process	Load	Conversion to gas
Entire Waste Stream		
Completely mixed mesophilic	High	35 to 45%
Completely mixed thermophilic	High	45 to 55%
Partial Waste Stream		
Plug mesophilic	High	35 to 45%
Covered Lagoon	Low	35 to 45%

2.4.4.1. Plug Flow Digester

A plug flow digester is a long rectangular concrete tank with an air-tight cover where manure flows in one end and out the other with no axial agitation (Betts and Ling, 2009). Some internal mixing does occur because it is filled daily with biomass (Pennsylvania State University, 2009). Theoretically, as one plug of manure is added to the digester, one plug will leave the digester. A fraction of methanogens is displaced with the effluent, therefore part of the waste must be converted to new methanogens because they are not conserved (Burke, 2001).

This type of digester is best suited for thicker manure or waste containing a higher percentage of solid material (Pennsylvania State University, 2009). They are subject to stratification, but it can be partially avoided by maintaining a relatively high solids concentration in the digester (Burke, 2001). The digester is ideal for scraped and partially washed manure operations (Wilkie, 2005).

2.4.4.2. Complete-mix Digester

The complete mix digester (also referred to as a “continually stirred tank reactor”) heats and mixes the manure in a cylindrical tank for more efficient biogas conversion. Manure is mixed by a motor-driven impeller, pump, or other types of devices. The manure is usually heated in order to maintain a mesophilic or thermophilic environment (Betts and Ling, 2009). Usually, when co-digestion is to be used, a complete mix system is desired, especially when the characteristics of the added waste are different than manure (Totzke, 2009).

Scraped or flushed systems that are used to clean barns with water generate slurry manure. Slurry manure contain between three to ten percent of total solids, which works best in complete mix digesters system (Betts and Ling, 2009). Burke (2001) recommended not using manure diluted with parlor or flush water with the thermophilic digestion of dairy because necessary energy will meet the heat requirements.

2.4.4.3. Covered Lagoon

Covered lagoon digesters are best suited for extremely dilute manures stored in an anaerobic lagoon. It is essentially a pond with a cover that treats liquid manure consisting of less than 2% solids (Nelson and Lamb 2002). The reaction rate is affected by seasonal temperature variations (Burke, 2001). Odor may not be entirely removed due to incomplete digestion. They are more appropriate for flush manure collection systems with total solids of 0.5 to 3 percent (Betts and Ling, 2009).

These systems have long retention times, between 35 and 60 days, and are generally not heated. Anaerobic lagoons in climates with low temperatures are the most inexpensive type of digester (Nelson and Lamb 2002). Thus, they produce more gas in warmer climates but are also used in northern climates to also reduce odors (Pennsylvania State University, 2009). Increasing gas yield is accomplished by mixing or heating a lagoon digester, which increases costs. Periodically, covered lagoons must be cleaned at considerable cost (Burke, 2001).

2.4.5. Dairy Manure Digester

Extensive types of manure pretreatment and treatment options are available. Typical pretreatment involves screening and gravity separation of the solids. But it is recommended not to use pretreatment processes before anaerobic digestion because they produce odor, are expensive and impact potential energy generation. However, excess of sands, silts, and fibers should be removed as part of the anaerobic digestion process. Anaerobic treatment is the most effective on minimizing odors, producing fertilizer and/or bedding, producing energy and it also has the lowest operation and maintenance cost (Burke, 2001).

Figure 3 shows the manure characteristics and handling systems that are applicable for particular types of biogas production systems. Table 6 can help in matching an anaerobic digester with a facility. The warm and cold climate, described in Table 6, refers to the moderate to warm region below the 40th parallel and the cold region is above the 40th parallel.

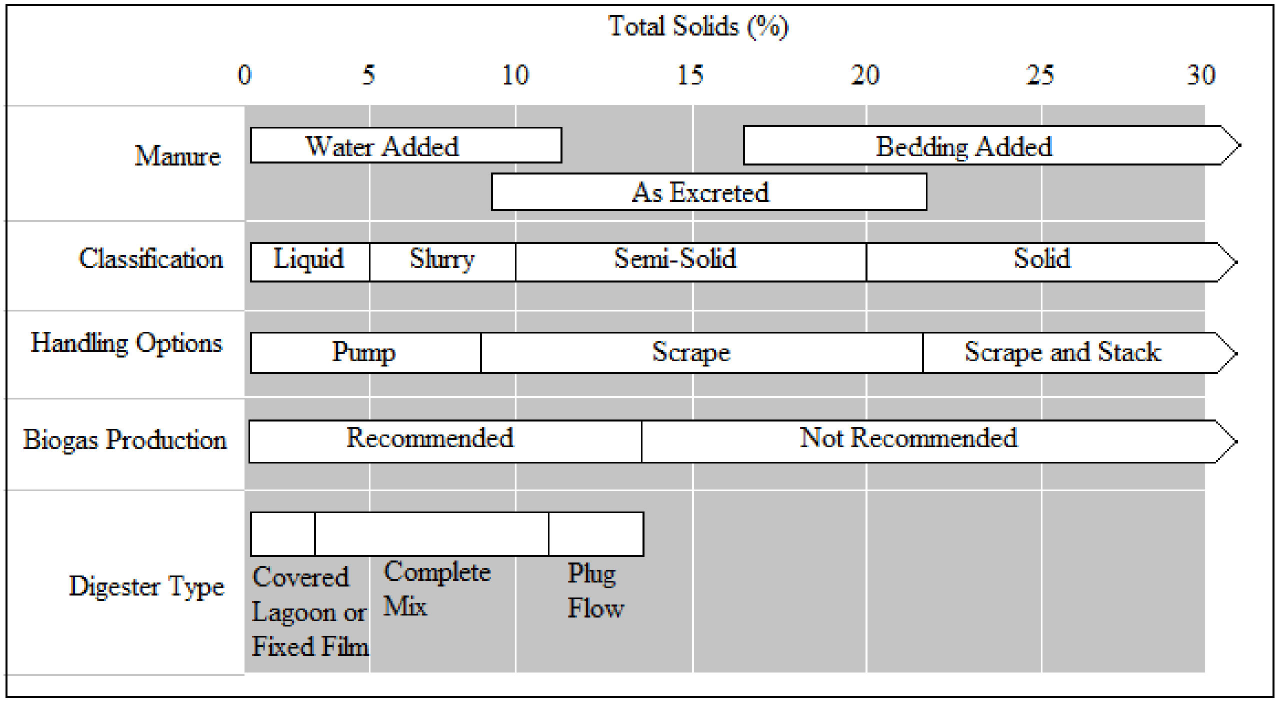


Figure 3. Appropriate manure characteristics and handling systems for specific types of biogas production systems (EPA-AgSTAR, 2004).

Table 6. Matching a Digester to a Dairy Facility (EPA-AgSTAR, 2004)

Climate	**Collection System**	**Estimated Min. Ratio of Water: Manure**	**%TS**	**Digester Type**
Moderate to warm	Flush	10:1	<3%	Covered lagoon
	Scrape and parlor wash water	4:1 – 1.1:1	3% - 11%	Complete mix
	Scrape manure only	N/A	>11%	Plug flow
Cold	Flush	10:1	<3%	Limited possibility for covered lagoon
	Scrape and Parlor wash water	4:1 – 1.1:1	3% - 8%	Complete mix
	Scrape manure only	N/A	>11%	Plug flow

Kirk and Faivor (2011) recommend understanding how site-specific conditions influence the solids characteristics and the biogas potential of the manure. The TS concentration of manure is a key in selection of an appropriate anaerobic digester and it can vary in several ways depending on the type of dairy housing facility and use of bedding and manure collection system.

A typical lactating dairy cow can support the production of 1.33 cubic meters (47.1 cubic feet) of biogas per day (Betts and Ling, 2009). Assuming that the biogas contains 65 percent methane, this would mean 1.33 cubic meters (47.1 cubic feet) of biogas per day or 0.62 kg (1.37 lb) of methane per cow per day (Table 7).

Table 7. Characteristics of lactating dairy cow manure and biogas potential (ASABE, 2005)

Component	Units	Per cow
Weight	Kg/day (lb/day)	68. 04 (150.00)
Volume	m^3/day (ft^3/day)	0.07 (2.40)
Moisture	%	87.00
Total solids	Kg/day (lb/day)	9.07 (20.00)
Total volatile solids	Kg/day (lb/day)	7.71 (17.00)
Chemical Oxygen Demand	Kg/day (lb/day)	8.16 (18.00)
Biological Oxygen Demand	Kg/day (lb/day)	1.32 (2.90)
Nitrogen	Kg/day (lb/day)	0.45 (0.99)
Phosphorous	Kg/day (lb/day)	0.08 (0.17)
Potassium	Kg/day (lb/day)	0.1 (0.23)
Biogas production[a]	m^3/day (ft^3/day)	1.33 (47.10)
Methane production[b]	m^3/day (ft^3/day)	0.87 (30.60)
Methane (CH_4)[b]	Kg/day (lb/day)	0.62 (1.37)
Btu[c]	Kg/day (lb/day)	14.02 (30.90)
kWh[d]	1055 KJ/day (1000 Btu/day)	2.00
Annual kWh per cow	Per day	744.00

[a] 90% of the manure collected; 30% conversion rate of COD of methane; 0.18 m^3 (6.3 ft^3) CH_4 per lb COD; 65% CH_4 in biogas (NRCS)

[b] Biogas with 65% CH_4 weighing 0.717 kg/m^3 (NRCS).

[c] Represents an average biogas with 65% CH_4, where CH_4 has a heating value of 35518.4kJ/m^3 (1010 Btu/ft^3) CH_4 (EPA, 2005).

[d] 66.6 kWh per 28.3m^3(1000 ft^3) CH_4; assuming 25% thermal conversion efficiency and 90% run-time (EPA, 2005).

2.4.5.1. Capital cost

The cost of a dairy waste management system involves: housing, collection, pre-processing, anaerobic digestion, energy production, liquid and handling irrigation, and solids disposal. Housing determines the amount of manure collected. Manure can be collected manually, or by automatic scraper, vacuum truck, or flush. Pre-processing (prior to digestion) and post-digestion (concentration of solids after digestion) can be realized by screening and or sedimentation. After digestion, energy is produced with an engine generator or turbine with heat recovery. It is also important to know the quantity of digestate produced, to know the storage size and disposal of liquid waste (Burke, 2001).

EPA-AgSTAR (2010b) analyzed AD system capital cost based on quotes for systems designed only for manure in 2003–2009. Data was collected from 40 dairy farms; from which 13 were complete mix digesters systems, 19 plug flow digesters, and 8 covered lagoons. The capital cost for each system includes the cost of the digester, the engine-generator set, engineering design, and installation. In order to analyze costs evenly, they omitted costs of post-digestion solids separation, hydrogen sulfide reduction systems, and utility charges including line upgrades and interconnection equipment costs and fees (EPA-AgSTAR, 2010b) Figure 4 shows while the smallest farm did have the highest cost per cow for the digester ($1,600), the largest farm did not have the lowest cost per cow ($750). Farms with the second and third smallest number of cows had relatively low costs per cow ($700).

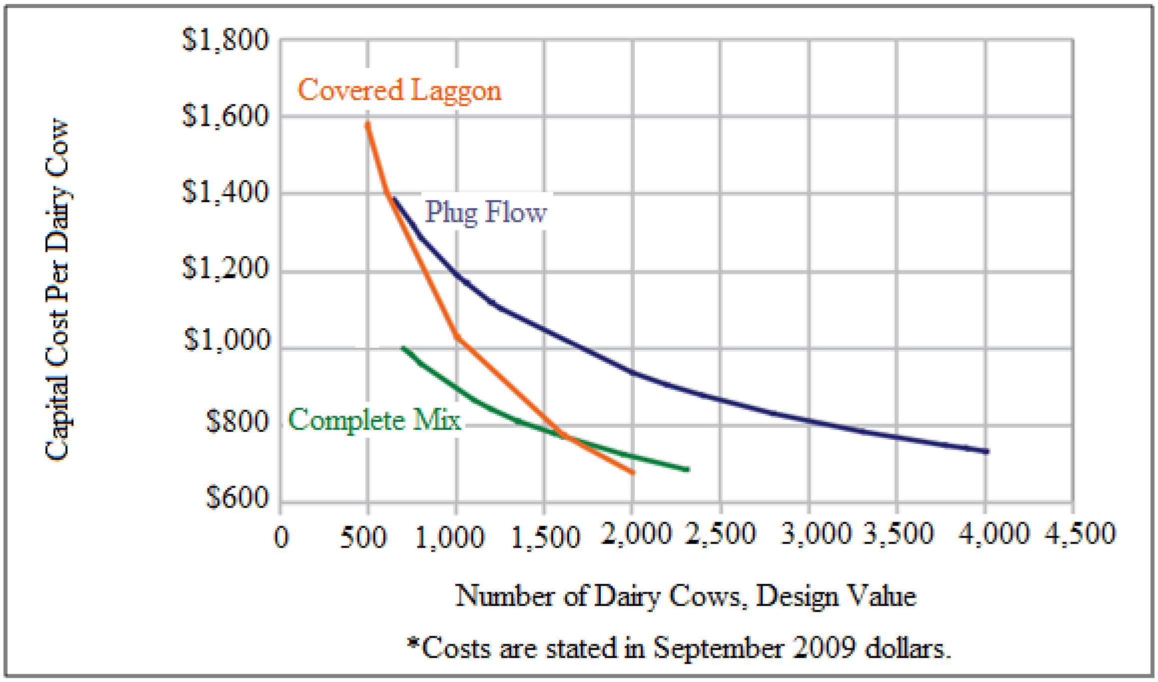


Figure 4. Capital cost per dairy cow for complete mix, plug flow, and covered lagoon AD systems (EPA-AgSTAR, 2010b).

The feasibility of setting up an anaerobic digester on a dairy production system will depend on how the managers use the byproducts (biogas and digestate). The average cost of additional digester equipment include: 1) post-digestion solids separators, 6.4% of total capital costs (range from: 1.5-12%), 2) biogas treatment system, 3.1% of total capital costs (range: 0.3-6.0%) and 3) estimated utility charges, 5.3% (range: 1.7-13.5%). The engine and generator costs usually account for 40% of project costs (EPA-AgSTAR, 2010b).

In the case of small-scale digesters, U.S. EPA does not recommend biogas recovery systems for livestock farms with less than 500 cows. Moser (2011) reported that 200-400 cows were needed for an economically viable digester system. In 2010 the majority (74%) of U.S. dairy farms had less than 100 cows and in 2011, 88% had less than 200 cows, making anaerobic digestion not feasible to most of U.S. dairy farms (U.S. Census Bureau, 2012).

Revenue from electricity sales has been profitable for large-scale operations (Nelson and Lamb, 2002), but small-scale digesters are not often profitable due to their dependence on the electricity price and the high cost of infrastructure needed to sell electricity back to the grid (Lazarus and Rudstrom, 2007; Ghafoori and Flynn, 2007).

Electrical generation from biogas was not economically viable but the use of biogas to accomplish the heating requirements on-farm was found to be economically feasible in small-scale dairy farms (Bishop and Shumway, 2009). However, Millen (2008) reported on two small dairy farms (130 and 70 cows) in Ontario that were producing electricity and were profitable. The farmers credited their success to receiving additional waste (130 cow farm only), having a buyer for their electricity, and substantial time dedicated to the project development stage.

Several studies have found that direct use of biogas can be profitable on smaller farms when the on-farm heating requirements were high enough to regularly utilize all the produced biogas (Bishop and Shumway, 2009). Another motivation for farmers to install an anaerobic digester is the reduction of odor and improvement of air and water quality. A survey of 64 producers across the United States and 10 in California found that both were the main motivation for digester installation (EPA-AgSTAR, 2007).

Possibly the biggest economic challenge for small-scale digestion systems is the uncertainty of traditional (e.g. electricity) and non-market factors (e.g. bedding reuse). Stokes et al. (2008) emphasized the lack of quantifiable data on non-market benefits as a major obstacle to widespread anaerobic digestion implementation. Another challenge is the cooperation of the local electrical utility. In many cases this has discouraged dairies from installing digesters that had been planned (Lazarus, 2008).

The Minnesota Project, a group funded by EPA-AgSTAR, is searching for solutions for small- and mid-sized dairies. In 2005 they started a feasibility study on the use of the anaerobic digestion technology by scaling it down and still providing financial incentives for farmers to use it. The Minnesota Project evaluated six anaerobic digestion systems designed for confinement dairies between 100 and 300 cows. They concluded that the digester costs, which were between $105,000 and $230,000, were still too high (Goodrich, 2005).

The Minnesota Project prepared a case study based on the Jer-Lindy confinement dairy farm in central Minnesota with 97 ha (240 acres) and 160 milking cows producing about 11,356 L (3,000 gallons) per day of manure based on built a small-scale digester with an up-flow tank system with a 124,918 L (33,000 gallon) holding capacity and five-day HRT. The total a cost of the system was $460,000 (Table 8) (Lazarus, 2009). In operation several technical and maintenance issues caused problems: engine failure, computer control system problems and issues with manure handling (Lazarus, 2009).

Table 8. Investment required for similar or any dairy operation with 160 milking cows (Lazarus, 2009)

Items	Investment
Digester tank, gen-set and set up	$ 267,000
Fan separator	$ 36,000
Building costs and concrete	$ 33,000
Utility hook up	$ 12,000
Flare and boiler	$ 13,000
Specific items that vary from operation to operation	
Tank insulation	$ 32,000
Labor	$ 15,000
Additional plumbing and electrical work	$ 20,000
Pump and agitator	$ 22,000
Excavation	$ 10,000
Total digester investment	$460,000

The economic analysis evaluated the added value by the generator and the projected costs of owning and operating it. The analysis assumed that the system would produce 430 kWh of electricity per day in which 95 kWh was used to run the pumps, digester and fan separation equipment and 335 kWh per day to replace electricity purchases or to sell back to the grid (Table 9). The manure solids from the separator replaced the sand bedding that normally costs around $1,000 per month (Table 9) (Lazarus, 2009).

Solids breakdown in the digester was assumed to reduce manure hauling and agitation costs by $2,400 per year. The most liquid fraction of the digestate could be applied at higher rates on less areas and possibly reduce the pumping cost (Table 9). The sale of carbon credits due to the breakdown of methane in the anaerobic digestion process (Table 9) was considered as an additional source of income (Lazarus, 2009).

Table 9. Economic analysis of the digester (Lazarus, 2009)

Items	$/year
Sources of value	
Electricity generated (335 KWh/day x 365 x $0.085/KWh)	$10,393
Bedding ($75/cow)	$12,000
Reduced manure agitation and hauling	$ 2,400
MN Renewable Energy Production Incentive	$ 1,834
Carbon credits (around $5.75 per metric ton of CO_2 on the Chicago Climate Exchange on 6/12/08)	$ 556
Total annual benefits	$27,184
Project investment	
Engine overhauls (assume every 3-5 years)	$ 1,250
Other O&M (2% of investment) and labor (assume 0.3 h/day)	$ 11,390
Depreciation and interest on digester and mechanicals (20 years life, 6% interest rate)	$ 29,453
Total annual cost	$ 42,093
Grant funds (covered 72% of the Project)	$ 329,900
Project investment net of grants	$ 130,100
Annualized value of grants amortized over 20 year life	$ 16,495
Total annual costs net of grants	$ 25,598
Net return/year over operating and ownership costs	$ 1,586
Years to payback	11

2.4.5.2. Electricity

In Michigan, two anaerobic digesters are producing 16,897 MWh per year, both from a dairy farm with about 3,000 cows feeding the complete mix digester (EPA, 2012b). One cow can produce roughly 14,770 KJ (14,000 Btu) per day (0.00017 MWh). It would require the manure from around 50 cows to produce enough biogas each day for heating one home (Colorado State University, undated). The annual value of avoided electricity purchases or electricity sales may amount to $94 per cow, based on an electricity rate of 12.96 cents per kWh (2012 U.S. Michigan, Large commercial average) and assuming the digester supports the generation of 2 kWh per cow per day (Betts and Ling, 2009).

Various arrangements have been used to capture the value of electricity generated by the combustion of biogas from anaerobic digestion of manure. EPA (2004) showed the arrangement for selling on-farm generated electricity:

- Biogas sales: The electricity produced is owned by the utility which operates the on-farm generator. The dairy digester operation sells biogas to the utility and purchases all electricity needed for dairy operations at retail rates.
- All electricity sold: The dairy digester operation sells all its biogas-generated electricity to a utility (usually at the utilities avoided cost rate) and purchases all the electricity needed for dairy operations from the utility at retail rates.
- Surplus electricity sales: The dairy digester operation generates the electricity needed for dairy operations on-farm, and excess of electricity produced is sold to the utility (usually at the utilities avoided cost rate). If the dairy requires any excess of electricity, this will be purchased from the utility at retail rates.
- Net metering: The dairy farm will purchase only the net difference between the quantity of electricity consumed and the quantity that the dairy digester operation produces.

Binkley (2010) concluded that net metering benefits over the other arrangements for herd sizes between 500 to 1,450 cows. The farm would not pay charges related to standby or administration that is based on the capacity of the engine-generator required to produce the electricity.

2.4.5.3. Biomethane

Biomethane can be upgraded to natural gas containing more than 95% methane. Biomethane is obtained from gas produced in the digester by removing hydrogen sulfide, moisture, and carbon dioxide, and when treated correctly it can be used as a substitute of natural gas (Krich et al, 2005). Biogas produced in an anaerobic digester usually contains around 40% carbon dioxide, however pipeline quality natural gas contains less than 1% carbon dioxide (EPA, 2005), making the conversion from biogas to natural gas costly (Krich et al, 2005). Biomethane can substitute pipeline quality natural gas which is used for households, commercials or industries (EPA, 2005). However, few projects have upgraded the biogas to pipeline quality and provided methane to a nearby commercial natural gas pipeline (Krich et al, 2005).

2.4.5.4. Heat

Almost half of the engine fuel energy can be recuperated with the waste heat which comes from the engine jacket and exhaust gas. This waste heat can be used for maintaining the temperature in the digester, heating farm buildings, water, and/or alley floors. Also waste heat could be used to warm the manure that is entering the digester, reducing the amount of heat used for changing the manure temperature to the optimum digester temperature (EPA, 2005). Avoided fuel purchases for heating will depend on the price of fuel and the ability of the operation to utilize the heat (Betts and Ling, 2009).

2.4.5.5. Digested solids

Using digested solids as cow bedding has advantages and disadvantages. An advantage is that it may improve cow health (reduced pathogens) and improve milk production (increased revenue). However, additional equipment and operating costs for separating the digested solids from the effluent are required. In addition, using digested solids as bedding requires operator time to avoid potential mastitis problems leading to higher veterinary expenses and lower milk production and sales (Betts and Ling, 2009).

2.4.5.6. Carbon-credits

Methane captured from the anaerobic digestion of dairy manure may meet the requirements for carbon credits if it is prevented from escaping to the atmosphere. The global warming potential of methane is equivalent to 25 times that of carbon dioxide (IPCC, 2007). Reducing one metric ton of methane gas emission has the same impact as reducing 25 metric tons of carbon dioxide emissions. Based on 2009 national analysis, the use of methane through anaerobic digesters reduced greenhouse gas emissions by over 1.1 million metric tons of carbon dioxide in U.S (EPA-AgSTAR, 2010a).

In the United States, there are several trading mechanisms for buying and selling carbon credits. The transaction could be by private negotiations or trading through formal exchange mechanisms. It could also be by auction through The World Green Exchange, which provides a superior price detection system by enabling buyers and sellers to see what the market will command in real time.

2.4.5.7. Fertilizer

Improved fertilizer value (over raw manure) could allow some sales of effluent, and less viable weed seeds potentially lower herbicide costs. The minimal odor of the effluent may allow more flexibility in the timing of land application than for raw manure. This flexibility may afford economic benefits to the dairy operation.

2.4.5.8. Environment

Using the AD also reduces the water contamination risk, greenhouse gas emission and the quantity of pathogens. Some firms may be willing to pay the dairy a tipping fee for disposal of their organic waste. However, this additional substrate will require increased management (e.g. handling the substrate) and negotiation (Betts and Ling, 2009).

2.4.6. Regulations

Odor and water quality complaints accounted for 75% of all complaints related to livestock facilities registered with the Michigan Department of Agriculture (1,289 observations) between 1998 and 2007 (Hadrich and Wolf, 2010). The costs of corrective actions on water quality improvement are significantly higher than odor reductions in dairy farms that incorporate manure.

In general, small farms are not required to get a permit unless it is proven that pollutants are discharged to surface water bodies. At that point, farms of any size are required to obtain permits and follow regulations set forth by the Michigan Department of Environmental Quality (MDEQ Rector, 2007).

Agriculture impact on greenhouse gases is another important aspect that has been regulated. Carbon dioxide, nitrous oxide and methane are emitted to and/or removed from the atmosphere through agricultural activities. The concentrated animal feeding operations (CAFOs) emit air pollutants that are harmful to public health and damaging the environment. Ammonia emissions from animal agriculture account for about 50% of the total ammonia emissions into terrestrial systems (National Research Council, 2003). In 2007, the dairy sector emitted 1,969 million tonnes CO_{2e} (±26 percent) globally of which 1,328 million tonnes was attributed to milk production (FAO, 2010). Currently, the EPA provides no regulation for air pollution from CAFOs. Federal laws establish minimum standards for the regulation of any activity that causes air pollution.

2.4.6.1. Federal Regulations related to Anaerobic Digestion

2.4.6.1.1. Air regulations

In general, state permits are required if on-site combustion devices exceed federal emissions limits. EPA-AgSTAR (2012b) presents federal air permitting requirements for:

- <u>Internal combustion engines</u>: should fulfill federal emission standards (40 CFR Part 89) for non-road engines, which include limits for nitrogen oxides (NO_X), hydrocarbons, carbon monoxide (CO), and particulate matter (PM).
- <u>Steam generating devices:</u> Only for the case of devices built after June 19, 1984 and with a heat capacity over 10.5 million KJ per hour should fulfill federal emission standards which include limits for PM, sulfur dioxide, and NO_X (40 CFR Part 60, Subpart Db or 40 CFR Part 60, Subpart Dc).
- <u>Boilers</u>: Only for the case of devices with a heat capacity over 10.5 million KJ per hour should fulfill National Emission Standards for Hazardous Air Pollutants (40 CFR 63 Subpart DDDD), which include limits for arsenic, cadmium, chromium, lead, magnesium, mercury, and nickel.

Additionally the Clean Air Act of 2012 requires EPA to set National Ambient Air Quality Standards (40 CFR part 50) for contaminants harmful to public health and the environment. Therefore EPA's National Ambient Air Quality Standards (NAASQS) states the limits of combustion devices emissions such as ozone, PM, CO, NO_X and sulfur dioxide.

2.4.6.1.2. Solid Waste regulations

Permits for manure solid waste are not required by the federal laws, but in some states the mixing or use of other types of substrates may denominate the anaerobic digester as a waste management facility (EPA-AgSTAR, 2012b).

2.4.6.1.3. Water regulations

The discharges by CAFOs are regulated by The Clean Water Act which requires the dairy facilities a National Pollutant Discharge Elimination System (NPDES) permit. Part of the discharges to the U.S waters includes improper land application of manure (EPA-AgSTAR, 2012b). For large CAFOs (more than 700 mature dairy cows), additionally to the NPDES permit a Nutrient Management Plans (NMPs) should be developed and maintained to guarantee correct land application of manure. If smaller farms discharge to water bodies through a manufactured device or through direct contact of the animals, they will also be required to have a NPDES permit and NMPs (EPA-AgSTAR, 2012b).

2.4.6.2. Michigan permitting requirements related to Anaerobic Digestion

Individual states have regulations on how farms operate anaerobic digesters. The Michigan Department of Environmental Quality presents air and water quality and solid waste regulations.

2.4.6.2.1. Air permits

Anaerobic digesters require an air permit if combustion is occurring onsite and produces more than 0.45 kilogram (1 pound) of sulfur dioxide in an hour or has a heat input capacity greater than 10.5 million KJ per hour, with no difference if organics are included (MDEQ Rector, 2007).

2.4.6.2.2. Solid waste permits

If the anaerobic digester has only manure as biomass, a solid waste permit would not be required. But if other biomass is added to the digester a permit is needed for composting or land applying the solids (MDEQ Rector, 2007). There are some substrates that do not require a permit if the digester receives less than 20% of the substrate, such as food processing waste, syrup from ethanol production, and grease trap wastes that do not include seepage and fish wastes (Department of Natural Resources and Environment, 2009).

2.4.6.2.3. Water permits

If the anaerobic digester is operated with only manure a water permit is not required. But if other types of biomass are added to the anaerobic digester a water permit will be needed for land application. CAFOs with permission must include an anaerobic digester in their nutrient management plan (NMP) (MDEQ Rector, 2007).

2.5. Systems Modeling and Simulation

Computer models allow the analyst to predict the effects of changes in complex systems (Maria, 1997). Models can help to access the benefits, tradeoffs, costs and impacts associated with management, environment, and other factors (Loucks and Beek, 2005). A model should accurately represent the system (Maria, 1997). The decision to include or assume information in the model requires judgment, experience, and knowledge about the issues, the system being modeled and the decision-making environment (Loucks and Beek, 2005).

Usually, a simulation model is a mathematical representation developed with simulation software (Maria, 1997). Mathematical models include “known variables” or “parameters” and “unknown variables” or “decision variables” to be determined. In mathematical terms the model describes the system being analyzed, and the constraints which are the conditions that the system has to satisfy. Constraints define the system components and their inter-relationships, and the permissible ranges of values of the decision-variables, either directly or indirectly. Typically, there exist many more decision-variables than constraints, therefore, if any feasible solution exists, there may be many solutions that satisfy all the constraints (Loucks and Beek, 2005).

Model parameter values can be uncertain; therefore, the relationship between various decision variables and assumed known model parameters may be uncertain. This is important because the output of the model will respond with respect to the parameters and model structures (Loucks and Beek, 2005).

The model types can be categorized by simulation process, which depends on the application. The main types of models are those based on simulation period such as discrete and continuous, and the models based on how they were simulated such as deterministic and stochastic.

Discrete models advance from event time to event time rather than using a continuously advancing time (Ündeğer, 2008). Continuous models use time-varying interactions among variables (Maria, 1997).

Deterministic simulation models use fixed input and output variables (Maria, 1997). The model does not contain probability. Every run result will be the same, but a single run is enough to evaluate the result (Ündeğer, 2008). Stochastic simulation models have at least one probabilistic input or output variable initiated using random numbers (Maria, 1997). Different runs initiated with different random numbers generate different results. This requires multiple runs to evaluate the results (Ündeğer, 2008).

No model is perfect. However, modeling and simulation should consider every aspect of a proposed changes; therefore, operating procedures or methods can be explored without the need of experimenting with the real world systems. Models provide understanding of how a system operates; therefore, be able to give predictions about how a system will operate under different scenarios (Ündeğer, 2008). An advantage is a better understanding of interactions within the variables that make up a complex system. Modeling and simulation determines answers to “why” questions by recreating the scene and taking a closer look at what has happened during the run. There can also be answers to “what-if” questions for determining future improvements and new designs to the system (Ündeğer, 2008).

Simulation modeling also has disadvantages such as special training for model building and results interpretation, such as determining if an observation is due to system interrelationships or just arbitrariness. It can also be time consuming and expensive. Economizing on resources for modeling and analysis may result in a simulation not detailed enough for the problem and may consume time, effort and money for nothing (Ündeğer, 2008).

There are several models that have been developed for crop modeling, farm economics, farm environmental and animal modeling.

2.5.1. Crop models

ALFALFA is a dynamic computer simulation model of the growth and development of alfalfa (University of California, 2010). Crop Environment Resource Synthesis (CERES-Maize) is a deterministic model that simulates in a field scale corn growth, soil, water, temperature and soil nitrogen dynamics during one growing season (Ritchie et al., undated). Therefore, CERES-Maize predicts the duration of growth, the average growth rates, and the economics related to it (Ritchie et al., 1998).

In order to simulate the carbon and nitrogen biogeochemistry in agro-ecosystems the Denitrification-Decomposition model (DNDC) was created. The model predicts crop yield, C sequestration, nitrate leaching loss, and emissions of C and N gases in agro-ecosystems. It was developed by the institute for the Study of Earth, Oceans and Space University of New Hampshire (University of New Hampshire , 2009). GLYCIM is a dynamic soybean simulation model with hour time scale. It uses deterministic simulation of organism-level processes (photosynthesis, transpiration, carbon partitioning, organic growth and development) to predict growth and yield of a soybean crop depending on climate, soil, and management practices (Acock and Trent, 1991).

2.5.2. Farm economic models

Some models focus on farm economics such as BIOCOST, which is an EXCEL-based software program that can be used to estimate the cost of producing bioenergy crops in seven U.S regions (Walsh and Becker, 1996). FARMSIM is a simulation model used for projecting the probable economic and nutritional impacts of alternative technologies, farming systems, livestock management programs, marketing arrangements, crop mixes, risk management schemes, and environmental remediation programs on a representative crop/livestock farm (Schaber, undated; Edwards, 2007).

2.5.3. Farm environmental and animal models

Livestock models typically focus on management and economics. Gaseous emissions submodels are being added to many livestock models. Livestock Analysis Model (LAM) characterizes cattle and buffalo herds used to produce livestock products: milk, meat, and draft power. LAM evaluates the impact of changes in production, and present and future methane emissions from cattle and buffalo populations (EPA, 2010). The Dairy Gas Emissions Model (DairyGEM) is a process level simulation for estimating ammonia, hydrogen sulfide and greenhouse gas emissions of dairy operations based on climate and farm management (Rotz et al.,2012).

2.5.4. Whole farm simulation models

Livestock and cropping systems models are often constrained by geographic location or cropping options. The DairyWise dairy farm model simulates popular feed crops like grazed grasses or corn (Sendich, 2008). The Dairy Greenhouse Gas Abatement Calculator (DGAS) is designed for the Australian climate and is not applicable for the Great Lakes Region (The University of Tasmania, 2013).

Whole farm simulation models such as the Integrated Farm System Model (IFSM) and I-FARM which integrates crop and animal management components are uncommon (Sendich, 2008). Iowa State University created a whole-farm simulation model called I-FARM, which predicts economic and ecosystem impacts due to farm operations across the United States. The model includes several crops and crop rotations with associated tillage, fertilization, planting, weed control, harvesting, and residue removal. Livestock systems are simulated based on feed intake, growth rate, grazing or confinement options, and manure management systems (Iowa State University, 2010). One of the differences between I-FARM and IFSM is that IFSM integrates anaerobic digestion as a waste management system.

2.5.1. Integrated Farm System Model

The Integrated Farming Systems Model (IFSM) is a whole-farm simulation model that has been in development since the early 1980’s and was first known as the Dairy Forage System Model or DAFOSYM. The model operates with a daily time step and includes all major components of the livestock and crop production system including feed production, storage and disappearance, animal performance, manure handling, tillage, and planting operations. In order to make the model more comprehensive it was included the simulation of growth, harvest, and storage of grass, small grain, and soybean, beef production and the option of only crop production (no animals). An anaerobic digestion sub-model (Rotz et al, 2011b) and environmental components such as ammonia volatilization, nitrate leaching, phosphorus runoff, and greenhouse gas emissions were also added (USDA, 2012).

The main difference between IFSM and most farm models is that IFSM simulates all major farm components on a process level. This allows the components to link the major biological and physical processes interacting on the farm and is a powerful tool for analyzing the effects of management and new technologies in the context of the whole-farm system (USDA, 2012). IFSM is designed mainly for temperate regions of the northern United States and southern Canada.

Belflower (2012) used IFSM to simulate an intensively-managed rotational pasture-based dairy and a confinement fed dairy in the southeastern part of United States. The study evaluated management effects on the environment, such as greenhouse gas emissions, carbon footprint, etc. Rotz et al. (2009) used IFSM to compare the predicted environmental impacts of four different dairy production systems in Pennsylvania and reported that the use of a grazing system could reduce erosion of sediment, runoff of soluble P, the volatilization of ammonia, the net emission of greenhouse gases, and the C footprint.

Rotz et al. (2011a) evaluated environmental and economic impact of manure application methods in farming systems in Pennsylvania and reported that shallow disk injection was the most affordable with the lowest environmental influence. Rotz and Hafner (2011b) simulated the addition of an anaerobic digestion on a dairy farm in New York over 25 years of weather. Farm records were used to validate the simulations of feed production and use, milk production, biogas production, and electric generation and use. The anaerobic digester decreased net greenhouse gas emissions and the carbon footprint. The economic analysis showed no direct profits to the producer.

CHAPTER 3: PROCEDURE

A comprehensive analysis was conducted using the Integrated Farm System Model to describe, evaluate, and compare the economics, resource use and environmental impacts of representative dairy farms transitioning from conventional confinement to a year round pasture-based system and the potential for integration of an anaerobic digester in a small confinement and seasonal pasture dairy.

In order to describe, evaluate and compare a range of farming systems, five representative dairy farms were compared using the IFSM model. The representative farms do not describe a specific farm; rather they are designed to reflect common features regarding land base, machine selection, crop production, number of cows and young stock and other key components. The five systems include: 1) conventional confinement system with 100 large-frame Holsteins, 2) conventional confinement system with 100 large-frame Holsteins and an anaerobic digester, 3) seasonal pasture system with 142 medium-frame Holsteins, 4) seasonal pasture system with 142 medium-frame Holsteins, an expanded land base for cash crop production with imported manure and an anaerobic digester and, 5) annual pasture-based system with 160 small-frame New Zealand Friesian cows. The analysis was conducted over 26 years of East Lansing, Michigan weather conditions to obtain a comprehensive analysis of system performance.

Based on farm visits (Appendix A and B) and discussions with dairy farmers considering the transition from total confinement to an annual pasture-based system, a herd size of 100 cows is a common tipping point in the decision to continue with total confinement facilities and expand herd size or maintain herd size and begin the transition to a seasonal or annual pasture-based system to reduce operating costs. Total confinement systems typically have large-frame

Holsteins bred for high milk production. The initial representative farm for analysis was a milking herd of 100 large-frame Holstein (726 kg mature weight) cows with 80 replacements in conventional confinement housing and a land base of 111 ha (275 ac, 1.11 ha (2.75 ac) per cow). This land base balanced feed produced on the farm with small amounts of purchased or sold forage or grain, and balanced manure nutrient application with crop removal to maintain a near nutrient balance on the farm.

In a seasonal pasture system cattle are on pasture during summer growing season and confined during winter. For seasonal pasture systems farmers typically prefer smaller cattle with traits and genetic potential for milk production between the large-frame and small-frame cows, such as medium-frame Holsteins. Smaller frame cattle generally consume less feed and produce less manure than large-frame cattle. Therefore, a seasonal pasture system with 142 medium-frame Holstein cows (590 kg mature weight) with the same land base as the confinement system (111 ha) was evaluated as the representative seasonal pasture farm. The land base was held constant and the cow numbers were increased to maintain the balance between land available for feed production and the nutrient balance on the farm with only small amounts of forage purchased or sold.

In an annual pasture-based system, New Zealand Friesian cows (454 kg mature weight) are the typical cattle (similar to a small-frame Holstein) because of their efficient conversion of grass to milk. Cattle are supplemented with some dry hay, round bale silage and a small amount of purchased grain with minimal housing throughout the year. The representative annual pasture-based system had 160 New Zealand Friesian cows with replacements on the 111 ha (275 acre) land base. These cow numbers and land base provided a near balance of feed produced and nutrient use on the farm.

Biogas recovery systems on livestock operations can produce renewable energy and provide additional benefits to the farm. Biogas from anaerobic digestion can heat water and potentially satisfy other farm energy needs. The digestate can be used as a fertilizer, and bedding and can be often recovered for reuse. Revenue from electricity generated on-farm can be obtained through biogas and electricity sale, reduction in purchased electricity use, and in some cases, net metering (EPA, 2004). Other revenue may be obtained through carbon credits if methane is captured and prevented from escaping to the atmosphere. The Michigan Department of Labor and Economic Growth reported that this technology is gaining interest because of new laws regulating odor, the potential to reduce groundwater contamination, and concerns about greenhouse gas production (Simpkins, 2005).

Currently, a herd size of 500 cows is considered the break-even point for a typical AD system for dairy farms (EPA-AgSTAR, 2010b). In this work, this was confirmed by the addition of an anaerobic digester to the total confinement farm with 100 large-frame Holsteins resulted in an annual reduction of the net return to management and unpaid factors of more than $14,000 per year. When an anaerobic digester was added to a 500-cow, total confinement dairy there was an increase in net return to management and unpaid factors of $9,000 per year. This confirmed that manure from about 500 cows (about 15,600 t/yr) is needed for a break-even investment on a typical dairy farm producing energy for on-farm use with recovered bedding.

Seasonal pasture dairies in the Great Lakes region are typically smaller than 500 cows. Additionally, anaerobic digesters require a steady supply of manure throughout the year for efficient use. The expansion of many dairy farms is restricted by the lack of land available for application of manure nutrients. These farms can benefit by exporting manure nutrients for off-farm use. Cropping systems benefit from the nutrients and other soil quality building factors that livestock manure provides. One alternative for the cost effective integration of an anaerobic digester on a small, seasonal dairy may be to import manure from nearby dairies, thereby providing a steady, year round supply of manure in a quantity that is economically feasible.

The economics and performance of the representative 142-cow seasonal dairy was evaluated when importing 12,882 wet t of dairy manure from nearby dairies (0.75 miles). This volume of manure, when added to the manure deposited in the barn by the milking herd (2,885 t/yr), provided an annual manure volume similar to that produced on a 500-cow dairy (15,600 t/yr). Additional cash crop land was added to the land base of the seasonal dairy to balance the additional nutrients with crop removal.

3.1. Representative farm development

Five representative farms were simulated based on information collected from farm visits (Appendix A and B), literature review and discussions with dairy extension professionals. Appendix C presents the selected information for each farm. These representative farms were selected to provide a near balance between the land base and feed produced, and a nutrient balance between the manure nutrients applied and imported in purchased feed, and the nutrients used for crop production, exported milk and meat, or otherwise exported from the farm.

3.1.1. Type of dairy farm

The most common housing system on dairies in the Great Lakes Region is the total confinement system, which typically has cattle inside a free stall barn all year round consuming rations that are relatively high in concentrates and harvested forages. Large, confined herds require large structures for housing and feed storage, and material handling equipment and waste management systems (USDA-NRCS, 2007). Confinement dairies have more control of feed quantity and nutrient concentration during the year, which influences milk production and the quantity and nutrient concentration in manure (Wattiaux and Karg, 2004).

In an annual pasture-based system cattle are on pasture or open lots throughout the year consuming grazed forage during the growing season and stored feed throughout the winter. Pasture-based dairies can reduce feed, labor, equipment, and fuel costs. They provide a lower-cost option for small farms without the need to expand herd size (USDA-NRCS, 2007). Mechanical feed harvesting and storage are greatly reduced because the cows harvest the crop directly from the field much of the year.

Seasonal pasturing has been adopted largely due to the profitability of the dairy industry in the Great Lakes Region (Nott, 2003). Less purchased feed is required; therefore, fewer hectares need to be harvested as stored forage. Some producers use seasonal grazing which is a combination of the two systems and is attractive because it reduces costs by allowing the feeding of concentrate to improve milk production levels.

3.1.2. Cattle frame

Ninety percent of U.S dairy cows are black and white Holsteins. Holsteins can produce large volumes of milk, butterfat and protein. When fed high levels of grain the cow can be very profitable (EPA, 2012a). Cattle frame varies depending on the type of dairy system. Large-frame Holsteins are typical in conventional confinement systems with a mature body weight of 726 kg (1,600 lb), bred for high milk production. Cattle in seasonal pasture systems are typically medium-framed cattle (590 kg mature weight) with traits and genetic potential for milk production between the large-frame and small-frame cows. Managers of annual pasture-based systems prefer small-framed New Zealand Friesian cattle (454 kg mature weight) because of their efficient conversion of grass to milk.

3.1.3. Land base

A land base of 111 ha (275 ac) was selected for each of the dairy systems evaluated (confinement, seasonal pasture and annual pasture) while varying areas for grazing, corn and alfalfa production. This land base maintained a near balance of feed produced on farm with small amount of purchased or sold forage or grain, and nutrient balance on the farm with manure application. The key farm parameters when matching cow numbers with the available land base were:

- Feed production and utilization: indicates how much feed is produced, sold or purchased. The target was to match feed production with use, with only small amounts of forage and grain purchased or sold.
- Nutrient balance: used to maintain soil fertility with small amount of soil phosphorus and potassium build-up or depletion.

3.1.4. Milk production

Milk production is a function of genotype, management level, nutrition and environmental factors. Large-frame Holsteins in confinement typically have greater annual milk production than small-frame cattle on pasture. The confinement system with 100 large-frame Holsteins had a target annual (305 days) milk production without fat in the ration of 10,886 kg/cow-yr (24,000 lb/cow-yr). The seasonal pasture system with 142 medium-frame Holstein cows had a target milk production of 9,071 kg/cow-yr (20,000 lb/cow-yr). The annual pasture-based system had a target milk production of 7,252 kg/cow-yr (16,000 lb/cow-yr). Potential milk fat content was 3.5% for the large-frame cows, 3.8% for the medium frame cows and 4.2% for the small-frame cows (Utsumi, personal communication, 2013). At these production levels forage quality was the primary constraint to milk production.

3.1.5. Type of Manure Treatment

Two types of manure treatment were evaluated: land application of raw manure and anaerobic digestion. Land application of raw manure means that all manure collected on-farm was applied to the crop land. When an anaerobic digester was used all the manure collected or imported was used as biomass for the digester and the digestate from the digester was applied to crop land.

Five representative farms scenarios were evaluated: 1) conventional confinement system with 100 large-frame Holstein, 2) conventional confinement system with 100 large-frame Holstein and AD, 3) seasonal pasture system with 142 medium-frame Holstein, 4) seasonal pasture system with 142 medium-frame Holstein, imported manure, cash crop and AD and, 5) annual pasture-based system with 160 small-frame New Zealand Friesian. The different farms were compared by observing the outputs of farm performance, costs, gas emissions and footprints (Appendix D). A calculation of the difference between means of each farm was compared.

IFSM is not currently designed to evaluate an anaerobic digester with imported manure. Therefore the performance, economics and environmental impact of the seasonal pasture dairy was approximated by comparing multiple representative farms, one with an anaerobic digester and a seasonal pasture dairy with imported manure and an expanded land base for cash crop production and manure use. Because the manure production from a 500-cow dairy is generally considered to be the threshold for a breakeven investment in an anaerobic digester a 500-cow confinement dairy with an anaerobic digester was evaluated and found to produce 15,600 t (17,200 ton) per year of manure. The AD installed on the seasonal dairy was sized to process this volume of manure (15,600 t) with 2,885 wet t produced by the cattle at the dairy and 12,882 wet t of manure imported from nearby farms. In addition, to evaluate the environmental impact of an anaerobic digester in the seasonal farm an AD sized to process the amount of manure produced by 142-cows (2,885 t) was evaluated.

In order to evaluate the integration of a seasonal pasture farm with an anaerobic digester the differences and percentages obtained between the confinement farm with 500 cows with and without AD and, between the seasonal farm with 142 cows with and without AD were used (Table 10 and Table D.1). Information that is not included in Table 10 is the same as the seasonal dairy farm with 142 medium-frame Holsteins with additional land for cash crop and imported manure.

Because IFSM does not account for the separate labor and machinery requirements for imported manure in the seasonal farm with AD, the costs related to importing the additional manure and the land application of it were calculated, and these costs were added to the farm production costs (Table C.19). Due to the imported manure the seasonal farm crop land was increased from 111 ha to 809 ha to achieve a near nutrient balance. Corn acreage was increased from 75 ha to 374 ha and 374 ha of soybeans were added as a cash crop (Figure 5). Additional description of farm input parameters are included in Appendix C. Farm performance, economics and environmental impacts due to the integration of an AD into a seasonal pasture farm were evaluated by comparing the seasonal dairy farm and the seasonal dairy farm with AD, imported manure and additional land for cash crop.

The final analysis included the farm performance and economic and environmental impacts due to the transition from confinement systems to an annual pasture-based system and the integration of anaerobic digester in a confinement and seasonal pasture system.

Farm performance included economics and resource use, annual production costs and net return to management; crop production costs and total feed costs. Environmental impacts included nutrients available on farm, used, and lost to the environment; annual emissions of important gaseous compounds; and environmental footprints of water, nitrogen, energy and carbon.

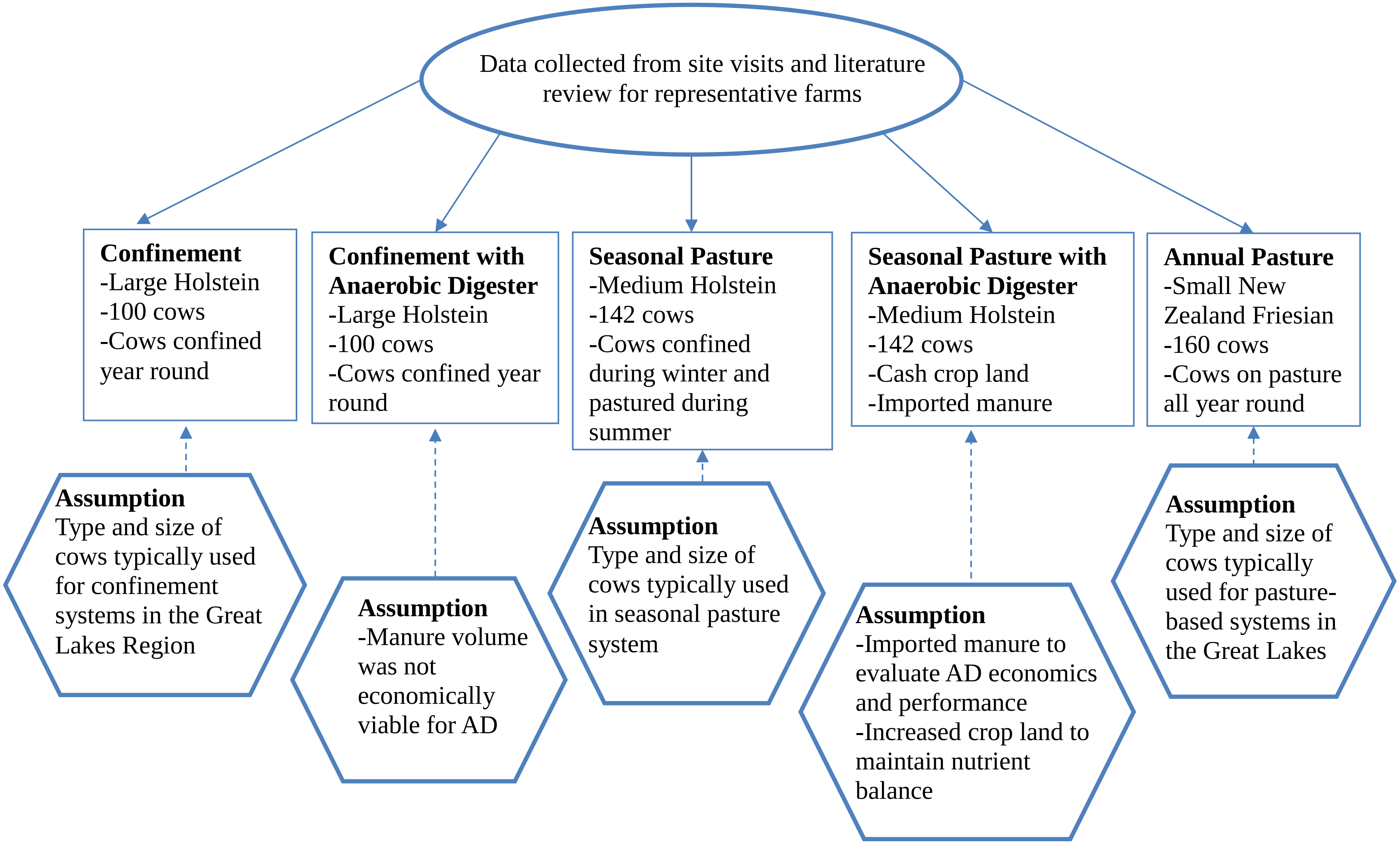


Figure 5. Development of five representative dairy production systems

Table 10. Estimated values for the seasonal pasture dairy with 142 medium-frame Holsteins, anaerobic digestion, imported manure and additional land for cash crop production.

	Equations used
Nutrients available, used, and lost to the environment	
Nitrogen lost by leaching	Seasonal 142[a] w[d] CC[b] w Import + (Seasonal 142 w CC w Import * (% Dif.[c] Seasonal 500[a] AD-Seasonal 500))
Nitrogen lost by denitrification	Seasonal 140 w CC w Import + (Seasonal 140 w CC w Import * (% Dif. Seasonal 500 AD-Seasonal 500))
Potassium loss through runoff	Seasonal 140 w CC w Import + (Seasonal 140 w CC w Import * (% Dif. Seasonal 500 AD-Seasonal 500))
Soil potassium depletion	Seasonal 140 w CC w Import
Crop removal over that available on farm	Seasonal 140 w CC w Import + (Seasonal 140 w CC w Import * (% Dif. Seasonal 140 AD-Seasonal 140))
Annual manure production and handling cost	
Manure handled	Confine 500 AD
Manure applied to corn land	Confine 500 AD
Machinery cost	Seasonal 140 w CC w Import + (Dif. Confine 500 AD-Confine 500)
Fuel and electric cost	Seasonal 140 w CC w Import + (Dif. Confine 500 AD-Confine 500)
Storage cost	Seasonal 140 + (Dif. Confine 500 AD-Confine 500)
Labor cost	Seasonal 140 w CC w Import + (Dif. Confine 500 AD-Confine 500)
Annual crop production and feeding costs and the net return over those costs	
Equipment cost	Machinery cost of manure+ Equipment cost of crop-custom cost (Seasonal 140 w CC w Import w AD)
Facilities cost	Seasonal 140 w CC w Import + (Dif. Confine 500 AD-Confine 500)
Energy cost	[(Total energy (Mbtu) - Energy Animal housing ventilation and lighting (Mbtu)) + Excess electricity (Mbtu)] * 0.028 ($/Mbtu)
Land rental cost	Seasonal 140 w CC w Import + (Dif. Confine 500 AD-Confine 500)
Return to management and	Costs-Incomes

Table 10 (cont'd)

unpaid factors	
Annual emissions of important gaseous compounds	
Ammonia	
Housing facility	Seasonal 140 w CC w Import + (Seasonal 140 w CC w Import * (% Dif. Seasonal 140 AD-Seasonal 140))
Manure storage	Seasonal 140 w CC w Import + (Seasonal 140 w CC w Import * (% Dif. Seasonal 140 AD-Seasonal 140))
Methane	
Manure storage	Seasonal 140 w CC w Import + (Seasonal 140 w CC w Import * (% Dif. Seasonal 140 AD-Seasonal 140))
Biogenic Carbon Dioxide	
Manure storage	Seasonal 140 w CC w Import + (Seasonal 140 w CC w Import * (% Dif. Seasonal 140 AD-Seasonal 140))
Combustion Carbon Dioxide	Seasonal 140 w CC w Import + (Seasonal 140 w CC w Import * (% Dif. Seasonal 140 AD-Seasonal 140))
Environmental footprints of water, nitrogen, energy and carbon for a dairy farm	
Water Use	
Production of purchased feed and inputs	Seasonal 140 w CC w Import
Not allocated to milk production	Seasonal 140 w CC w Import + (Seasonal 140 w CC w Import * (% Dif. Seasonal 140 AD-Seasonal 140))
Water footprint with rainfall	Seasonal 140 w CC w Import + (Seasonal 140 w CC w Import * (% Dif. Seasonal 140 AD-Seasonal 140))
Water footprint without rainfall	Seasonal 140 w CC w Import + (Seasonal 140 w CC w Import * (% Dif. Seasonal 140 AD-Seasonal 140))
Reactive Nitrogen Loss	
Ammonia emission	Seasonal 140 w CC w Import + (Seasonal 140 w CC w Import * (% Dif. Seasonal 140 AD-Seasonal 140))

Table 10 (cont'd)

Nitrate leaching	Seasonal 140 w CC w Import + (Seasonal 140 w CC w Import * (% Dif. Seasonal 140 AD-Seasonal 140))
Nitrous oxide emission	Seasonal 140 w CC w Import + (Seasonal 140 w CC w Import * (% Dif. Seasonal 140 AD-Seasonal 140))
Fuel combustion emissions	Seasonal 140 w CC w Import + (Seasonal 140 w CC w Import * (% Dif. Seasonal 500 AD-Seasonal 500))
Reactive nitrogen footprint	Seasonal 140 w CC w Import + (Seasonal 140 w CC w Import * (% Dif. Seasonal 140 AD-Seasonal 140))
Energy Use	
Manure handling	Cost for manure handling/ 0.028 (Seasonal 140 w CC w Import /AD)
Production of resource inputs	Seasonal 140 w CC w Import + (Seasonal 140 w CC w Import * (% Dif. Seasonal 140 AD-Seasonal 140))
Not allocated to milk production	Seasonal 140 w CC w Import + (Seasonal 140 w CC w Import * (% Dif. Seasonal 140 AD-Seasonal 140))
Energy footprint	(Sum Energy Seasonal 140 w CC w Import w AD)/ (lb FPCM Seasonal 140 w CC w Import)
Greenhouse Gas Emissions (CO_{2e})	
Manure emissions	Seasonal 140 w CC w Import + (Seasonal 140 w CC w Import * (% Dif. Seasonal 140 AD-Seasonal 140))
Emission during feed production	Seasonal 140 w CC w Import + (Seasonal 140 w CC w Import * (% Dif. Seasonal 140 AD-Seasonal 140))
Net biogenic carbon dioxide emission	Seasonal 140 w CC w Import + (Seasonal 140 w CC w Import * (% Dif. Seasonal 140 AD-Seasonal 140))
Fuel combustion emissions	Seasonal 140 w CC w Import + (Seasonal 140 w CC w Import * (% Dif. Seasonal 140 AD-Seasonal 140))
Production of resource inputs	Seasonal 140 w CC w Import + (Seasonal 140 w CC w Import * (% Dif. Seasonal 140 AD-Seasonal 140))
Not allocated to milk	Seasonal 140 w CC w Import + (Seasonal 140 w CC w Import * (% Dif. Seasonal 140 AD-

Table 10 (cont'd)

production	Seasonal 140))
Carbon footprint without biogenic CO_2	Seasonal 140 w CC w Import + (Seasonal 140 w CC w Import * (% Dif. Seasonal 140 AD-Seasonal 140))
Carbon footprint w/ biogenic CO_2	Seasonal 140 w CC w Import + (Seasonal 140 w CC w Import * (% Dif. Seasonal 140 AD-Seasonal 140))

[a] 140/500 = number of cows; [b] CC= cash crop; [c] Dif.= difference; [d] w = with

3.2. Herd and crop information of representative farms

The dairy herds included large and medium-frame Holstein cows, small-frame New Zealand Friesians cows and replacement stock. Dry cows formed 15% of the milking herd. The land base was selected to provide all forage and grain to a herd of 100 large-frame Holsteins with only a small amount of forage or grain purchased and sold on an annual basis to balance the feed produced on the farm. The number of cows in the milking herd was increased to provide a near nutrient balance on crop removal, available feed and manure produced by the dairy herd (Table 11).

The mature cow body weight was 726 kg (1,600 lb) for the large-framed cows and, 590 kg (1,300 lb) and 454 kg (1,000 lb) for the medium and small-framed Holsteins, respectively. Potential annual (305 day) milk production without fat in the ration was 10,886 kg/cow (24,000 lb/cow) for the large-frame Holsteins, 9,071 kg/cow (20,000 lb/cow) for the medium-frame Holsteins and 7,257 kg/cow (16,000 lb/cow) for the small-frame New Zealand Friesian. At these milk production levels forage quality was the primary constraint. Potential milk fat content was 3.5% for the large-frame cows, 3.8% for the medium frame cows and 4.2% for the small-frame cows (Utsumi, personal communication, 2013). The herds followed a year-around calving strategy with a 35% culling rate for the confinement system, 25% for the seasonal pasture system and 30% for the annual pasture system as a result of healthier lactating cows, with less stress, more natural diet and, improved reproductive performance (Utsumi, personal comunication based on Benbrook, et al., 2010). Labor for milking and animal handling was 5.25 min per cow-day for the confinement system, based on three times per day milking schedule and, 3.0 min per cow-day for the seasonal and annual pasture systems, assuming 2 times milking per day and lower milk production (Utsumi, personal communication, 2013) (Appendix Table C.5).

Table 11.Major descriptive parameters of five representative dairy production systems

	Unit	Confine	Confine w/ AD	Seasonal Pasture	Seasonal Pasture w/ AD[a]	Annual Pasture
Livestock						
Lactating cows	-	85	85	121	121	136
Dry cows	-	15	15	21	21	24
Young stock over one year	-	38	38	54	54	61
Young stock under one year	-	42	42	60	60	67
Alfalfa						
Land area	ha (ac)	36.4 (90)	36.4 (90)	10.1 (25)	10.1 (25)	40.5 (100)
Harvest system	-	Hay and silage	Hay and silage	Hay and silage	Hay and silage	Hay and silage
Number of cuttings	-	4	4	4	4	4
Avg. yield	t DM[b]/ha (ton DM/ac)	11.78 (5.26)	11.78 (5.26)	11.62 (5.19)	11.61 (5.18)	11.64 (5.20)
Corn						
Land area for confinement	ha (ac)	74.8 (185)	74.8 (185)	50.6 (125)	374 (925)	0
Harvest system	-	Grain, silage	Grain, silage	Grain, silage	Grain, silage	-
Number of cuttings	-	1	1	1	1	-
Avg. dry corn yield	t DM/ha (ton DM/ac)	6.45 (2.88)	6.41 (2.86)	5.98 (2.67)	6.18 (2.76)	-
Avg. high moisture yield	t DM/ha (ton DM/ac)	6.11 (2.73)	6.09 (2.72)	-	-	-
Avg. silage yield	t DM/ha (ton DM/ac)	12.74 (5.69)	12.64 (5.64)	12.92 (5.77)	13.79 (6.15)	-
Grass						
Land area	ha (ac)	0	0	50.6 (125)	50.6 (125)	70.8 (175)
Harvest system	-	-	-	Silage	Silage	Silage
Number of cuttings	-	-	-	1	1	1
Avg. yield	t DM/ha (ton DM/ac)	-	-	3.78 (1.69)	4.12 (1.84)	3.83 (1.71)

[a] Seasonal Pasture with AD, cash crop and imported manure
[b] t = metric ton; DM=Dry matter

The feed ration was determined by a linear program embedded in IFSM and it was selected to provide a relatively high forage-to-grain ratio and a minimum of 5% dry hay in cow rations was fed for all farms. The phosphorous and protein were fed at 100% of National Research Council (NRC) recommendations. Corn grain, corn silage, dry hay, pasture, grass and alfalfa chopped and baled silage was produced on the farm. A soybean meal crude protein supplement, distiller grain and minerals were imported to the farm. A loader and mixer wagon were used for feeding grain and silage. A bale grinder was used for feeding hay (Appendix Table C.6).

The animal facilities for confinement and seasonal pasture included a double six parlor milking center, free stall barn naturally ventilated as cow housing, calf hutches and a dry lot as heifer housing, and short-term storage of premix feed (Appendix Table C.7). Bedding was chopped straw providing 1.4 kilograms per cow- day (3 lb/cow-day). The purchased bedding for the farms with an anaerobic digester was reduced to 0.45 kg per cow-day (1 lb/cow-day) because 0.95 kg/d was recycled from the solid part of the digestate (Appendix Table C.8). The annual pasture-based system included a double-six parlor milking center, calf hutches and a dry lot as heifer housing with short-term storage for premix feed. No bedding was provided.

Corn and alfalfa were grown on each farm other than the annual pasture-based farm where only alfalfa and grass/legume pasture were grown. The pasture was 70% cool-season grass and 30% legume mix pasture on the pasture-based farms. The soil was a medium sandy loam with total water holding capacity of 19 cm (7.5 in), and soil phosphorus at an optimum level between of 30 to 50 ppm. Alfalfa had a stand life of 4 years, and grass 10 years. The relative maturity index of corn was 100 days, with a plant population of 69,189 plants per hectare (28,000 plants/ac). The P and K balance was achieved with the manure application with a small, long-term build-up or draw-down. Twenty-eight kilograms per hectare (25 lb/ac) of nitrogen was applied to the corn at planting time. All manure was applied to land going to corn production.

Nitrogen from legumes and manure applied by the grazing animals supplied the nutrients for the grass pasture. In the annual pasture-based system 80% of manure collected from the milking center was applied to grass and 20% to alfalfa (Appendix Table C.3).

The confinement, seasonal pasture and annual pasture-based systems had 111 ha available for crop production. The confinement farm had 36 ha of land in alfalfa and 75 ha for corn production. The annual pasture-based farm had 40 ha for alfalfa and 79 ha as grazing area. The seasonal pasture farm had 10 ha for alfalfa, and 51 for corn and 51 ha as grazing area. The seasonal pasture with additional cash crops and an AD system had additional crop land to maintain the nutrient balance with the imported manure. The total land area of the seasonal pasture with cash crop and AD was 809 ha: 374 ha in corn, 374 ha in soybeans, 10 ha in alfalfa, and 51 ha in pasture (Table 11).

Manure was collected, stored and applied as a semi-solid (12-14% DM), which represents fresh manure plus bedding. Total manure dry matter was the sum of manure excreted by the cows plus bedding and feed lost into the manure. Manure characteristics were based ASABE D384.2 standard (ASABE, 2013a) (Appendix Table C.8). In the confinement and seasonal pasture-based systems manure was collected with a scraper, stored in a top-loaded, clay-lined earthen basin and loaded in a slurry spreader tank with a slurry pump. The quantity of manure handled was dependent on the amount and type of bedding used and the amount of water contained in the manure. Six months manure storage capacity was provided on the farms with confinement housing, meaning storage was emptied twice each year in the spring and fall (Table 12). Manure on the annual pasture farm was collected from the milking center with scraper bucket loading and short-term storage with a few days capacity (daily haul).

Manure was imported to the seasonal pasture farm when an AD was used. 12,882 t/yr of manure was imported and applied to crop land along with 2,885 t/yr produced on the farm. Additional rented land (809 ha) was used to maintain the whole-farm nutrient balance.

IFSM does not account for the separate labor and machinery requirements for imported manure (12,882 t/yr). When manure was imported to the farm, additional costs were calculated and added to the farm ownership and operating costs. Agitation, pumping and trucking manure from nearby farms to the AD was done on a custom hire basis at $90 per hour assuming custom hauling with a 22,712 L (6,000 gallons) truck-mounted tank and a 1.6 km hauling distance with a hauling rate of 52,769 L/h (13,940 gal/h) for 15,812 t of wet manure per year. Custom manure hauling required 301 hours per year. Machine efficiency and labor hours were calculated based on Harrigan (2010).

Hauling manure from the AD to the field required two 18,927 L (5,000 gallons) tank spreaders with 100 kW tractors with an average hauling distance of 1.2 km. The average hauling rate was 53,942 L/h (14,250 gal/h) and required 148 hours for each tractor and spreader (296 h) based on Harrigan (2010). Labor for pumping and agitating manure required 42 machine hours for agitating and pumping, and 8 hours for agitating and clean-up each time the manure storage was emptied (assumed two times per year) (Appendix Table C.19). Machine efficiency and labor hours were also calculated based on Harrigan (2010). Repair factors, operating costs, salvage value and interest rates were calculated based on Hadrich et al. (2010), ASABE standard D497.7 (2013c) and ASABE standard EP496.3 (2013b) (Appendix Table C.19).

3.3. Tillage and planting information

Tillage and planting operations only occurred on days when soil and weather conditions were appropriate for field work. A suitable day was when the soil moisture conditions were suitable to support field operations. Depending on the size and type of equipment specified for each field operation (Table 12), fuel use and labor requirements were determined. A detailed description can be found in Rotz et al. (2011a).

Tillage and planting operations primarily occurred in the spring and/or fall. For spring operations, suitable days were determined considering a bare soil (without crop). For summer and fall operations, suitable days were determined using the soil under or following the growing crop using the soil moisture after crop production.

Spring operations began with manure application and proceeded through the designated sequence of tillage operations ending with planting. The number of operations that could occur simultaneously was two, and the maximum time that tillage and planting operations could be performed during any given suitable day was 8 hours.

Fall operations were similar to spring operations beginning with manure application or after some of the crops were harvested. Tillage and planting operations began with alfalfa and continue with grass and corn. At the end of each simulated year, machine, energy, and labor were summed.

The sequence of operations of tillage and planting for alfalfa, corn and grass and the machinery are shown on Table 12. The alfalfa tillage start date was on October 15 using a chisel plow, followed by a field cultivation beginning April 10 and seeding on April 15. Tillage of corn ground began on September 10 with spring seed bed tillage beginning on April 10 and corn planting on May 1, corn operations ended on May 10 with a sprayer. Spring tillage for grass seeding began on April 15 with field cultivation followed by grass seeding on April 20. Soybean tillage began on April 10 with field cultivation followed by soybean planting on May 1 and ended on May 10 with a sprayer (Appendix Table C.14).

Table 12. Major machines and structures used for planting and manure storage for five representative dairy production systems

Machinery or storage type	Farm	Size	Number	Price
Tractors and loaders				
Transport tractors	All farms	35 kW (47 hp)	2-5	$12,000
Round bale loader	Confinement	50 kW (67hp)	1	$35,100
	Annual pasture	65 kW (87 hp)	1	$54,000
	Seasonal	80 kW (108hp)	1	$73,350
Skid-steer loader	Annual pasture	15 kW (20hp)	1	$30,600
	Confinement and seasonal	24 kW (33 hp)	1	$39,600
Tillage and planting				
Chisel plow	All farms	3.7 m (12 ft)	1	$17,100
Seedbed conditioner	Confinement and seasonal	5.8 m (19 ft)	1	$37,800
	Annual pasture	4.6 m (15 ft)	1	$30,600
Corn planter	Confinement and seasonal	8 row	1	$31,500
Grain drill	Confinement and seasonal	3.7 m (12 ft) 2.4 m (8 ft)	1	$9,900
	Annual pasture		1	$6,750
Sprayer	Confinement and seasonal	15.2 m (50 ft)	1	$9,900
Manure handling and storage				
Slurry tank spreader	Confinement and seasonal	18 t (20 ton)	1	$39,600
Small V-tank spreader	Annual pasture	6.0 t (6.6 ton)	1	$24,300
Clay lined storage pit				
Confine		1,707 t (1,882 ton)	1	$45,224
Seasonal pasture		1,541 t (1,699 ton)	1	$44,322
Annual pasture		3 day storage slab and back wall	1	0

Grain harvest and grain crop planting were custom hired, performing the same daily operations using the determined equipment and operations. Machinery, energy, and labor use were not considered part of the farm expenses or energy use. The land area tilled and planted for each crop under custom operation was totaled and multiplied by the custom rate to obtain the total cost. In the annual pasture-based farm forage crop tillage and planting was considered a custom operation.

Alfalfa and corn harvest procedures were similar for all farms (Appendix Table C.15 to C.18). Grain harvest was custom-hired for the confinement and pasture-based systems. Corn silage harvest started on September 1 at a maximum silage moisture content of 68% (wet basis). High moisture corn harvest started October 1 and dry corn was harvest started on October 21. Alfalfa was harvest in a four cutting system with the first two cuttings beginning at bud stage on May 25 and July 1 and cuttings three and four at early flower in mid-August and mid-October. Alfalfa was mechanically conditioned and raked before harvest. The critical NDF for high quality storage was 42% for all harvests. Alfalfa was stored as wilted, chopped silage with a maximum moisture content of 60% on the confinement farms and as round bale silage on the farms with cattle on pasture from May 25 to October 15. The maximum moisture content for round bale silage was 68%. Grass for stored silage was harvested at the early head stage with a maximum moisture content of 60% beginning May 20 when the forage supply exceeded forage demand.

Corn and alfalfa silage were chopped and stored in bunk silos on the confinement farms and baled and bagged on the pasture-based farms. Dry hay was baled in round bales and stored inside a shed. Farms using confinement stored high moisture grain in an upright silo. A large, portable mixer was used for feed mixing (Table 13) (Appendix Table C.9).

The harvested feed was transported on round bale wagons for hay, dump wagons for alfalfa and grain crop silage, and grain wagons for grain. All the feed was transported an average of one-half mile for the confinement, seasonal pasture and annual pasture-based systems and 0.75 mile for the seasonal pasture with cash crop system (Appendix Table C.12 and C.13).

Table 13.Major machines and structures used for crop harvest and storage on the five representative dairy production systems

Machine or storage type	**Confinement**			**Seasonal and Annual pasture**		
	Size	Number	Price	Size	Number	Price
Mower conditioner	4.3 m (14 ft)	1	$26,460	2.7 m (9 ft) 3.0 m (10 ft)	1(S)[a] 1 (A)[b]	$18,900 $20,700
Tandem rake	5.5 m (18 ft)	1	$19,350	5.5 m (18 ft)	1(A)	$19,350
Single rake	-	-	-	2.7 m (9 ft)	1(S)	$6,300
Round baler	Small	1	$20,340	Medium	1	$30,240
Bale wrapping	-	-	-	Large	1	$9,720
Forage harvester	Medium	1	$32,400	Medium	1(S)	$32,400
Corn combine	8 row	1	$267,300	8 row	1(S)	$267,300
Feed mixer	12 t (13 ton)	1	$63,900	12 t (13 ton)	1	$63,900
Forage blower	-	1	$40,050	-	1(S)	$40,050
Forage wagons	3.6 t (4 ton)		$6,000			$6,000
Hay storage shed	109 t (120 ton)	1	$25,960	109 t (120 ton)	1	$25,960
Alfalfa bunker silo	384 t (423 ton)	1	$56,982	82 t (202 ton)	1(S)	$32.567
				384 t (423 ton)	1(A)	$56,982
Corn silage bunker silo	432 t (476 ton)	1	$61,637	432 t (476 ton)	1(S)	$61,637
High moisture corn stave silo	173 t (191 ton)	1	$38,910	-	-	-

[a] S = seasonal pasture
[b] A = annual pasture-based

3.4. Economic information

The economic analysis included costs of all major operations on typical farms. The costs were related to resources grown on and brought onto the farm while income was received for milk and feed leaving the farm. All monetary returns from milk, feed, and animal sales occurred in the same year as well as the costs for producing those products. This annual accounting provided a measure of system performance that reflected one year’s use of resources to produce that year’s production (Rotz et al, 2011a).

The economic information was based on ownership costs determined by amortizing the initial investment over the life of the system. General economic parameters specify the prices of energy inputs, the economic life and salvage values of machines and structures, labor wage, land rental, and the real interest rate (Table 15). Cropping cost parameters include the cost of fertilizer, seed, and chemicals for producing each crop. Commodity price parameters include the buying prices of feeds and the selling prices for milk, animals and excess feed. Custom operation parameters describe the costs associated with hiring a custom operator to carry out specific farm operations. In this case the hired custom operations were for corn grain harvest and planting, forage crop tillage and planting and transport of manure from off farm to the AD.

The budgeting process included fixed and variable costs of production. Annual fixed costs for equipment and structures were a function of their initial cost and economic life which was 10 years for machinery and 20 years for structures (IRS publication 94b) and a real interest rate of 6%. Annual fixed costs were summed with annual expenses to obtain a total production cost. This total cost was subtracted from the total income received for milk, animal, and excess feed sales to determine a net return to the herd and management (Rotz et al., 2011a). Table 14 presents the major dairy costs and Table 15 presents economic parameters used in all farms, which were obtained between the years 2011 and 2013 from USDA-NASS, USDA-NRCS, U.S Energy, Michigan Public Service, Michigan adverse effect wage rate (AEWR), Michigan State University Extension, Purdue University Extension and Iowa State University (Appendix Table B.9).

Table 14. Major dairy costs ($/cow-year)

	Confine	Seasonal pasture	Annual pasture
Cow housing[a]	$1,400	$1,380	0
Heifer housing[b]	$267	$264	$267
Milking center[c]	$3,120	$2,197	$1,950
Feed facility[d]	$45	$44	$45
Livestock expenses[e]	$551	$359	$418
Total	$5,383	$4,244	$2,680

[a] Free stall barn, naturally ventilated
[b] Calf hutches and dry lot
[c] Double six parlor
[d] Short term storage of premix
[e] Includes veterinary and medication, semen and breeding, animal and milking supplies, insurance of animals, utilities for milking and animal handling, animal hauling and DHIA, registration.

Table 15. Economic parameters and prices assumed for five representative dairy production systems

Parameter	**Value**
General rates	
Diesel fuel	$0.98/L ($3.698/gal)
Electricity	$0.13/KWh
Grain drying	$ 1.76/pt-t ($1.6/pt-ton DM)
Labor wage	$16.13/h
Land rental	$126/ha ($50.98/acre)
Property tax	2.5%
Fertilizer prices	
N	$1.19/kg ($0.54/lb)
P	$1.63/kg ($0.74/lb)
K	$1.26/kg ($0.57/lb)
Lime	$33/t ($30/ton)
Annual seed and chemicals	
New forage stand	$494/ha ($200/acre)
Established forage stand	$17.3/ha ($7/acre)
Corn land	$551/ha ($223/acre)
Additional for corn following corn rotation	$12.4/ha ($5/acre)
Selling prices	
Grain crop silage	$110/t DM ($100/ton DM)

Table 15 (cont'd)

High moisture grain	\$243/t DM (\$220/ton DM)
Corn grain	\$298/t DM (\$270/ton DM)
High quality hay	\$14/t DM (\$13/ton DM)
Milk	\$0.42/kg (\$19/cwt)
Cull cow	\$1.88/kg (\$85.5/cwt)
Bred heifer	\$300/ animal
Buying prices	
Soybean meal 48%	\$402/ t DM (\$365/ ton DM)
Distillers grain	\$165/t DM (\$150/ ton DM)
Corn grain	\$160/ t DM (\$145/ ton DM)
Hay	\$198/t DM (\$180/ ton DM)
Minerals / vitamins	\$220/t (\$200/ ton)
Bedding material	\$110/t (\$100/ ton)
Custom operations	
Grain harvest	\$77.5/ha (\$31.4/acre)
Grain crop planting	\$40.0/ha (\$16.22/acre)
Forage crop tillage/planting	\$138.3/ha (\$56.0/acre)
Economic life	
Machinery	10 years
Structures	20 years
Machinery salvage value	30%
Real Interest rate	6%

3.5. Pasture growth and management

Part of the forage produced (alfalfa or grass-based) can be fed directly to the animals by grazing. The grazing area was varied during the spring, summer and fall to reflect the reduction of land needed when excess forage in the spring exceeded demand, and a small portion of land lost from production in the fall for grassland renovation. Excess forage in the spring was harvested as grass silage and stored in plastic-wrapped bales (Table 16). Spring grazing occurred during the months of April, May, and June; summer grazing in July and August; fall grazing in September and October. Detailed information about pasture management can be found in Rotz et al. (2011a).

The model provided yield and nutritive content of pastures for the grazed land based on the GRASIM model. GRASIM predicts pasture production and plant growth for hay and silage production. For a grass-based pasture, production was simulated in thirty-day intervals between harvests and makes 60% of the forage for the grazing animals available. The remaining 40% was considered the initial condition for regrowth.

The required information was investment in fence and watering equipment, and the labor needed to manage this equipment and the grazing animals. This information was used to determine the production costs related to pasture. Fence was divided in perimeter and temporary fence. Perimeter fence was a permanent fence such as high tensile wire. Temporary fence was movable polywire. Also included in the fencing system are gates and lanes for moving animals (Table 16) (Appendix Table C.4).

The labor required for pasture management included the time for evaluating pasture and the animals on that pasture, labor for moving temporary fence and watering equipment, and the labor required for retrieving animals for milking or moving them to new paddocks (Table 16).

Most of the pasture area was assumed to be clipped once per year. The pasture area clipped each year was set to the area defined as the summer grazing area. The clipping rate and fuel consumptions are functions of the size and type of mower used and the tractor used to power the mower.

The grazing strategy was based on the animal groups placed on pasture and the amount of time they spent on the pasture. The groups of animals that were on pasture were: older heifers, dry cows and, lactating cows (Table 16).

The time animals spent on pasture was set as full days during the grazing season (from April through October), which means between 16 and 18 hours per day (Table 16) for the seasonal pasture farm. The pasture-based farm was set as full days all year, which means between 18 and 20 hours per day. The animals were maintained outdoors year around even though pasture growth may not be available during some months. When not on pasture, animals were housed in the selected facility.

Table 16. Grazing parameters for the seasonal and annual pasture systems

	Unit	Seasonal	Annual
Grazing area			
Spring	ha (ac)	30.4 (75)	40.5 (100)
Summer	ha (ac)	50.6 (125)	70.8 (175)
Fall	ha (ac)	40.5 (100)	60.7(150)
Grazing management costs			
Investment in perimeter fence	$	3,625	5,075
Investment in temporary fence	$	2,125	2,975
Investment in watering system	$	3,125	4,375
Added annual cost of seed and chemical	$/ha ($/ac)	74 (30)	74 (30)
Grazing strategy			
Labor for grazing management	h/ week	10	10
Types of animals grazed	-	All cows	All cows
Time on pasture	h	Full days during grazing	Full days during grazing

Pasture was allocated along with other available feeds to meet the nutrient needs of each animal group in the herd. This was done using a partial mixed ration that best complimented the quantity and nutrient content of the pasture consumed. The pasture consumed was limited by either what available or the maximum amount of pasture forage that was consumed, which was the maximum amount of forage that could be included in the animal diet along with the available supplemental feeds required to maintain the desired production level.

Diets of each animal group were formulated with a linear program set to maximize forage use in the ration. If there was some excess of pasture forage available on the farm, all the animal groups that were being grazed could consume that forage in the ration. When forage was supplemented to meet herd needs, pasture was allocated first to grazing heifers and dry cows. Any remaining pasture was combined with available hay and silage or purchased hay to meet the roughage needs of the lactating cows. If during one month the pasture ran out before all animals were fed or during the months pasture was not available, animals were fed using hay and silage.

The nutritive content of pasture varied throughout the grazing season. Crude protein was set at 26% in the spring, dropped to 23% in the summer, and rebounded to 26% in the fall. Net energy for lactation started at 1.57 Mcal/kg DM in the spring and slowly decreased to 1.42 Mcal/kg DM in the fall. Neutral detergent fiber started at 52% in the spring, increased to 55% in the summer, and dropped to 53% in the fall. The rumen degradability of protein was set at 80% of CP, and the ADIP content was set at 2% of DM. Phosphorus and K contents were a function of the predominant crop. For grass-based pasture, the assigned P and K contents were 0.35% and 3%, respectively. For alfalfa, the P content was 0.26%, and the K content was 2.5% of DM (Rotz et al., 2011a).

3.6. Crop nutrient requirements, nutrient availability and loss

An embedded soil model was used to predict moisture and nitrogen available for the growth and development of each crop. Moisture content was predicted by tracing precipitation based on 26 years of local weather data, runoff, evapotranspiration, moisture migration, and drainage through time. Nitrate Leaching and Economic Analysis Package (NLEAP) was the model used to predict nitrogen cycling in the soil. Each soil layer includes nitrate, ammonia, crop residue nitrogen, manure organic nitrogen, and other soil organic matter. Nitrogen uptake by the crop was limited by availability or demand of the crop. Additional information about crop nutrient requirements can be found in Rotz et al. (2011a).

Daily nitrogen losses from the soil due to volatilization, leaching, and denitrification were also predicted by the model. Volatilization was a function of the amount of ammonia, temperature, and a volatilization rate. Leaching loss was related to the amount of nitrate and moisture that drained from the lower layer. Denitrification was a function of denitrification rate, temperature, and the water-filled pore space in the soil.

The fertilizer application rates included: nitrogen, phosphorous and potassium, and the percentage of manure applied. The manure application rate was determined by the manure application divided by the crop land area. Manure nutrients were calculated as dry matter of manure times the concentration of each nutrient in the dry matter manure. Nitrogen concentrations of manure were determined after subtracting the losses during collection, storage, and application.

The nutrient accumulation in the soil and the loss to the environment were predicted by the whole-farm mass balance. The whole-farm mass balance of nitrogen, phosphorus, potassium, and carbon was determined as the sum of all nutrient imports in feed, fertilizer, manure deposition and legume fixation minus the exports in milk, excess feed, animals, manure, and losses leaving the farm.

The amount of manure applied to each crop was the percentage of the total manure applied to that crop times the total amount of manure handled annually. The percentage of manure deposited during grazing was not included in the total manure handled. The amount of manure applied during grazing was determined by the animal groups and the time they spend on pasture. For this study the animals were set to be year around on pasture for the annual pasture-based system and summer grazing for the seasonal pasture system, meaning that about 85% of the total manure produced was deposited during grazing.

3.8. Anaerobic digestion

IFSM predicted the production and use of energy, and the effects that anaerobic digestion has on manure, nitrogen, phosphorous and economics (Figure 6). The AD manure loading rate was the amount of manure excreted and collected from barns or transported to the farm from off farm locations. Biogas is produced through the microbial degradation of the volatile solids in the manure. Energy production was based on the rate of volatile solids (VS) flow into the digester from animals. The amount of methane produced was a function of the productivity, which was set at 0.35 kg CH_4/Kg VS (Moller et al, 2007), and a function of the conversion efficiency, which had typical values close to 35% (Burke, 2001; Rotz et al., 2011a).

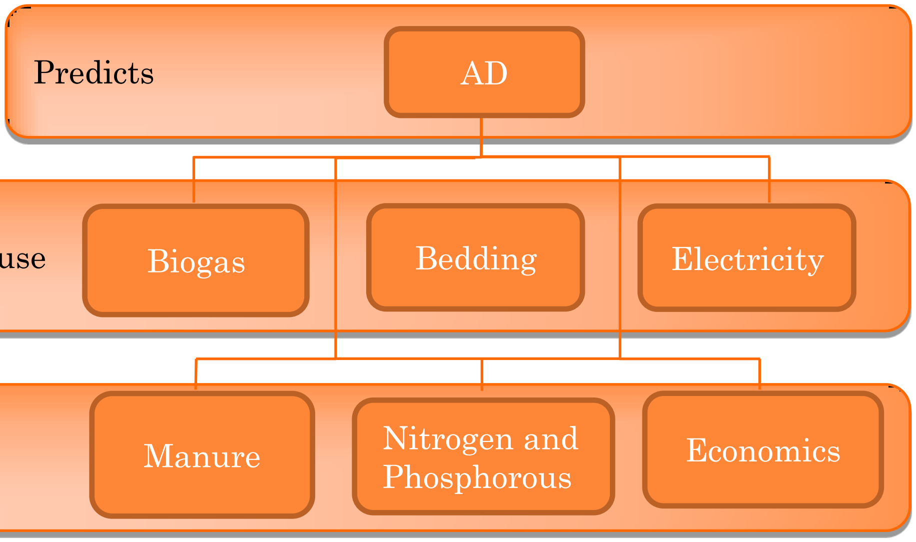


Figure 6. Anaerobic Digestion in IFSM

Producing power with biogas was a function of the energy content of methane, which also depended on biogas leakage (set as a typical value of 15%) (Kirk, personal communication, 2013). IFSM first predicted the amount used to heat water, which was set as 40% of the gas production, and the remaining was available to generate electricity (Table 17). The amount of electricity produced each day was limited by either the capacity of the generator, operation time and the amount of biogas. The efficiency of the engine-generator was set as 35% (Kirk, personal communication). Any remaining biogas that was not used for either electricity generation or water heating was burned off in a flare. By burning the biogas the lost carbon converted to carbon dioxide, which reduced the global warming potential of methane emission.

The initial costs for the anaerobic digester were calculated using a model provided by Safferman (personal communication, 2013) where the cost of the digester was calculated based on $7,000/kW and the generator was assumed to be 50% of the cost of the digester. The digester cost ($7,000/kW) was obtained from a review of like projects around United States and Michigan State. The initial costs of the digester and generator included: digester structure, electrical generator, design, construction, planning and, digestate management. The model do not include modifications required to collect and hold manure prior entering the digester. The costs may be lower because the electric generation equipment, which is smaller than usual, may be difficult to find.

The input parameters were: quantity of manure, moisture content, volatile solids, total solids, volatile solids conversion efficiency and run time efficiency (Table 17). The model outputs were: initial cost of digester and generator, repair and maintenance cost, electric generation equipment, gross energy from biomass, net energy from electricity including efficiency, transportation waste energy, energy for heating influent and to operate AD and, heat production from generator.

For IFSM only the initial costs of the digester and generator described above, repair and maintenance costs and, electric generation equipment calculated from the model provided by Safferman (personal communication, 2013) were used (Table 17).

Table 17. Anaerobic digester parameters

	Unit	Confine	Seasonal pasture with AD
Manure collected on farm	wet t/yr (wet ton/yr)	3,155 (3,478)	2,885 (3,180)
Manure imported to farm	wet t/yr (wet ton/yr)	0	12,882 (14,200)
Moisture content	%	90	90
Volatile solids	%	80	80
Total solids	%	10	10
VS/TS (% of TS)	%	80	80
CH_4 content	%	55	55
Heat of combustion	kJ/mole methane	890	890
Digester			
Initial cost purchase price[a]	$	117,000	539,000
Repair and maintenance cost	% of initial cost	2	2
Biogas leakage	% of gas produced	15	15
Volatile solids conversion efficiency	% of initial volatile solids	35	35
Generator and other Equipment			
Generator Capital cost[a]	$	59,000	270,000
Repair and maintenance cost ($0.015/ kWh)	$/ year	1,755	7,920
Annual repair and maintenance	% of initial equipment cost	3	3
Operation labor requirement	h/week	20	20
Electric generation equipment	kW	17	77
Electric generator efficiency	% of energy input	35	35
Run time efficiency	% of total time	85	85
Biogas used for water heating	% of gas produced	40	40
Total digester, generator and other equipment	$	176,000	809,000
Energy			
Gross energy from biomass	MMBtu/yr	1,143	5,173
Net Energy from electricity including efficiency	MMBtu/yr	400	1,810
Transportation waste energy	MMBtu/yr	2	8
Energy for heating influent	MMBtu/yr	213	963
Energy to operate AD	MMBtu/yr	57	259
Heat production from generator	MMBtu/yr	594	2,690
Total net energy[b]	MMBtu/yr	178	806

[a]Structure economic life is 20 years, and real interest rate is 6%.

Table 17 (cont'd)

[b] Total net energy accounting for all operational needs including transportation, biomass availability, influent heat, digester heat, digester operation, digester operational time, generator efficiency, and generator operational time.

The quantity and nutrient content of the manure produced were predicted based on the feeds consumed and the characteristics of the herd. The digestion process reduced the volatile solids content in the effluent, reduced the odor and methane produced compared to untreated manure.

The digestion process also affected the nitrogen fractions in the manure. A portion of the organic N in the raw manure was decomposed to NH_3 and NH_4^+, also referred as TAN (total ammoniacal N). IFSM based the amount of TAN in effluent entering long term storage upon data collected by Gooch et al. (2007), which is modeled as 15% greater than that entering the digester. This increase in TAN potentially increases the ammonia emissions from the storage and field applied effluent (Rotz et al., 2011a).

Phosphorous solubility was also increased during the digestion process. The amount of soluble phosphorus entering long term storage in the digester effluent was increased by 13% compared to untreated manure (Gooch et al., 2007). The increased solubility affected phosphorus runoff following field application (Rotz et al., 2011a). Regarding cost, adding an anaerobic digester to the dairy farm increased the ownership and operating costs and reduced purchased electricity and bedding cost. When bedding and electricity was produced on the farm, the cost was reduced in proportion to the reduction in purchased bedding or electricity.

3.9. Environmental impacts

In the environmental section of IFSM, the model does not allow adjustment of parameters. The environmental impacts modeled by IFSM included volatile, leaching and denitrification losses of N; volatile loss of hydrogen sulfide; surface runoff and leaching of phosphorous; and greenhouse gas emissions of carbon dioxide, methane, and nitrous oxide. In addition, other sources of emissions such as ammonia and hydrogen sulfide originating from manure on the barn floor, the manure storage and field applied manure were included. More detail about the environmental impacts can be found in Rotz et al. (2011a).

Most of the methane emissions were due to enteric fermentation and long term manure storage with minor sources being the barn floor, field applied manure, and feces deposited by grazing animals. Carbon dioxide sources included plant, animal and microbial respiration, both in soil and stored manure. Nitrous oxide is the strongest of all greenhouse gas emissions occurring in agricultural production with a global warming potential 298 times that of CO_2 (IPCC, 2007). Nitrous oxide sources included nitrification and denitrification processes in the soil, and these processes also occurred in the crust of slurry manure storage (Rotz et al., 2011a).

The phosphorous cycle is a complex process because it has various chemical forms and transformations. These processes are modeled in IFSM using relationships from the Erosion-Productivity Impact Calculator (EPIC) and the Soil and Water Assessment Tool (SWAT) to better represent surface processes. Surface processes include surface application, runoff, and transformation along with soil-surface interactions through infiltration and tillage. Erosion sediment loss is predicted using the Modified Universal Soil Loss Equation (MUSLE).

Total manure nitrogen consists of organic and ammoniacal nitrogen (NH_3-N). During manure handling, ammoniacal nitrogen is transformed and volatilized as ammonia. The primary source of ammoniacal nitrogen is urine, but a portion of the feces can also transform to an ammoniacal form during prolonged storage periods. Between 1% and 10% of TAN was lost when manure was applied through broadcast spreading. When manure was applied to a soil surface, the TAN readily volatilized as ammonia. Therefore, its amount varied through time. During each time step, ammonia loss occurred to the atmosphere and TAN moved into the soil through infiltration.

Hydrogen sulfide is mainly created and emitted from decomposing manure under anaerobic conditions. Main sources include the barn floor and long-term manure storage with minor losses following field application. Hydrogen sulfide is one of the contributors of manure odor. It is also a toxic compound when the concentration builds up in a confined space such as enclosed manure storage.

Environmental footprints are expressed as the environment impacts per unit of product. In IFSM, four environmental footprints were evaluated: water use, reactive N loss, energy use, and carbon emission. A footprint was determined by summing the estimates for each of the uses (removing that allocated to co-products), and dividing by the amount of milk produced.

Functions or factors were used to estimate values for important uses in the production system. This includes the major uses of water, fossil fuel, and the reactive nitrogen and GHG emissions that occur during the manufacture of resources used in the production system. Secondary uses can include the manufacture or production of fuel, electricity, machinery, fertilizer, pesticides, seed, and plastic used on the farm. Other secondary inputs include any feed or replacement animals purchased and imported to the production system.

The major water requirement was for the production of feed crops. Other uses include drinking water for animals, water used for animal cooling, cleaning of the parlor, and holding areas on dairy farms.

Reactive nitrogen is essential in the growing of crops and feeding of animals. Only nitrogen in this form can be taken up by crops to form the proteins needed by the animal. The increase in reactive nitrogen in our environment is a concern due to its effect on natural ecosystems and contributions to other forms of air and water pollution. Primary losses of reactive nitrogen include ammonia and nitrous oxide emissions to the atmosphere, nitrate leaching to ground water, and the combustion of fuels.

The energy footprint is defined as the total energy required to produce feed and milk, except for the solar energy captured by the growing feed crops. This includes all fuel and electricity directly used in the production system as well as the secondary energy used in the production of resources used on the farm. One of the major uses of energy on farms is the fuel used to operate tractors and other equipment for feed production, feeding, and manure handling. Fuel use was converted to energy units assuming 35.8 MJ/L of fuel. Electricity was another major use mainly for milking, ventilation, and lighting. Electrical use was converted to energy units (3.6 MJ/kWh of electricity).

Carbon footprint is the total GHG emission expressed in CO_2 equivalent units (CO_{2e}). The conversion factor for CH_4 and N_2O are 25 and 298 CO_{2e}/kg, respectively (IPCC, 2001; EPA, 2007). The carbon footprint was primarily determined as the net emission of the three GHGs including all sources and sinks of CO_2. A carbon balance was enforced, so a portion of the CO_2 assimilated in the feed was in the carbon exported during feed, milk, and animal productions (Rotz et al., 2011a).

CHAPTER 4. RESULTS AND DISCUSSION

The IFSM model was used to analyze the transition from a 100-cow conventional confinement dairy to an annual pasture-based system. The analysis included economics and resource use, farm performance and environmental impacts of representative farms. The representative farms included year-around confinement with conventional large-frame Holstein cattle; seasonal pasture with winter confinement and summer pasture with medium-frame Holsteins; an annual pasture-based dairy with New Zealand-style Friesian cattle whereby the cows were on pasture or open lots throughout the year; and the integration of an anaerobic digester on a total confinement dairy and a seasonal pasture dairy with imported manure and an expanded land base for cash crop production and manure application.

The representative dairy systems were compared on a fixed land base (111 ha) with large- medium- and small-framed cattle, except the seasonal pasture with AD which had a land base of 809 ha. The base farm for comparison included 100 large-frame cows (85 milking, 15 dry cows) with 80 replacements over 26 years of Lansing, MI weather. Based on the nutrient balance when producing alfalfa, corn silage and corn grain while importing some concentrate and returning the manure nutrients to the land for crop production, the nutrient balance with 100 large-frame cattle with replacements was similar to a seasonal dairy with 142 medium-frame cattle and an annual pasture-based dairy with 160 small-frame cattle plus replacements.

4.1. Comparison of farm performance and resource use

The transition from conventional confinement to a pasture-based system affected feed production and the purchase of feed supplements, milk and manure production. Overall, feed consumption increased 23% with the seasonal pasture and 12% with the annual pasture-based system compared to confinement because grazed forage was added to the cattle diet replacing high moisture grain and some alfalfa silage (seasonal pasture) and grain silage (annual pasture). On-farm feed production varied depending on the type of dairy and decreased from confinement to seasonal to annual pasture-based systems. The seasonal pasture produced 15% less milk per cow-yr compared to confinement and the annual pasture-based system produce 31% less per cow-yr. The confinement farms collected more manure than the seasonal and annual pasture-based farms because the cows stayed inside the barn year-around. Additional discussion and detail follows.

4.1.1. Milk, feed and manure production

The annual target milk production (305 day) without fat in the ration was 10,886 kg/cow (24,000 lb/cow) for the large-frame Holsteins, 9,071 kg/cow (20,000 lb/cow) for the medium-frame Holsteins and 7,257 kg/cow (16,000 lb/cow) for the small-frame New Zealand Friesians. The annual milk production with the feeds fed was 9,946 kg/cow for the large-frame Holsteins, 8,482 kg/cow for the medium-frame Holsteins and 6,829 kg/cow for the small-frame New Zealand Friesians (Table 18). Because fat was not fed in the diet, forage quality was the limiting factor in milk production. Total annual milk production was 845,430 kg for the large-frame cattle, 1,026,277 kg with the medium-frame cattle and 928,753 kg with the small-frame cattle.

Table 18. Average annual milk, feed and manure production of five representative dairy production systems

		Confine	Confine AD	Seasonal pasture	Seasonal pasture w cash crop and AD	Annual Pasture
Manure handled	t DM/yr	3,155	3,102	2,891	15,329	2,599
Milk production	kg/cow-yr	9,946	9,952	8,482	8,479	6,829
Feed and grain production						
High-quality hay	t DM/yr	46	46	16	15	56
Low-quality hay	t DM/yr	28	28	5	5	24
Alfalfa/grass silage	t DM/yr	233	233	96	101	342
Grain crop silage	t DM/yr	374	374	371	375	-
High moisture grain	t DM/yr	151	151	-	-	-
Dry grain	t DM/yr	82	79	100	2,889	-
Total produced	t DM/yr	914	911	588	3,385	423
Feed and grain sold						
Alfalfa Silage	t DM/yr	11	13	4	10	25
Hay	t DM/yr	14	16	-	-	16
Grain silage	t DM/yr	15	15	19	41	-
Cash crop corn and soybeans	t DM/yr	-	-	-	852	-
Dry grain	t DM/yr	18	15	37	2,039	-
Total sold	t DM/yr	59	59	60	2,942	41
Feed purchased						
Hay purchased	t DM/yr	-	-	13	7	-
Dry grain	t DM/yr	-	-	-	-	114
Soybean meal 48%	t DM/yr	16	17	251	255	204
Distillers grain	t DM/yr	121	122	141	148	136
Mineral and vitamin	t DM/yr	7	7	6	6	5
Total purchased	t DM/yr	144	147	411	416	460
Feed consumed						
Grazed forage	t DM/yr	-		290	306	281
Hay	t DM/yr	60	59	34	27	65
Alfalfa silage	t DM/yr	222	220	93	91	317
Grain crop silage	t DM/yr	359	359	352	334	-
High moisture grain	t DM/yr	151	151	-	-	-
Dry grain	t DM/yr	64	64	63	850	114
Total consumed	t DM/yr	999	999	1,229	1,165	1,123

The seasonal pasture produced 1,465 kg/cow-yr less milk and the pasture-based system produced 3,117 kg/cow-yr less milk than the confinement dairy. Generally, milk production per cow is lower on pasture-based than confinement systems (Winsten et al, 2000). Reduced milk production in pasture-based systems is usually because of the additional energy the cow expends in harvesting its own forage and the difficulty in balancing cow rations (Muller and Holden, 1994). Typically, the diets of grazing cattle are higher in forages and lower in grain and concentrate. The annual diet in the seasonal pasture system was 24% grazed forage and the annual pasture was 25% grazed forage (Table 18).

Feed consumption (including grazed forage) increased by 231 t DM/yr with the seasonal pasture and 124 t DM/yr with the pasture-based system compared to confinement (Table 18). In the seasonal pasture system there was no high moisture corn fed and 129 t DM/yr of alfalfa silage and 26 t DM/yr less hay was fed compared to confinement; however, this was replaced by 290 t DM/yr of grazed forage. In the annual pasture no high moisture corn or grain crop silage was included in the cattle diet but was replaced by 95 t DM/yr of alfalfa silage, 51 t DM/yr of dry grain and 281 t DM/yr of grazed forage.

Feed production varied with the cropping system. The confinement and pasture-based dairies produced more high and low quality hay (between 24 and 56 t DM/yr), and more alfalfa and grass silage (between 233 and 342 t DM/yr). The seasonal pasture dairy produced 16 t DM/yr of high quality hay and 5 t DM/yr of low quality hay because only 10 ha were allocated for alfalfa production. The confinement and annual pasture-based systems allocated 36 ha and 40 ha, respectively (Table 18).

The pasture-based system did not produce any grain. Grain crop silage production was similar for the confinement and seasonal pasture systems (between 371 and 375 t DM/yr) because the confinement dairy had 75 ha for corn production and the seasonal pasture had 51 ha available. The seasonal pasture with an expanded land for cash crop and AD produced 2,808 t DM/yr of dry grain more than the confinement farm because of the increased crop land in corn (374 ha) and soybean (374 ha) ground. Because of the increased crop land the seasonal pasture with AD produced the greatest quantity of feed sold per year (2,942 t DM/yr) compared to the confinement (59 t/yr), seasonal pasture (60 t/yr) and the annual pasture-based systems (41 t/yr) (Table 18).

The confinement dairy purchased 144 t DM/yr of feed compared to 411 t DM/yr for the seasonal pasture and 460 t DM/yr for the annual pasture system. The reduction was primarily soybean meal, 188 and 235 t DM/yr compared to the seasonal pasture and annual pasture-based system, respectively (Table 18). Eighty-six percent of the feed consumed on the confinement dairy was produced on-farm and 14% was purchased. The seasonal pasture system produced 67% of total feed consumed and 33% was purchased. The annual pasture dairy produced 59% of the total feed consumed and purchased 41%. The seasonal pasture with expanded land for cash crop and AD system produced 64% of total feed consumed, 36% was purchased and the remaining crops were sold.

The confinement dairy collected more manure (3,155 wet t/yr) than the seasonal pasture (2,891wet t/yr) and annual pasture dairies (2,599 wet t/yr) because the cows were confined in the barn throughout the year.

4.2. Economics

The evaluation of farm economics accounted for the major costs related to manure handling and production on-farm and their income from milk and animal sales. Main production costs analyzed on farm were: equipment, facilities, energy, labor, land rental, custom operations, crop production, feed costs and animal expenses. The analysis relates these costs with the type of dairy system (confinement, seasonal pasture or annual pasture-based) and the addition of an anaerobic digester.

Overall, the seasonal pasture with imported manure, expanded land base for cash crop production and an integrated anaerobic digester had the highest annual cost for manure handling ($146,985/yr), followed by the confinement dairy with AD ($63,077/yr), seasonal pasture ($36,595/yr), confinement ($35,225/yr) and annual pasture ($15,969/yr), respectively. The seasonal pasture had the highest production cost ($517,738/yr) followed by confinement with AD ($450,238/yr), confinement ($435,960/yr) and annual pasture ($435,894/yr). The seasonal pasture with imported manure, cash crop production and AD had the lowest production cost ($183,481/yr) and the highest net return to management and unpaid factors ($420,192/yr) followed by annual pasture ($88,162/yr), seasonal pasture ($86,133/yr), confinement ($73,594/yr) and, confinement with AD ($62,578/yr). Additional discussion and detail follows.

4.2.1. Manure handling costs

Manure was collected, stored and applied as a semi-solid (12-14% DM). In the confinement and seasonal pasture systems manure was collected with a scraper, stored in a top-loaded, clay-lined earthen basin with 6-month storage capacity and loaded in a slurry spreader tank with a slurry pump. The bedding was chopped straw supplied at 1.4 kilograms per cow- day (3 lb/cow-day). For the annual pasture system manure was collected only in the milking center with scraper bucket loading and short-term storage with a few days capacity (daily haul). No bedding was added on the pasture-based system.

The seasonal pasture with imported manure and an anaerobic digester had the highest cost for manure handling, followed by confinement with anaerobic digestion, seasonal pasture, confinement, and annual pasture. In the confinement and seasonal pasture systems the annual costs for manure handling were: machinery, bedding, labor, storage and fuel and electricity cost (Table 19). The costs for the annual pasture were: machinery, labor and, fuel and electricity costs. There was no storage and bedding cost because manure was hauled daily and no bedding was provided.

Table 19. Manure handling costs ($/year) for five representative production systems

	Confine	Confine AD	Seasonal pasture	Seasonal pasture w cash crop and AD	Annual Pasture
Machinery	16,468	14,097	18,762	25,360	8,562
Fuel and electric	1,947	1,677	1,771	6,836	1,790
Storage	3,943	24,062	3,864	96,246	-
Labor	4,561	20,473	4,114	15,848	5,617
Bedding	8,306	2,768	8,084	2,695	-
Total manure handling	35,225	63,077	36,595	146,985	15,969

The major costs for confinement with AD were storage ($24,062/yr) and labor ($20,473/yr). Storage cost increased 6 times ($20,119/yr) and labor 4 times ($15,912/yr) compared to confinement without AD. The storage cost increased because of the addition of the anaerobic digester which included design, construction, installation, generator and digester. The total capital cost for the digester, generator and other equipment was $141,000/yr. Labor increased because 20 additional hours per week were required for maintenance of the digester.

The seasonal pasture with imported manure and AD followed a different trend than confinement and seasonal pasture. Total manure handling cost increased 4 times ($110,390/yr) compared to the seasonal pasture without AD. Storage cost was $92,382/yr greater than the same farm without an anaerobic digester and imported manure because of the investment in the digester and related equipment (Table 19). Machinery costs for hauling manure increased

$6,598/yr, fuel and electric cost increased $5,065/yr and labor increased 4 times ($11,734/yr) compared to the same farm without an anaerobic digester and imported manure. The increase was from hauling the imported manure from the farm where was produced to the anaerobic digester and then hauling and land application of the digestate.

4.2.2. Production costs

The seasonal pasture had the highest production cost, followed by confinement with AD, confinement and annual pasture (Table 20). The seasonal pasture with AD had the lowest production cost.

Table 20. Total production costs ($/year) for five representative dairy production systems

	Confine	Confine AD	Seasonal pasture	Seasonal pasture w cash crop and AD	Annual Pasture
Equipment	98,926	98,090	95,937	92,017	51,273
Facilities	84,452	104,581	85,262	177,623	57,599
Energy	21,871	5,348	20,196	13,293	15,998
Labor	73,943	89,828	64,294	81,912	71,418
Custom operation	3,093	3,078	3,295	97,677	2,380
Seed, fertilizer and chemical	51,111	51,112	38,949	340,373	17,128
Land rental	5,270	5,270	5,270	96,178	5,270
Net purchased feed and bedding	21,791	17,414	120,973	(799,143)	120,873
Animal purchase and livestock expense	46,600	46,600	50,978	50,978	66,880
Milk hauling and marketing fees	23,730	23,744	27,370	27,359	23,348
Property tax	5,173	5,173	5,214	5,214	3,727
Total production costs	435,960	450,238	517,738	183,481	435,894

The major production costs in the confinement and seasonal pasture systems were for equipment, facilities, labor, seed, fertilizer and chemical and animal purchase and livestock expenses (Table 20). The seasonal pasture had higher facilities costs and animal purchase and livestock expenses compared to the confinement system because these costs increased with the number of cows. The confinement system had higher costs for labor, seed, fertilizer and chemicals because it had more crop land for corn and alfalfa production (111 ha) than the seasonal pasture (61 ha) due to the shift in land for grazing animals.

The transition from confinement to a seasonal pasture system increased production costs by 18% ($81,778/yr). The transition from confinement to annual pasture decreased production costs by $66/yr (Table 20). The increase in production cost in the seasonal pasture system was because of the increase in purchased feed which was 3.4 times more ($91,515/yr) than the confinement system. The seasonal dairy purchased 235 t DM/yr of soybean meal and 20 t DM/yr of distillers grain more than the confinement system (Table 18) because of the decrease corn production and the change in diet which included 24% of grazed forage.

The annual pasture dairy had production costs similar to the confinement system (Table 20). Although housing, machinery, manure handling and other costs decreased on the annual pasture dairy, net purchased feed cost increased ($99,082/yr) with the purchase of 204 t DM/yr more of soybean meal, 136 t DM/yr more distillers grain and 114 t DM/yr of dry grain (Table 18). These energy and protein feeds were needed to approach the target milk production level.

Animal purchase and livestock expenses increased by 44% ($20,280/yr) for the annual pasture dairy compared to the confinement dairy because of the increase in cow numbers. Most livestock expenses are related to the number of first lactation animals (Utsumi, personal communication, 2013), therefore high replacement rates are driven by the need to cull cows with recurrent health problems. Grazing cows tend to have fewer serious health problems and improved reproductive performance (Benbrook et al., 2010), therefore, for the annual pasture system 25% were first lactation animals and for the confinement system 35% were first lactation animals. Even though the annual livestock expenses were less ($418/cow-yr) for the annual pasture system compared to the confinement system ($551/cow-yr), total livestock expenses were higher for the annual pasture system because there were more animals on the farm.

Compared to confinement, the annual pasture-based system had the greatest reduction in the cost of seed, fertilizer and chemical (66%, $33,983/yr), equipment cost (48%, $47,653/yr), energy cost (27%, $5,873/yr), labor cost (3%, $2,525/yr), property tax (28%, $1,446/yr) and, custom operation (23%, $713/yr) because there was no grain crop production. There was a decrease of 32% ($26,853/yr) in facilities cost because the annual pasture-based system did not have a structure for cow housing (Table 20).

Production costs for the seasonal pasture with AD and additional land for cash cropping decreased $252,479/yr because of $820,934/yr decrease in net purchased feed and bedding cost compared to the confinement system. There were 2,942 t DM/yr feed sold compared to 60 t DM/yr sold by the confinement farm. The return from feed and cash crop sales more than offset the increased costs of custom hire, seed, fertilizer and chemicals, and land rental (Table 20).

The addition of the anaerobic digester on the seasonal farm with additional land for cash cropping increased facilities cost by 108% (92,361/yr) and labor cost by 27% ($17,618/yr) compared to the seasonal pasture without AD. Energy cost decreased by 34% ($6,903/yr) compared to the seasonal farm without AD and without an expanded land base. Comparing a seasonal farm with cash crop and imported manure without AD with the representative seasonal farm with expanded cash crop, imported manure and AD there was a reduction in energy cost by 68% ($28,321/yr). This included a 16% decrease ($1,318/yr) in energy for manure handling for the reduction in the amount of purchased bedding from 1.4 kg/cow/day (3 lb/cow/day) to 0.4 kg/cow/day (1 lb/cow/day). There was a 33% ($2,346/yr) decrease in energy for milking and milk cooling related to water heating that was partially replaced by gas from the digester. Energy for animal housing, ventilation and lighting ($1,500/yr) was completely offset the biogas produced by the AD.

The major reduction of energy costs with the AD was a reduction of 24% ($3,971/yr) in electricity purchased (production of resource inputs). Additionally, there was 352,783 MBtu/yr more electricity produced than consumed by the farm, and this was sold. However, the selling price was the same as the buying price which over-estimated the farm selling price. The revenue from electricity sold was $9,878/yr.

The confinement system with AD experienced an increase in facilities costs of 24% ($20,129/yr) and labor by 21% ($15,885/yr) due to the anaerobic digester. Bedding costs decreased 20% ($4,377/yr). Energy cost was reduced by 76% ($16,523/yr).

4.2.3. Income and net return

Income from milk sales was higher in the seasonal pasture system ($520,062/yr) followed by confinement ($450,900/yr) and the annual pasture ($443,650/yr). The annual milk production of the farms was 8,482 kg/cow for the seasonal pasture system, 9,946 kg/cow for the confinement system and 6,829 kg/cow for the annual pasture-based system. Even though the confinement had higher milk production per cow, the income from milk sales was higher for seasonal pasture farm because it had more lactating cows than the confinement farm.

Income from animal sales increased 36% ($22,155/yr) with the seasonal pasture system and 30% ($18,752/yr) with the annual pasture-based system compared to confinement (Table 21). The difference was related to the culling rate; 25% for the seasonal pasture, 30% for the annual pasture, and 35% for the confinement system.

Table 21. Income and net return to management and unpaid factors ($/year) for five representative dairy production systems

	Confine	Confine AD	Seasonal pasture	Seasonal pasture w cash crop and AD	Annual Pasture
Income from milk sales	450,900	451,160	520,062	519,862	443,650
Income from animal sales	61,655	61,655	83,810	83,810	80,407
Livestock expenses ($/cow-yr)	551	551	359	359	418
Return to management and unpaid factors	73,594	62,578	86,133	420,192	88,162

Return to management and unpaid factors varied depending on the farming system (Table 21). The seasonal pasture with AD and cash crop production had the greatest net return to management and unpaid factors, followed by the annual pasture, seasonal pasture, confinement and confinement with AD. Seasonal pasture with additional land for cash cropping and AD had the highest net return because it had the lowest production cost ($183,481/yr) and the highest income from milk ($519,862/yr) and animal sales ($83,810/yr) which were 70% less, and 15% and 36% more, respectively, than the confinement dairy. The farm had a net return to management and unpaid factors of $334,059/yr greater than the seasonal dairy, indicating returns from both the AD and cash crop sales.

The confinement farm with AD had the lowest net return to management and unpaid factors because of the high production cost ($450,238/yr) which included an increase of $14,278 per year from the AD. The addition of the AD on the confinement farm reduced the net return to management and unpaid factors by $11,016/yr.

The annual pasture and seasonal pasture had similar net returns (Table 21). The confinement system had a lower net return to management and unpaid factors compared to the annual pasture and seasonal pasture systems because it had $20,500/yr less income from animal sales.

4.3. Environmental impact

The evaluation of the environmental impact focused on: 1) nutrient balance and nutrient loss to the environment, 2) emissions of ammonia, hydrogen sulfide, methane, nitrous oxide, biogenic carbon dioxide and combustion of carbon dioxide) and 3) environmental footprints (water, reactive nitrogen loss, energy use and greenhouse gas emissions). The analysis links the environmental impact with the type of dairy housing and management system (confinement, seasonal pasture or annual pasture) and the integration of an anaerobic digester on confinement and seasonal pasture dairies.

4.3.1. On-farm nutrient cycling

Nutrients that flow through the farm either accumulated in the soil or were lost to the environment. The whole-farm mass balance of nitrogen, phosphorus and potassium was determined as the sum of all nutrient imports in feed, fertilizer, manure deposition and legume fixation minus the exports in milk, feed, animals, manure, and losses to the environment (Figure 11). The quantity and nutrient content of the manure produced was a function of the quantity and nutrient content of the feeds consumed. Total manure nitrogen consisted of organic and ammoniacal nitrogen (NH_3-N). During manure handling, ammoniacal nitrogen was transformed and volatilized as ammonia (Figure 7).

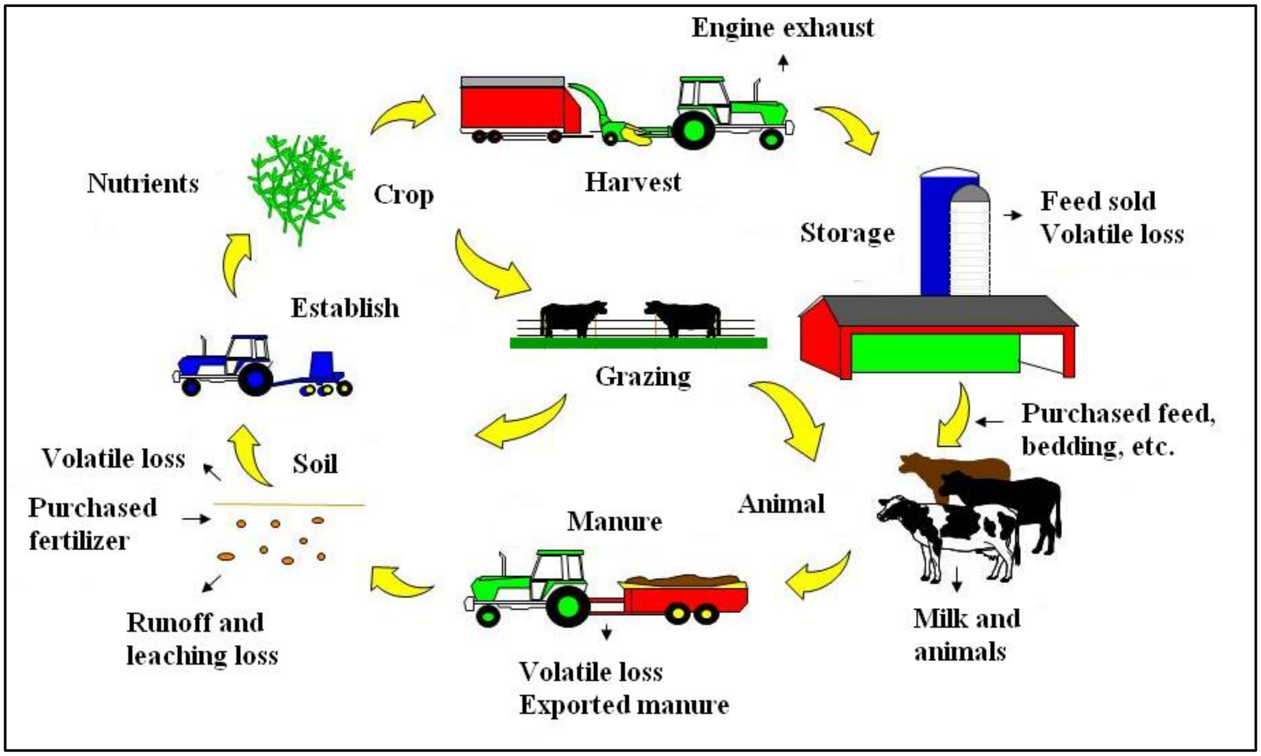


Figure 7. Integrated Farm System Model Overview (USDA, 2013)

An embedded soil model was used to predict moisture and nitrogen available for the growth and development of each crop. Each soil layer included nitrate, ammonia, crop residue nitrogen, manure organic nitrogen, and other soil organic matter. Nitrogen uptake by the crop was limited by availability or demand of the crop. In the confinement and seasonal farms all manure collected in the milking parlor and barn was applied to land going to corn production. Nitrogen from legumes and manure applied by the grazing animals supplied the nutrients for the grass pasture. In the annual pasture-based dairy, 80% of manure collected in the milking parlor was applied to grass and 20% to alfalfa.

Daily nitrogen losses from the soil were from volatilization, leaching and denitrification (Figure 8). Nitrogen volatilization losses occurred in the barn, during storage, following field application and during grazing. Denitrification and leaching losses were related to the rate of moisture movement and drainage from the soil profile as influenced by soil properties, rainfall, and the amount and timing of manure and fertilizer applications. Erosion of sediment was a function of daily runoff depth, peak runoff rate, field area, soil erodibility, slope, and soil cover. Phosphorus transformation and movement were among surface and subsurface soil pools of organic and inorganic P. Surface processes included surface application, runoff, and transformation along with soil-surface interactions through infiltration and tillage. Runoff losses of sediment-bound P and soluble P were influenced by manure and tillage management as well as daily soil and weather conditions.

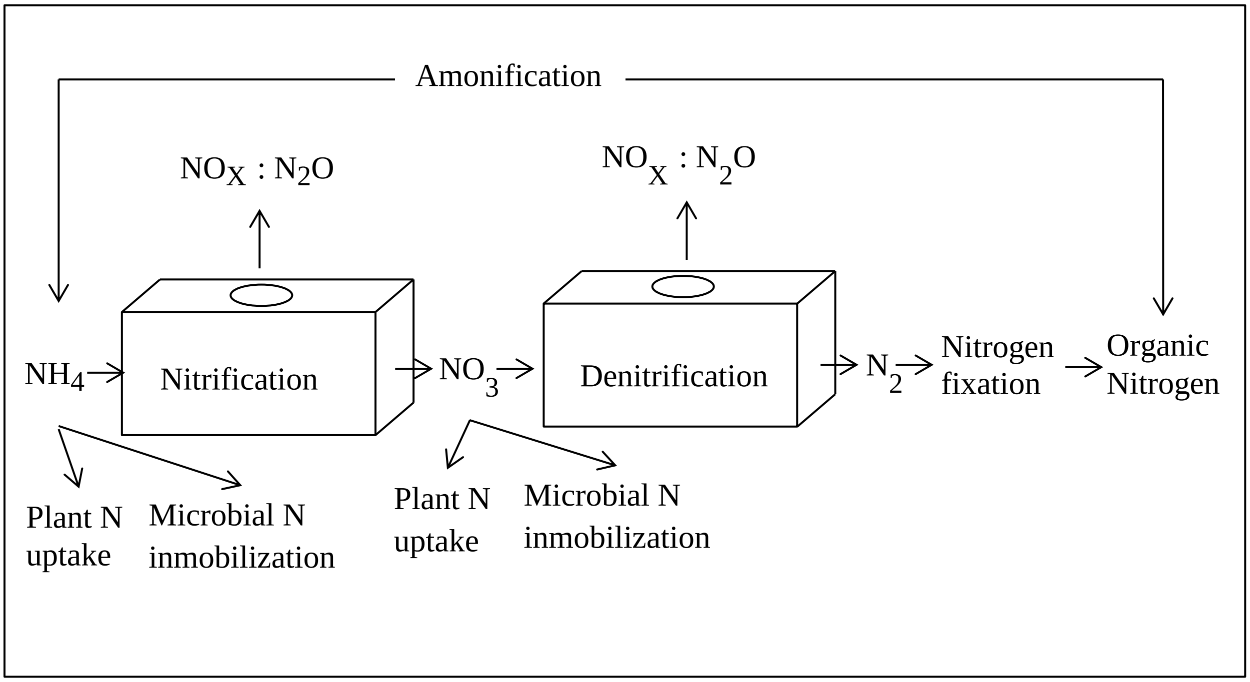


Figure 8. Conceptual model of controls on N gas emissions from soil (modified from Parton et al., 2001)

The nutrient balance included the crop nutrients available on-farm (N, P, K) and crop nutrient removal over that available on the farm, and included annual soil P and K build-up or depletion. Nutrient balance was influenced by the cropping system and the area designated for each one (Table 22).

Table 22. Land area of five representative dairy production systems (ha)

	Confine	Confine AD	Seasonal pasture	Seasonal pasture w cash crop and AD	Annual Pasture
Total land	111	111	111	809	111
Alfalfa area	36	36	10	10	40
Grass area	0	0	51	51	71
Corn area	75	75	51	374	0
Soybeans area	0	0	0	374	0

4.3.2. Confinement systems

4.3.2.1. On-farm nutrient cycling

On the confinement farms most of the nutrients were imported through purchased feed (such as soybean meal, distillers grain, minerals and vitamins), fertilizer, and legume fixation. Twenty-eight kilograms per hectare (25 lb/ac-yr) of nitrogen was applied to the corn at planting time. To supply the N, P and K required by the corn, all manure was applied to land going to corn production. The export of nutrients was through sales of milk, animals and feed, and losses such as nitrogen volatilization, denitrification and leaching, and P and K loss through runoff. There was also carbon loss as carbon dioxide, methane and through runoff.

Both confinement farms (with and without AD) had similar nutrient imports and exports, nutrients available on-farm, nutrient crop removal, nutrients build-up or depletion (Table 23) and nutrients loss (Table 24). When the AD was introduced there was a reduction in potassium import because a portion of the bedding was recycled so less bedding was purchased.

Table 23. Annual nutrient cycling on five representative dairy farms.

	Unit	Confine	Confine AD	Seasonal pasture	Seasonal pasture w cash crop and AD	Annual Pasture
Nutrients imported and exported						
N imported	kg/ha	195	195	326	212	342
N exported	kg/ha	83	84	79	123	76
P imported	kg/ha	12	12	23	16	22
P exported	kg/ha	14	14	14	16	11
K imported	kg/ha	26	15	72	41	52
K exported	kg/ha	28	28	21	31	27
Nutrients available on farm						
N	kg/ha	298	293	479	235	500
P	kg/ha	19	19	31	17	30
K	kg/ha	108	97	193	59	195
Nutrients crop removal over that available on farm						
N	%	60	61	46	60	46
P	%	115	117	76	105	64
K	%	101	112	76	80	83
Nutrients build up or depletion						
P build-up	kg/ha	0	0	9.0	0	11.2
P depletion	kg/ha	2.2	2.5	0	0.2	0
K build-up	kg/ha	0	0	41.9	10.2	14.6
K depletion	kg/ha	7.1	17.8	0	0	0

Table 24. Nutrient loss to the environment on five representative dairy farms (kg/ha-yr).

	Confine	Confine AD	Seasonal pasture	Seasonal pasture w/cash crop and AD	Annual pasture
Nitrogen lost by volatilization	76.3	78.4	166	34.9	157
Nitrogen lost by leaching	12.1	11.1	51.3	11.5	19.4
Nitrogen lost by denitrification	8.1	7.2	40.6	6.7	12.2
Phosphorous loss in runoff and leachate	0.34	0.34	0.22	0.56	0.00
Potassium loss through runoff	5.38	4.82	9.64	2.91	9.75
Carbon loss as carbon dioxide	6,194	6,044	5,380	8,857	7,869
Carbon loss as methane	209	189	250	31	197
Carbon loss through runoff	1.3	1.3	1.3	1.5	0.3

4.3.2.1.1. Potassium

Adding the AD on the confinement farm decreased the amount of K imported from 26 kg/ha-yr to 15 kg/ha-yr, and on-farm nutrient availability decreased from 108 kg/ha-yr to 97 kg/ha-yr (Table 23) because chopped straw bedding purchases decreased from 1.4 kg/cow-day to 0.5 kg/cow-day as a portion of the bedding was separated and recycled. Overall, K exports did not change although there was a small decrease in K runoff related to the reduction in manure volume with the AD digestate.

The land area available and crops produced were selected to provide the forage and corn grain for the herd with only small amounts purchased or sold. The cropping system on the confinement farm caused a small, long-term, K depletion (7.1 kg/ha-yr) which would require periodic purchases of commercial K to correct. When the AD was added and less bedding was imported the soil K depletion increased to 17.8 kg/ha-yr. This need for additional fertilizer would offset a portion of the savings from the reduction in purchased bedding (Figure 9).

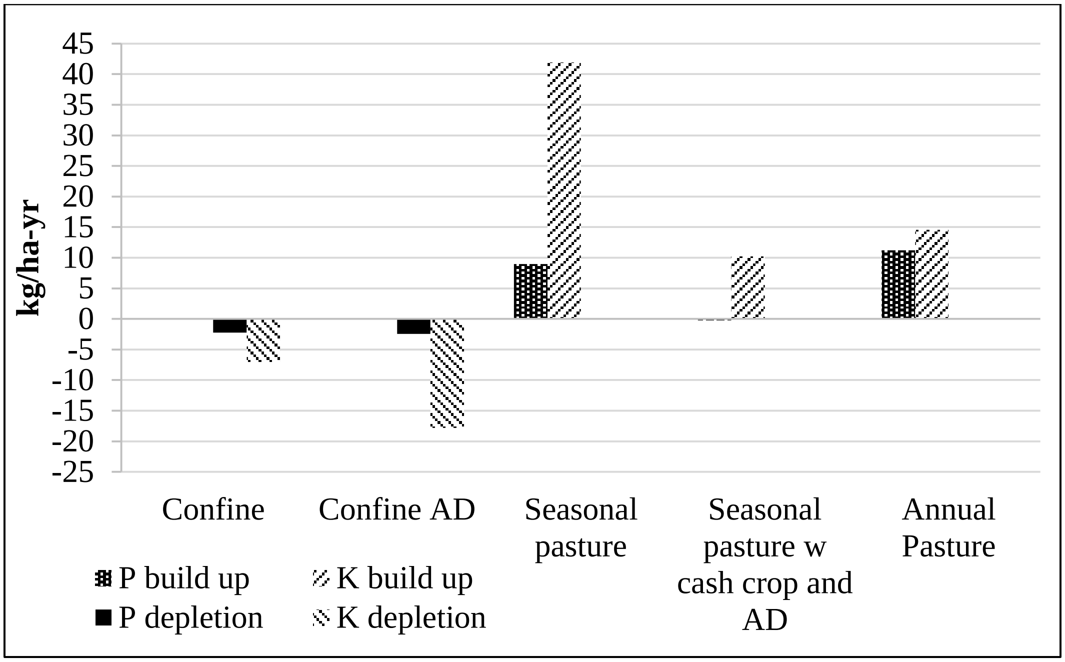


Figure 9. Soil phosphorous and potassium build up and depletion

4.3.1.1.2. Nitrogen

Nitrogen imported to farm was the same in both confinement farms (195 kg/ha-yr). Nitrogen was mainly imported through purchased soybean meal and distillers grain. In addition 28 kg/ ha-yr (25 lb/ac-yr) of nitrogen was imported as fertilizer for corn land. Alfalfa and pasture legumes imported N to the farm through N fixation. Perennial and forage legumes, such as alfalfa and white clover may fix 280-560 kg of nitrogen per hectare (Lindemann and Glover, 2003). Nitrogen crop removal over that available on farm was 60%-yr, allowing between 293 and 298 kg/ha-yr of N available on farm (Table 23).

The export of N was through milk, animals, alfalfa silage and hay sold. Nitrogen also had losses, most of all through volatilization (76.3 to 78.4 kg/ha-yr) that occurred in the barn, during storage and field application (Table 24). There were also some losses through denitrification and leaching which were related to soil properties and the amount and timing of manure and fertilizer applications.

4.3.1.1.3. Phosphorus

Phosphorous imported to the farm was the same on both confinement farms (12 kg/ha-yr). It was primarily imported through purchased soybean meal and distillers grain. Phosphorous crop removal was between 115 and 117%-yr over that available on farm, allowing 19 kg/ha-yr of P available on farm (Table 23). The export of P was through milk, animals, feed sold and losses through runoff and leachate (0.34 kg/ha-yr) (Table 24). The low P available on farm and the exports and losses produced a small P depletion between 2.2 and 2.5 kg/ha-yr (Table 23, Figure 9).

4.3.2.2 .Environmental emissions

Greenhouse gas emissions of carbon dioxide, methane, and nitrous oxide in addition to ammonia and hydrogen sulfide originating from manure on the barn floor, the manure storage structure and field applied manure were evaluated. The major emissions from each of the dairies (from highest to lowest) were: methane, combustion carbon dioxide, ammonia, nitrous oxide, hydrogen sulfide and, biogenic carbon dioxide (Table 25).

Table 25. Environmental emissions of five representative dairy production systems

	Confine	Confine AD	Seasonal pasture	Seasonal pasture w cash crop and AD	Annual Pasture
Ammonia					
Total farm (kg/yr)	10,340	10,619	22,436	35,068	21,234
Total farm (kg/ha-yr)	93	96	202	43	191
Hydrogen Sulfide					
Total farm (kg/yr)	326	313	264	1,043	40
Total farm (kg/ha-yr)	2.9	2.8	2.4	1.3	0.4
Methane					
Total farm (kg/yr)	31,001	28,062	37,192	37,582	29,174
Total farm (kg/ha-yr)	279	253	335	46	263
Nitrous Oxide					
Total farm (kg/yr)	486	468	934	1,662	630
Total farm (kg/ha-yr)	4.4	4.2	8.4	2.1	5.7
Biogenic Carbon Dioxide					
Net emission (kg/yr)	-365,875	-357,925	-422,615	1,745,611	-347,118
Net emission (kg/ha-yr)	-3,296	-3,225	-3,807	2,158	-3,127
Combustion CO_2					
Total farm (kg/yr)	35,683	30,210	29,864	20,371	24,093
Total farm (kg/ha-yr)	321	272	269	25	217

4.3.2.2.1. Carbon dioxide and methane emissions

Carbon loss as carbon dioxide was the greatest source of carbon loss in the total confinement dairy systems. Ninety-five percent of the total carbon loss was lost as biogenic CO_2

(Figure 10, Table 24) which was from plant, animal and microbial respiration from soil and stored manure. Most of the biogenic carbon dioxide emissions originated in the housing facilities from animal respiration and decomposition of organic matter in manure on floors in the barn (Table 26). Confinement barn emissions were greater than the systems incorporating grazing because of the extended period of time the animals were in the barn. When the AD was added biogenic carbon dioxide emissions increased in manure storage (Table 26) because carbon dioxide was released in the combustion of methane during anaerobic digestion. There was a small decrease in biogenic carbon dioxide assimilated in feed because of the reduction in manure during the digestion process. The result was a small decrease in biogenic carbon dioxide with the AD.

Table 26. Biogenic carbon dioxide emissions of five representative dairy production systems (kg/yr)

	Confine	Confine AD	Seasonal pasture	Seasonal pasture w cash crop and AD	Annual Pasture
Housing facility	685,552	685,496	555,488	554,272	504,026
Manure storage	42,479	241,471	26,921	212,444	0
Assimilated in feed	-1,093,905	-1,284,892	-1,249,702	734,613	-1,069,259
Grazing animal	0	0	244,678	244,282	218,114
Net emission	-365,875	-357,925	-422,615	1,745,611	-347,118
Net emission (kg/ha-yr)	-3,296	-3,225	-3,807	2,158	-3,127

Other major sources of CO_2 emission were from fuel combustion (Table 25) related to field operations such as tillage, planting, harvesting and other operations requiring mechanization. Adding the AD lead to a 2% reduction in carbon loss as carbon dioxide and a 9% reduction of carbon loss as methane. Each decrease was related to the conversion of methane to biogas for electricity generation or water heating. The major source of methane was the long term manure storage. Because the manure storage structure served as short-term storage to hold manure before being deposited in the digester, carbon loss as methane decreased as the manure storage period decreased (Table 24).

Major sources of methane emissions were from enteric fermentation and long term manure storage with minor sources being in the barn floor and field applied manure. The dairy cattle were the main source of methane emissions for each of the confinement dairies (Table 27). The long term manure storage facility was also an important source of methane. The addition of the anaerobic digester on the confinement farm decreased methane emission from the manure storage structure by 26% (from 11,274 kg/yr to 8,360 kg/yr) by enclosing the manure in a tank where the methane was converted to biogas (Table 27).

Table 27. Methane emissions of five representative dairy production systems (kg/yr)

	Confine	Confine AD	Seasonal pasture	Seasonal pasture w cash crop and AD	Annual Pasture
Housing facility	19,690	19,661	20,115	20,238	19,497
Manure storage	11,274	8,360	7,070	7,118	0
Field application	38	40	71	203	39
Grazing	0	0	9,936	10,022	9,638
Total farm	31,001	28,062	37,192	37,582	29,174
Total farm (kg/ha-yr)	279	253	335	46	263

4.3.2.2.2. Ammonia emissions

Ammonia is produced when microbes breakdown protein and other nitrogen containing compounds during decomposition causing an increase in pH (Hoeksema et al., 2012). In raw manure there is a balance between ammonium concentration and volatile fatty acid concentration which results in a pH near neutral. When volatile fatty acids are reduced during anaerobic digestion, pH increases (Paul and Beauchamp, 1989) so pH is normally higher in digestate than in raw manure. Volatile ammonia is formed (NH_3), which could be up to 25% of the ammonium fraction (Scottish Executive Environment and Rural Affairs Department, 2007). Most of the ammonia emissions from the confinement farms originated from manure on the milking center and barn floors, manure storage structures and following field application (Table 28). Because of the increased volatility there was a small increase in ammonia emissions with AD.

Table 28. Ammonia emissions of five representative dairy production systems (kg/yr)

	Confine	Confine AD	Seasonal pasture	Seasonal pasture w cash crop and AD	Annual Pasture
Housing facility	4,310	4,217	6,773	6,804	15,150
Manure storage	2,172	2,315	4,549	5,153	0
Field application	3,859	4,086	7,151	19,106	2,309
Grazing	0	0	3,963	4,005	3,774
Total farm	10,340	10,619	22,436	35,068	21,234
Total farm (kg/ha-yr)	93	96	202	43	191

4.3.2.2.3. Nitrous oxide emission

Nitrous oxide emissions originate primarily from nitrification and denitrification processes in the soil, and also in the crust of the slurry manure storage (Rotz et al., 2011a). Nitrous oxide has a global warming potential 298 times that of carbon dioxide, making it the strongest of all greenhouse gas emissions in agricultural production (IPCC, 2007). Nitrous oxide emissions can be greater where manure remains for longer periods where nitrification or denitrification converts ammonium to nitrate or nitrate to atmospheric N_2 (Figure 8) (IPCC, 2007).

On the confinement farms nitrous oxide emissions originated primarily in the housing facilities, manure storage and farmland (Table 29). The pH of digested manure is typically higher thereby supporting nitrous oxide reduction. The addition of an AD on the confinement farm decreased the total farm emissions of nitrous oxide by a small amount (4%). Manure on the free stall barn floor is typically a minor source of nitrous oxide emission (Rotz et al., 2011a) but some enteric nitrous oxide could also be emitted by the animals (Hamilton et al., 2010).

Table 29. Nitrous oxide emissions of five representative dairy production systems (kg/yr)

	Confine	Confine AD	Seasonal pasture	Seasonal pasture w cash crop and AD	Annual Pasture
Housing facility	204	198	339	375	325
Manure storage	147	143	243	269	0
Farmland	134	126	352	1,019	305
Total farm	486	468	934	1,662	630
Total farm (kg/ha-yr)	4.4	4.2	8.4	2.1	5.7

4.3.2.2.4. Hydrogen sulfide emissions

Hydrogen sulfide is a toxic compound that is regulated by the US EPA under the Clean Air Act. Hydrogen sulfide is primarily created and emitted from decomposing manure under anaerobic conditions (Rotz et al., 2011a). The major source of hydrogen sulfide on all dairies was field application of manure (Table 30). On the confinement farms manure was stored under anaerobic conditions beneath the crust formed on the manure surface which increased the hydrogen sulfide emission. The anaerobic digester reduced hydrogen sulfide emissions by 4% because of the recycled bedding and reduction of manure handled after the digestion process. The confinement farm handled 3,155 t DM/yr of manure but when an anaerobic digester was used the amount of manure handled was reduced to 3,102 t DM/yr.

Table 30. Hydrogen sulfide emissions of five representative dairy production systems (kg/yr)

	Confine	Confine AD	Seasonal pasture	Seasonal pasture w cash crop and AD	Annual Pasture
Housing facility	35	34	30	29	39
Manure storage	63	61	50	49	0
Field application	228	218	184	964	0
Grazing	0	0	0	0	0
Total farm	326	313	264	1,043	40
Total farm (kg/ha-yr)	2.9	2.8	2.4	1.3	0.4

4.3.2.3. Environmental footprints

Environmental footprint is a measure of the demand on the ecosystem services of the earth. Footprints were evaluated for water, reactive nitrogen, energy, and greenhouse gas emissions. The footprints were determined by summing the estimates for each of the uses (removing those allocated to co-products), and dividing by the amount of milk produced.

Water was mainly used for the production of feed crops, drinking water for animals, animal cooling, cleaning of the parlor and holding areas on dairy farms. Reactive nitrogen is essential in the growing of crops and feeding of animals. Primary losses of reactive nitrogen include ammonia and nitrous oxide emissions to the atmosphere, nitrate leaching to ground water, and the combustion of fuels. The energy footprint was the total energy required to produce feed and milk which includes all fuel and electricity directly used in the production system as well as the secondary energy used in the production of resources used on the farm. The carbon footprint was determined as the net emission of the three GHG’s including all sources and sinks of CO_2, so a portion of the CO_2 assimilated in the feed is in the carbon exported during feed, milk, and animal productions.

4.3.2.3.1. Water footprint

In all dairies the major sources of water footprint were: feed production with rainfall, followed by production of purchased feed and inputs (Table 31). There was a 28% reduction in water use for purchased feed and inputs when the AD was used on the confinement farm because of the reduction in purchased bedding. Because less bedding was purchased less water was required for the production of bedding. Even though straw is a by-product of harvest it requires water for growth.

Table 31. Water footprints of five representative dairy production systems

	Unit	Confine	Confine AD	Seasonal pasture	Seasonal pasture w cash crop AD	Annual Pasture
Feed production, rainfall	t/yr	585,780	585,935	585,746	1,008,009	584,965
Drinking	t/yr	2,810	2,810	4,193	4,185	3,977
Animal cooling	t/yr	228	228	324	324	365
Parlor, equipment cleaning	t/yr	913	913	1,296	1,295	1,460
Production of purchased feed and inputs	t/yr	128,317	92,701	326,354	328,487	335,579
Not allocated to milk production	t/yr	-122,454	-117,049	-160,046	-200,348	-144,650
Water footprint with rainfall	kg/kg FPCM-yr	600	569	630	905	716
Water footprint without rainfall	kg/kg FPCM-yr	99	68	195	170	244
Water footprint w rainfall per ha	kg/kg FPCM-ha-yr	5.4	5.1	5.7	1.1	6.4

The water footprint decreased 4% with AD evaluated as the water footprint not allocated to milk production (Table 31). Water used in the production of machinery, fertilizer, pesticides, and plastic was considered to be insignificant (Rotz et al., 2011a). Water use for drinking, animal cooling and parlor and equipment cleaning on all farms increased with the number of cows.

4.3.2.3.2. Energy footprint

The major sources of energy use footprint were production of resource inputs, milking and milk cooling, feed production, animal feeding, manure handling and animal housing ventilation and lighting (Table 32). The confinement farms had the highest energy use in feed production (215,987 MJ/yr) because it produced 36 to 54% more feed than the seasonal and annual pasture farms. Because animals were kept in the barn all year, animal feeding (152,438 MJ) and animal housing ventilation and lighting (57,779 MJ/yr) were also the greatest energy demands of all the farms (Table 32).

Table 32. Energy footprint of five representative dairy production systems

	Unit	Confine	Confine AD	Seasonal pasture	Seasonal pasture w cash crop AD	Annual Pasture
Feed production	MJ	215,987	215,862	141,373	190,568	115,236
Animal feeding	MJ	152,438	151,968	122,344	120,557	110,996
Manure handling	MJ	74,329	64,052	67,626	256,978	68,338
Milking, milk cooling	MJ	232,312	155,099	267,928	179,039	228,576
Animal housing ventilation, lighting	MJ	57,799	57,799	56,576	56,444	18,091
Production of resource inputs	MJ	1,906,139	1,249,329	2,159,025	2,478,746	2,033,489
Not allocated to milk production	MJ	-451,019	-338,499	-533,488	-571,014	-434,975
Energy footprint	MJ/kg FPCM	2.2	1.6	1.9	2.1	2.0
Energy footprint per ha	MJ/kg FPCM-ha	0.02	0.01	0.02	0.003	0.02

Adding the AD on the confinement dairy reduced energy use for manure handling by 14% (10,277 MJ/yr), by reducing the volume of bedding handled and applied as manure. Energy for milking and milk cooling was reduced by 33% (77,213 MJ/yr) as energy for water heating was partially replaced by biogas from the digester. The greatest reduction of the energy footprint was from the reduction in fossil fuel energy used to generate electricity off-farm (production of resource inputs) which was reduced 34% (656,810 MJ/yr). There was also a 25% decrease in energy use not allocated to milk production (allocated to the cattle growth and sold as beef).

4.3.2.3.3. Reactive nitrogen loss footprint

The primary sources of reactive nitrogen loss were ammonia emissions, nitrate leaching, nitrous oxide emissions fuel combustion emissions and production of resource inputs (Table 33). Reactive nitrogen is essential to crop and livestock production. The confinement dairy had the smallest reactive nitrogen loss footprint (8.9 g/kg FPCM-yr) (Table 33) because it had the least ammonia emissions, nitrate leaching, nitrous oxide emissions and nitrogen loss during the production of resource inputs. Each of these (except ammonia) was reduced when the AD was used on the confinement farm. Ammonia emissions increased because the pH increased in the digestate, thereby producing more ammonium in the volatile form. Nitrate leaching decreased because less manure was being applied to the land. Nitrous oxide emissions decreased because the higher pH in the digestate allowed nitrous oxide reduction from ammonium or nitrate to nitrous oxide.

Nitrous oxide emissions due to fuel combustion were also reduced on the confinement farm with AD because less manure was being handled (Table 33). Combustion of fossil fuel releases nitrogen oxides to the atmosphere which increase with field operations that require more tillage, planting and harvesting.

Table 33. Reactive nitrogen loss footprint of five representative dairy production systems

	Unit	Confine	Confine AD	Seasonal pasture	Seasonal pasture w cash crop AD	Annual Pasture
Ammonia em[a]	kg	8,496	8,725	18,439	57,912	17,447
Nitrate leaching	kg	1,343	1,239	5,711	19,234	2,164
Nitrous oxide em	kg	309	297	594	2,165	401
Fuel combustion em	kg	118	100	94	644	76
Production of resource inputs	kg	428	352	1,052	1,941	1,135
Not allocated to milk production	kg	-1,825	-1,827	-3,690	-10,617	-3,045
Reactive nitrogen footprint	g/kg FPCM	8.9	8.9	18.5	30.1	16.7
Reactive nitrogen footprint per ha	g/kg FPCM-ha	0.1	0.1	0.2	0.04	0.1

[a]: em= emission

4.3.2.3.4. Carbon footprint

The carbon footprint measures total GHG emissions expressed in CO_2 equivalent units (CO_{2e}). The primary contributors to the carbon footprint were animal emissions (25 to 59% of total GHG), manure emissions (9 to 34% of total GHG), production of resource inputs (9 to 23% of total GHG), emissions during feed production (2 to 7% total GHG) and fuel combustion emissions (1 to 3% of total GHG) (Table 34).

The confinement dairies had the lowest animal emissions because animal respiration was based on daily intake of feed dry matter (Rotz et al., 2011a). Because animals in confinement consume less forage in the diet than grazing animals, carbon dioxide emissions decreased. When using an AD, carbon dioxide emissions from manure decreased because methane emissions were reduced by containing all manure in a closed tank where it was converted biogas. The carbon footprint associated with the production of resource inputs decreased by 31% because of the reduction of fossil fuel used to generate electricity off-farm.

Table 34. Carbon footprint of five representative dairy production systems

	Unit	Confine	Confine AD	Seasonal pasture	Seasonal pasture w cash crop AD	Annual Pasture
Animal em[a]	kg	481,602	481,395	741,392	1,493,521	716,839
Manure em	kg	397,334	321,179	360,953	766,547	108,683
Emission during feed production	kg	35,444	33,248	96,815	132,907	82,809
Net biogenic carbon dioxide em	kg	-365,550	-357,610	-422,188	2,928,001	-346,810
Fuel combustion em	kg	35,652	30,184	29,837	40,706	24,072
Production of resource inputs	kg	206,787	142,209	263,018	537,109	278,397
Not allocated to milk production	kg	-193,915	-171,407	-244,488	-489,918	-191,363
Carbon footprint without biogenic CO_2	kg/kg FPCM	0.97	0.84	1.04	1.00	0.93
Carbon footprint with biogenic CO_2	kg/kg FPCM	0.66	0.54	0.72	2.10	0.65
Carbon footprint with biogenic CO_2 per ha	kg/kg FPCM-ha	0.006	0.005	0.006	0.003	0.006

[a]: em= emission

4.3.3. Seasonal pasture farms

4.3.3.1. On-farm nutrient cycling

Most of the nutrients were imported on the seasonal pasture dairies were from purchased feed (such as hay, soybean meal, distillers grain, and minerals and vitamins), fertilizer, manure application and forage legume nitrogen fixation. All manure collected in the milking parlor and barn was applied to land going to corn production and twenty-eight kilograms per hectare (25 lb/ac) of commercial nitrogen fertilizer was applied to corn at planting time. Nitrogen from legumes and manure applied by the grazing animals supplied the nutrients for the grass pasture.

The exports of nutrients were through milk, animals and feed sold. Ten percent of the feed produced on the seasonal farm was sold and it was increased to 87% when additional land was acquired to accommodate the additional manure required for the AD. Some nutrients were the lost to the environment through nitrogen volatilization, denitrification, leaching, and loss of phosphorous and potassium through runoff. There were also carbon losses leaving the farm as carbon dioxide, methane or through runoff.

Nutrient cycling was different on the seasonal pasture farms because the land use and cropping system was different. The seasonal pasture had a 111 ha land base which expanded to 809 ha when cash crops were produced (Table 22).

4.3.3.1.1. Potassium

The seasonal pasture had the greatest soil potassium build up (41.9 kg/ha-yr) (Figure 9). Potassium imports (72 kg/ha-yr) (Table 23) were from the purchase of 13 t of hay (Table 20) following the shift of 26 ha of land for alfalfa production to land for grazing animals (Table 22). Potassium was also imported with purchase of chopped straw for bedding which contained nitrogen, phosphorous and potassium (Shaver and Hoffman, 2010). The seasonal farm also exported less potassium (21 kg/ha-yr), allowing potassium availability on-farm of 193 kg/ha-yr.

The seasonal farm with an expanded land base for cash crop production and AD had greater K exports (compared to the other farms) because 87% of the total crop production was sold (Table 23). The increase in pasture land also decreased potassium loss to the environment (Table 24).

4.3.3.1.2. Nitrogen

The seasonal pasture dairy imported more nitrogen per unit area than the seasonal farm with AD and additional land for cash crop production (Table 23) because relatively more bedding and feed were purchased. A greater percentage of the land was in alfalfa and grass/legume production, thereby increasing nitrogen import by fixation.

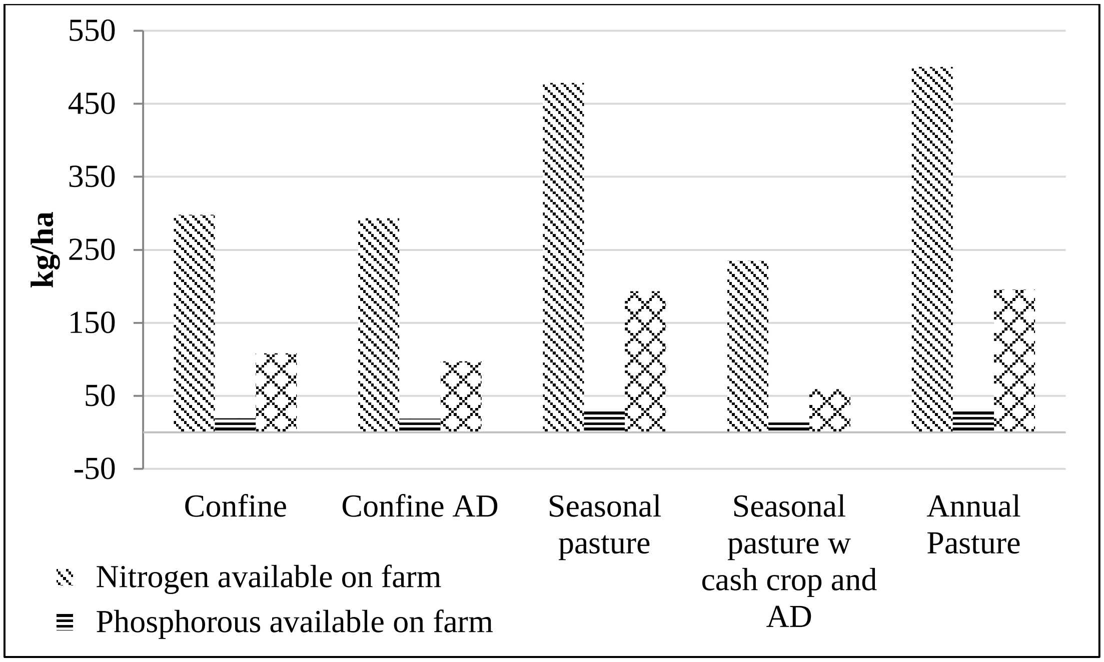


Figure 10. Nutrients available on farm

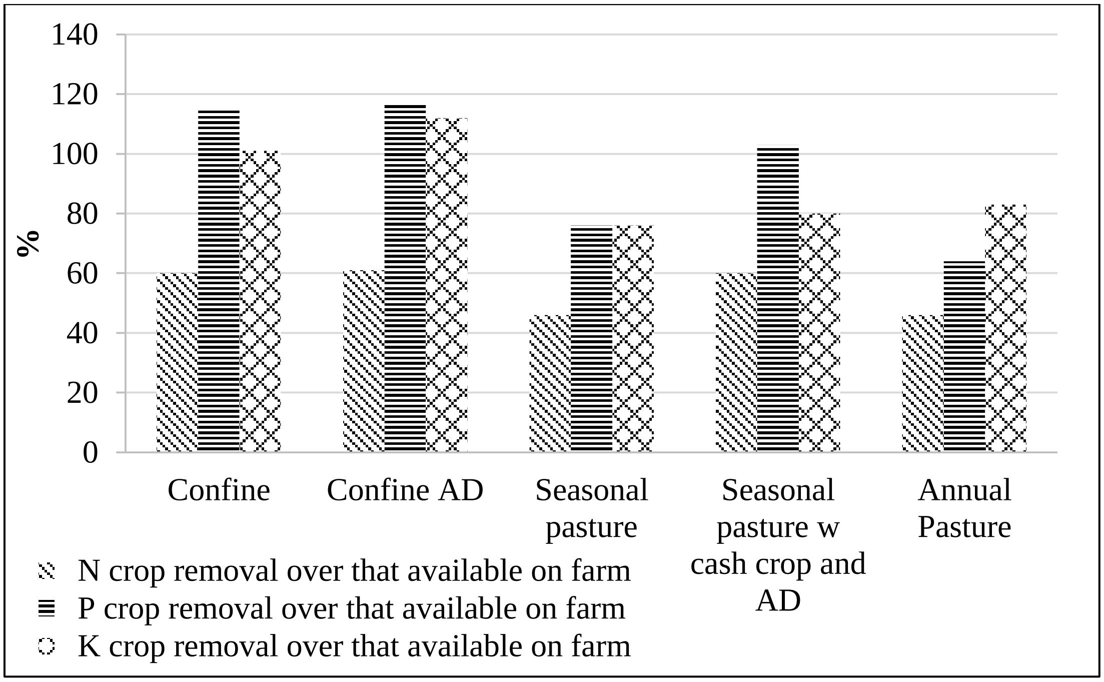


Figure 11. Nutrients crop removal over that available on farm.

The seasonal pasture dairies had the greatest nitrogen loss to the environment (258 kg/ha-yr). The losses were from leaching (51 kg/ha-yr), denitrification (40.6 kg/ha-yr) and volatilization (166 kg/ha-yr) (Figure 12). Denitrification and leaching losses from the soil were related to the rate of moisture movement and drainage from the soil profile as influenced by soil properties, rainfall, and the amount and timing of manure and fertilizer applications. There was more nitrogen loss by leaching because the urine deposited in the pasture had high concentrations of nitrogen which could exceed plant uptake (Table 24).

Nitrogen lost through volatilization was the greatest source of loss on all the dairies (Figure 12). Nitrogen is the most abundant nutrient in manure and the seasonal pasture dairy had the highest nitrogen lost by volatilization (166 kg/ha-yr) (Table 24) because of losses from manure in the barn, milking parlor, during land application and from the urine and manure deposited by the cattle.

On a unit area basis, nitrogen losses were reduced by 79% on the seasonal pasture with cash crop and AD compared to the seasonal pasture dairy (Figure 12, Table 24). Because of the increased land for cash crop production more nitrogen was used for crop production compared to that available on-farm.

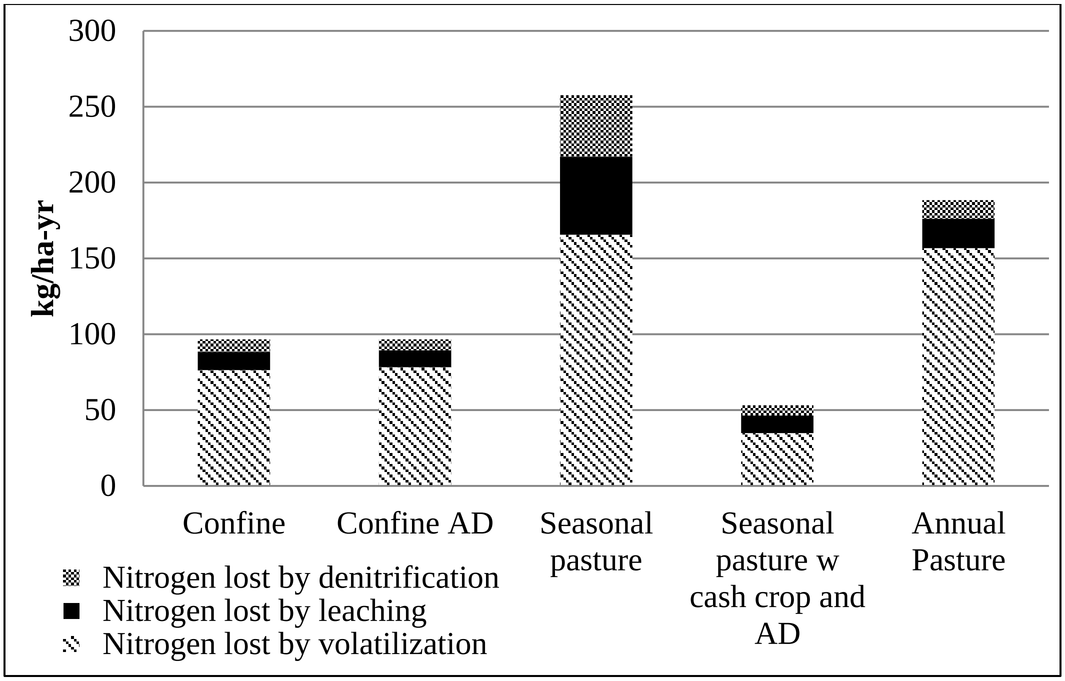


Figure 12. Nitrogen lost to the environment of five representative dairy production systems

4.3.3.1.3. Phosphorous

The seasonal pasture dairy had a greater phosphorous build-up (9.0 kg/ha-yr) because the P imported in feeds (primarily grain and concentrates) and bedding exceeded P exports in sales of meat, milk and excess feed (Table 22). The seasonal pasture with additional land for cash crop production and AD had greater P loss in runoff and leachate related to soil erosion and tillage of the crop land. Most of the P loss occurred with rainfall after land application of manure. Phosphorus imports equaled P exports and there was no long-term soil build-up or depletion.

4.3.3.2. Environmental emissions

Gaseous emissions from the seasonal pasture farms in rank order (from high to low) were: methane, combustion carbon dioxide, ammonia, nitrous oxide, hydrogen sulfide and, biogenic carbon dioxide (Table 25). When additional land was added with an AD the carbon dioxide released by the combustion of methane was offset by a reduction in carbon dioxide emission (20,371 kg/yr) from soil respiration. The major emissions from this farm were biogenic carbon dioxide (1,745,611 kg/yr) from the combustion of biogas (Table 25).

4.3.3.2.1. Carbon dioxide and methane emissions

The seasonal pasture with additional land for cash crop production and AD had the greatest carbon loss as carbon dioxide (8,857 kg/ha-yr) (Table 24) because any remaining biogas that was not used for either electricity generation or water heating was burned off in a flare.

Most of the biogenic carbon dioxide emissions on the seasonal pasture farm were from housing facilities related to animal respiration and manure on floors in the barn (Table 26). The grazing animals also increased biogenic carbon dioxide emissions (Table 26) because animal respiration was based on daily intake of feed dry matter (Rotz et al., 2011a). Because grazing animals consumes higher forage diets, carbon dioxide emission increased.

The greatest biogenic carbon dioxide emissions in the seasonal pasture with expanded cash crop and AD farm was because of the assimilation in feed due to the increased crop land. Croplands usually assimilate C from CO_2 in the atmosphere, but also emit CO_2 through plant (autotrophic) and soil (heterotrophic) respiration (Chianese et al., 2009a). Biogenic carbon dioxide emission in manure storage increased also increased in this farm (Table 26) because this emission includes the carbon dioxide created through combustion of methane.

The seasonal pasture with cash crop production and AD had the lowest carbon loss as methane (31 kg/ha-yr). Major sources of methane included long term storage and because storage time was reduced by holding the manure for a short time before placing it in the digester carbon loss as methane decreased (Table 24). The seasonal pasture farms had greater housing methane emissions than the confinement farm because grazing cows consumed more forage. The enteric methane emissions per cow increase with the percentage of fiber that was fed in the diet cow (Chianese et al., 200c).

Grazing animals in seasonal and annual pasture dairies increased methane emissions (9,630 to 10,022 kg/yr) because of the excreted feces and urine that were deposited on pastures (Table 27). Some studies have shown that feces are a small but significant source of methane and that emissions from urine are similar to background soil emissions (Jarvis et al., 1995; Yamulki et al., 1999).

4.3.3.2.2. Ammonia emissions

Ammonia emissions (22,436 kg/yr) from the seasonal pasture dairy were more than double that of the confinement farms (Figure 13, Table 28). Emissions from the housing facilities, manure storage and field application increased because there were more animals in the seasonal pasture system (142-cows) than the confinement system (100-cows), therefore more manure and urine was produced in these farms.

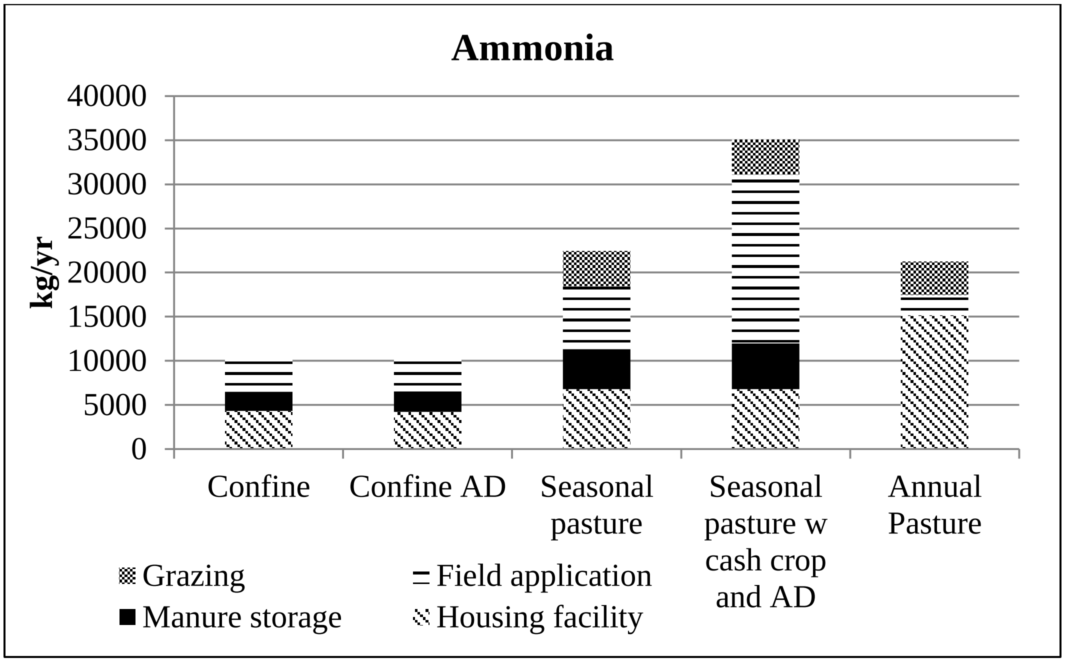


Figure 13. Ammonia emissions of five representative dairy production systems

The seasonal pasture with additional land for cash crop production and AD had the greatest ammonia emissions (35,068 kg/yr) because of the amount of manure applied to field (Figure 13, Table 28). Also, there was an increase in ammonia emissions as a result of the anaerobic digestion process due to an increase in slurry ammonium-N content.

4.3.3.2.3. Nitrous oxide emissions

The seasonal pasture with additional land for cash crop production and AD had the greatest emission of nitrous oxide (1,662 kg/yr) because of the additional nitrogen input on the additional crop land which increased farmland emissions (1,019 kg/yr) (Figure 14, Table 29).

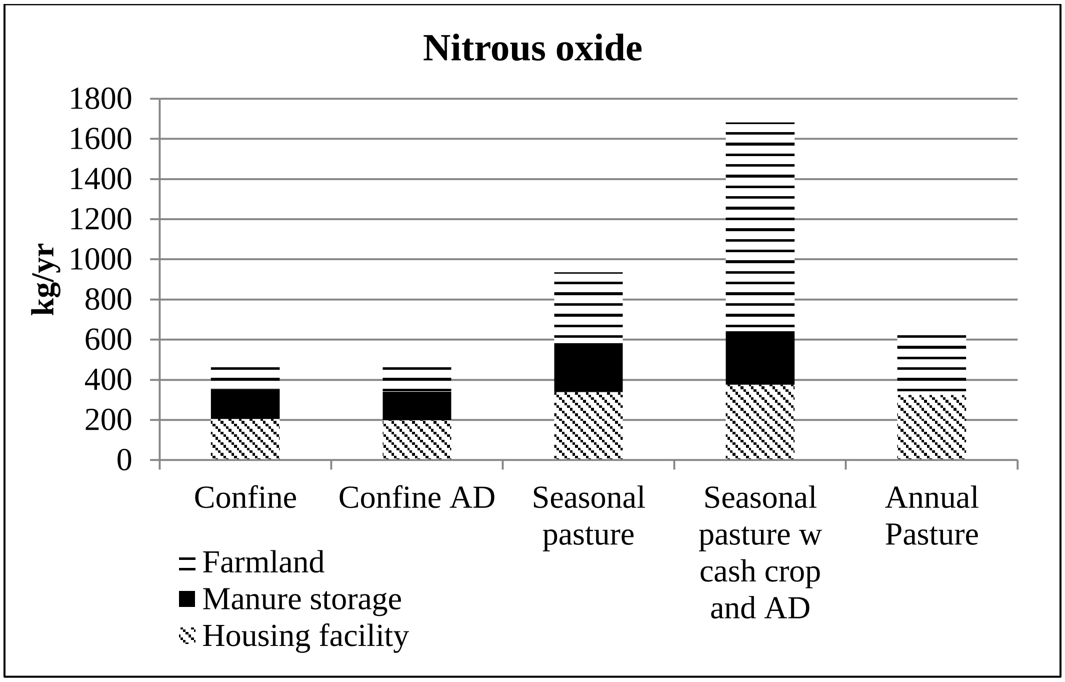


Figure 14. Nitrous oxide emissions of five representative dairy production systems.

The seasonal pasture with cash crops and AD had greater nitrous oxide emissions in the housing facilities (375 kg/yr). Nitrous oxide emissions can be greater where manure remains for longer periods as in the grazing areas. Manure on the floor of free stall barns appears to be a negligible source of nitrous oxide emission (Rotz et al., 2011a), but a small amount of enteric nitrous oxide is emitted by the animals (Hamilton et al., 2010) (Table 29).

Nitrous oxide emissions from the manure storage were from the natural crust that was formed on the stored slurry (Chianese et al., 2008b). The seasonal pasture dairies released more nitrous oxide (243 to 269 kg/yr) than the confinement dairies (143 to 147 kg/yr) (Table 29) because manure was collected less frequently during grazing season than in confinement storage.

4.3.3.2.4. Hydrogen sulfide emissions

The seasonal farm with AD and cash crops had the greatest hydrogen sulfide emissions (1,043 kg/yr) (Figure 15, Table 30). The major source of hydrogen sulfide was land application of manure (184 to 964 kg/yr). The seasonal pasture dairy had the lowest emissions from field application (184 kg/yr) because less manure was collected and applied to the field. The seasonal pasture with cash crops and AD emitted more hydrogen sulfide during field application (964 kg/yr) because: 1) The manure had been in anaerobic conditions (due to the anaerobic digester), encouraging the transformation from sulfide to hydrogen sulfide, and 2) since there was more crop land, more manure was applied on the soil, leading to more emissions.

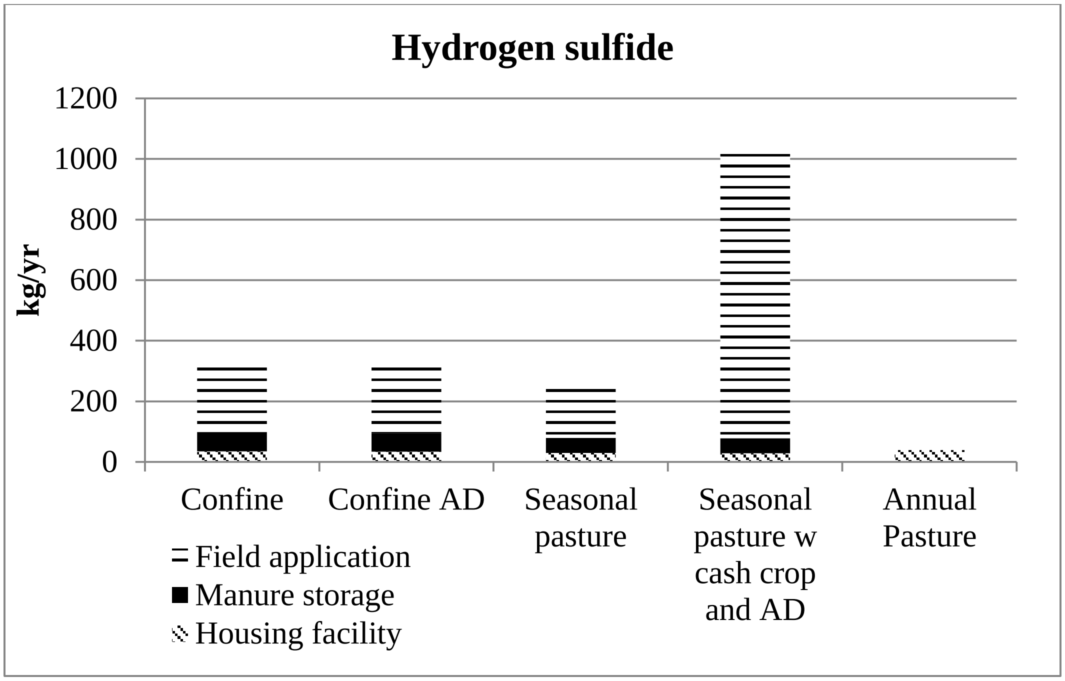


Figure 15. Hydrogen sulfide emission of five representative dairy production systems.

4.3.3.3 Environmental footprints

Water, reactive nitrogen, energy use and greenhouse gas emission footprints were evaluated for the seasonal pasture dairies.

4.3.3.3.1. Water footprint

The primary measures of the water footprint were rainfall for feed production followed by production of purchased feeds and inputs (Table 31). The seasonal pasture with additional land for cash crops and AD had the greatest water footprint (905 kg/kg FPCM-yr) due to feed production (sold and consumed) because this dairy had more area for crop production compared to the other dairies (Table 31). The dairy had less water footprint not allocated to milk production (-200,348 t/yr) because the cash crops sold were considered to be exported from the farm. Water used in the production of machinery, fertilizer, pesticides, and plastic was not significant (Rotz et al., 2011a). Water use for drinking, animal cooling and parlor and equipment cleaning was the same for both seasonal farms because it was based on the number of cows (Table 31).

4.3.3.3.2. Energy footprint

The transition from a confinement to a seasonal pasture dairy reduced the energy footprint by 14%. There was a reduction of 35% in on-farm feed production, 20% in animal feeding and 8% in manure handling (Table 32). These reductions were related to the shift of 24 ha of corn production to grazing. There was an 18% decrease in energy not allocated to milk production, which was allocated to the cattle growth produced and sold as beef. This was influenced by the relative quantities of milk and cattle sold.

The seasonal pasture with additional land for cash crops and AD dairy had the greatest energy use footprint for production of resources inputs (2,478,746 MJ/yr), such as fuel, electricity, machinery, fertilizer, pesticides, seed, and plastic for the additional land for cash crops. The farm also had the greatest energy footprint for manure handling related to the 12,882 wet t/yr of imported manure. However, the seasonal pasture with cash crops and AD dairy had 4% less energy use footprint 2.1 MJ/kg FPCM-yr (fat and protein corrected milk, 4% fat and 3.3% protein) compared to the confinement dairy (2.2 MJ/kg FPCM-yr) which had less area for crop production and an energy use for production resource inputs of 1,906,139 MJ/kg FPCM-yr (Table 32). The decrease in energy footprint was for two reasons: 1) the addition of the anaerobic digester and 2) because the seasonal pasture farm required less energy for feed production and animal feeding than the confinement farm. The addition of the AD on the seasonal farm reduced energy use by 23% (compared to the confinement farm) for milking, milk cooling and water heating. Energy for animal feeding was reduced by 21% and 12% for feed production compared to confinement because of the addition of grazing.

4.3.3.3.3. Reactive nitrogen loss footprint

The seasonal pasture dairy with cash crops and AD had the greatest reactive nitrogen loss footprint because of ammonia (57,912 kg/yr), nitrate leaching (19,234 kg/yr), nitrous oxide (2,165 kg/yr), production of resource inputs (1941 kg/yr) and fuel combustion emissions (644 kg/yr). Ammonia emissions were higher because more manure was applied (due to the imported manure). Also, there was an increase in ammonia emissions as a result of the anaerobic digestion process. Nitrate leaching, nitrous oxide, combustions emissions and production of resource inputs were increased because of the increased land for cash crop. Combustion of fossil fuels leads to the creation of nitrogen oxides in the atmosphere which increases with field operations that require more tillage, planting and harvesting.

4.3.3.3.4. Carbon footprint

The seasonal pasture with additional land for cash crops and AD had the greatest carbon footprint (2.10 kg/kg FPCM-yr) because of biogenic carbon dioxide, which accounted for 50% of the total GHG emissions. This farm also had the highest animal and manure emissions compared to the other dairies (Table 34) because of the 12,882 t/yr of imported manure. Emissions during feed production, fuel combustion and production of resource inputs were also higher due to the expanded land base for cash crop production (Table 34).

4.3.4. Annual Pasture-based farm

4.3.4.1. On-farm nutrient cycling

Most of the nutrients on the annual pasture-based farm were imported through purchased feed (such as hay, soybean meal, distillers grain and minerals and vitamins) and nitrogen fixation by alfalfa and legumes in the grass/legume pasture. Nitrogen from legumes and manure applied by the grazing animals supplied the nutrients for the grass pasture. Eighty percent of manure collected in the milking parlor was applied to grass and 20% to the alfalfa land. Nutrient exports were through milk, sales of animals and feed (10% of feed produced was sold), nitrogen volatilization, denitrification and leaching, and loss of phosphorous and potassium through runoff. There were also carbon losses leaving the farm as carbon dioxide, methane or through runoff.

4.3.4.1.1. Potassium

Potassium imports (52 kg/ha-yr) (Table 23) were mostly from the purchase of 114 t/yr of dry grain (Table 20) following the shift of land for crop production to land for grazing animals (Table 22). Grains contain less K than do legumes (forages contain 1-3% K; grain contains 0.5-0.8% K) (Dupchak, 2001), that is why the annual pasture (which purchased dry grain) had less potassium imported than the seasonal farm (which purchased hay and no dry grain).

4.3.4.1.2. Nitrogen

The annual pasture-based dairy had more nutrients available on-farm (500 kg/ha-yr) than the seasonal pasture farm (Table 23, Figure 10), because more N was imported through legumes fixation and purchased feed and less N was exported because this farm did not had grain production.

The annual pasture-based dairy had higher nitrogen loss from volatilization (157 kg/ha-yr) and leaching (12.2 kg/ha-yr) than the confinement dairy because the deposited urine could exceed the uptake by plants (Table 24).

4.3.4.1.3. Phosphorous

The annual pasture-based dairy had the greatest soil phosphorus build up (11.2 kg/ha-yr) (Figure 9) because beside it was the only farm that had application of manure collected on grass, also there were more imported feeds (primarily grain and concentrates) and less phosphorous was exported through crops that were sold as compared to the other farms (Table 23). This farm did not have P loss in runoff because of the permanent vegetative cover that reduced runoff and erosion (Table 24).

4.3.4.2. Environmental emissions

4.3.4.2.1. Carbon dioxide and methane emissions

The annual pasture-based dairy had the second greatest carbon loss as carbon dioxide (7,869 kg/ha-yr) because it had the greatest production of hay (Table 24). Large stacks of hay stored under cover goes through a heating process during the first few weeks of storage. Heating occurs due to the respiration of microbial organisms in the hay. Through respiration, carbohydrates in the plant tissue and oxygen are converted to carbon dioxide, water, and heat (Rotz et al., 2011a). This farm also had the lowest carbon loss through runoff (0.3 kg/ha-yr) because of the permanent vegetative cover.

The annual pasture-based farm had biogenic carbon dioxide emissions in the housing facility similar to the seasonal pasture farm (Table 26). Even though the annual pasture did not have housing facilities, biogenic carbon dioxide emissions were produced in the milking parlor by animal respiration and manure on the floor. This farm had less assimilation in feed than the seasonal farm because it did not produce corn. Also, biogenic carbon dioxide released by the grazing animals increased (Table 26) compared to the confinement farm because the animals consumed higher forage diets.

Methane emissions on the annual pasture-based farm were similar to the confinement farm. Even though the annual pasture only had a milking parlor as cow housing, similar methane emissions due to enteric fermentation (19,497 kg/yr) were produced because grazing cows consume more forage. Also, this farm did not have methane emissions from manure storage because this farm stacked the manure and applied to land daily.

4.3.4.2.2. Ammonia emissions

The annual pasture-based farm had more than twice the ammonia emissions (21,234 kg/yr) as the confinement farm (Table 28). Housing facilities emissions increased (15,150 kg/yr) because there were more animals in annual pasture (160-cows) compared to the confinement (100-cows), therefore more manure and urine was produced in this farm (Table 28, Figure 13). The manure on the milking center floors produced more ammonia than the urine deposited on pasture (3,774 kg/ha-yr). Ammonia emission due to field application was lower in the annual pasture-based dairy (2,309 kg/yr) because less manure was collected and consequently less was applied on the field (2,599 t DM/yr).

4.3.4.2.3. Nitrous oxide emissions

The annual pasture-based and seasonal pasture farm had similar nitrous oxide emissions from farmland (Table 29, Figure 14) because manure remained for longer periods in the grazing areas and the annual pasture farm did not have manure storage.

4.3.4.2.4. Hydrogen sulfide emissions

The annual pasture did not have hydrogen sulfide emissions in manure storage or field application because the manure was applied daily (Table 30, Figure 15). Without long term manure storage under anaerobic conditions only small amounts of sulfide could be formed. The manure in the milking parlor produced 39 kg/yr of hydrogen sulfide.

4.3.4.3 Environmental footprints

4.3.4.3.1. Water footprint

The annual pasture-based farm had the second greatest water footprint (716 kg/kg FPCM-yr) due to purchased feed and inputs (335,579 t/yr) because 41% of the animal feed consumed was purchased and required more animal and milking supplies, because it had more cows. Water use for drinking, animal cooling and parlor and equipment cleaning was higher for the annual pasture-based farm because it had the greatest number of cows (Table 31).

4.3.4.3.2. Energy footprint

The transition from confinement to an annual pasture-based farm reduced the energy footprint by 11%. This decrease was because of a reduction of 47% in feed production, 27% in animal feeding and 9% in manure handling (Table 32). There was also a decrease of 4% in energy not allocated to milk production which was allocated to the cattle weight produced and sold as beef. Additionally, the annual pasture farm had a 69% decrease in energy for animal housing and ventilation compared to the confinement farm because cattle were on pasture or open lots throughout the year.

The annual pasture had a greater energy use footprint for production of resources inputs (2,033,489 MJ/yr) because it purchased 41% of the feed for the animals. The 27% reduction in animal feeding and 47% reduction for feed production on the annual pasture-based farm compared to the confinement farm was because of the shift of crop land to grazing land and, consequently, the addition of grazed forage in the diet of the cattle.

The seasonal and annual pasture dairies required less energy for manure handling because manure was only collected from the milking parlor and from the barn (for the seasonal pasture). The annual pasture-based dairy has higher energy required for manure handling (68,338 MJ/yr) compared to the seasonal pasture (67,626 MJ/yr) because it hauls manure daily, increasing machinery use and fuel (Table 32).

4.3.4.3.3. Reactive nitrogen loss footprint

The annual pasture-based dairy had a 10% lower reactive nitrogen loss footprint than the seasonal farm because ammonia and nitrous oxide emissions, nitrate leaching, fuel combustion and footprint not allocated to milk production were lower (Table 33). Ammonia decreased because this farm did not have a housing facility where manure could produce emissions. Nitrous oxide emissions were less than the seasonal pasture farm because the annual pasture-based farm did not have manure storage. Fuel combustion emission and nitrate leaching were lower than the seasonal farm because the farm only had land for grazing and no crop production. The footprint not allocated to milk production decreased because it was allocated to the cattle weight gain produced and sold as beef. The footprint from the production of resource inputs increased because the annual pasture-based farm purchased 8% more or feed than the seasonal farm (Table 33).

4.3.4.3.4. Carbon footprint

The annual pasture-based farm had a carbon footprint similar to the confinement farm (Table 34). Animal, feed production and production of resource inputs emissions were similar to the seasonal pasture. However, the annual pasture-based farm had the lowest manure carbon footprint (108,683 kg/yr) because there was no manure storage or housing facilities and the primary source of emissions of carbon dioxide were from the decomposition of organic matter in manure deposited by animals in the floor of the milking parlor.

CHAPTER 5: CONCLUSIONS

Five representative dairy production systems were compared to evaluate resource use and conservation, economic and environmental impacts in the transition from total confinement to seasonal-and annual-pasture based systems. The available land base on four farms was held constant at 111 ha, which was the area needed to support 100 large Holstein cows plus replacements with small annual shortage or excess of feed, and a near-balance of phosphorous and potassium from manure cycling on the farm. The land base of a seasonal pasture system was expanded to 809 ha to provide additional land for cash crop production and land application of imported manure used to operate an anaerobic digester. Anaerobic digestion was evaluated on the confinement and seasonal pasture dairies.

1. Based on a whole-farm nutrient balance, the 111 ha land base supported 100 large-frame (726 kg) Holsteins cows on the total confinement farm, 142 medium-frame (590 kg) cows on the seasonal pasture dairy, and 160 small-frame (454 kg) New Zealand type cows with replacements on the annual pasture dairy.
2. The annual pasture-based system had the greatest net return to management and unpaid factors followed by the seasonal pasture and confinement systems. Compared to the total confinement system, net income on the annual pasture increased 20% and 17% on the seasonal pasture.
3. The addition of an anaerobic digester on the 100-cow total confinement dairy decreased the net return to management and unpaid factors by 15%.
4. When anaerobic digestion was added to the seasonal pasture with an increased land base for cash crop production and an imported manure volume equivalent to a 500-cow dairy, the net

return to management and unpaid factors increased 388% compared to the seasonal dairy alone. Facility and structure costs increased 108%, manure handling and related labor costs increased 302%, but bedding costs decreased 67% and energy costs decreased 34%. Net purchased feed and bedding costs decreased 761% mainly because of the sale of cash crops; therefore AD on the seasonal farm was primarily paid for from the sales of cash crops.

5. Nitrogen, phosphorous and potassium were imported primarily through purchased feed and a small amount (28 kg/ha) of commercial N applied to corn at planting. The primary source of N was fixation by alfalfa and other legumes in the grass/ legume pasture. Nutrient exports were from milk, meat and feed sales, nutrients lost to the environment by volatilization, leaching, and runoff. The corn/alfalfa rotation on the confinement dairy led to an annual depletion of soil P (2.2 kg/ha-yr) and K (7.1 kg/ha-yr). The seasonal pasture cropping system led to a build-up of P (9 kg/ha-yr) and k (41.9 kg/ha-yr) while the annual pasture led to a P build-up of 11.2 kg/ha-yr and K build-up of 14.6 kg/ha/yr.
6. The addition of an anaerobic digester on the confinement farm increased K depletion in the cropping system (from 7.1 to 17.8 kg/ha-yr) because a portion of the chopped straw bedding was separated and recycled, thereby reducing the amount of K imported in the purchased bedding.
7. There was 68% more N available on the annual pasture dairy and 61% more N available on the seasonal pasture dairy than was available on the confinement farm. Of the N imported to the confinement dairy (195 kg/ha-yr), 39% was lost by volatilization, 6% by leaching and 4% by denitrification. Of the N imported to the seasonal dairy (326 kg/ha-yr) 51% was lost to volatilization, 16% to leaching and 12% to denitrification. The annual pasture imported 342 kg/ha-yr and lost 46% to volatilization, 6% to leaching and 4% to denitrification.

8. There was little difference in nitrogen, phosphorus, potassium and carbon loss to the environment from anaerobic digestion.
9. On the seasonal pasture, compared to confinement, emissions of ammonia increased 117%, nitrous oxide 92%, methane 20% and biogenic carbon dioxide 16%. Emissions of hydrogen sulfide decreased 19% and combustion CO_2 decreased 16%.
10. On the annual pasture, compared to confinement, ammonia emissions increased 105% and nitrous oxide 30%. Hydrogen sulfide decreased 88%, combustion CO_2 decreased 32%, methane decreased 6% and biogenic carbon dioxide decreased 5%.
11. On the seasonal pasture, compared to confinement, the water use footprint increased 5% and in the annual pasture increased 19% because of an increase in purchased feed and an increase in number of cows.
12. On the seasonal pasture, compared to confinement, the energy footprint decreased 14% and decreased 9% in the annual pasture due to a reduction in on-farm feed production, animal feeding and manure handling related to the shift from corn production to grazing land.
13. On the seasonal pasture, compared to confinement, carbon footprint increased 9% because animal and feed production emissions increased due to an increase in number of animals and forage intake. The annual pasture dairy had a 2% decrease in carbon footprint because of a decrease in manure emissions and fuel combustion.
14. On the seasonal pasture, compared to confinement, the reactive nitrogen footprint increased 108% and the annual pasture reactive nitrogen footprint increased 86% because of an increase in production of resource inputs and ammonia emission. In addition, the seasonal pasture had a higher nitrogen footprint because of an increase of 325% on nitrate leaching.

15. When the land base on the seasonal pasture was increased with manure imported to maintain the digester the water footprint increased 44%, reactive nitrogen footprint increased 63%, the energy footprint 11% and the carbon footprint 192% compared to the seasonal dairy alone.

CHAPTER 6: SUGGESTIONS FOR FUTURE RESEARCH

- Since one of the limitations was to integrate an anaerobic digester into a small-scale farm with imported manure, is important to validate the procedure performed for this study using IFSM model by comparing results with actual farm records.
- Pasture-based dairy farms are gaining popularity, because of the economic benefits. There is a need to collect more information related to confinement-winter/pasture-summer and pasture-based systems, which could be representative information for performing similar researches.
- Currently small and medium scale dairy farms are the most common type of dairy (74% has less than 100 cows) in the United States and, anaerobic digestion and methane recovery is gaining importance because of the environmental and economic benefits. There is a need for further research to make this technology more available and cost effective for small-scale dairy farms.

APPENDICES

APPENDIX A: DATA COLLECTED FROM FARM VISITS ON CONVENTIONAL CONFINEMENT DAIRIES

Table A. 1. Land information collected from confinement farm

	Unit	**Farm**	**Other sources**
Total land	ac	420	-
Owned land	ac	88	452 (TelFarm, 2011)
Rented land	ac	332	280 (TelFarm, 2007)
Total crop area	ac	420	736 (TelFarm, 2011)
Alfalfa area	ac	160	-
Grass area	ac	0	-
Corn area	ac	230	-
Small grain area	ac	30	-
Soybeans area	ac	0	-
Grazing area	ac	0	-

Table A. 2. Crop information collected from confinement farm

	Unit	**Farm**	**Other sources**
Alfalfa			
Stand life for alfalfa	years	4	-
Manure applied to alfalfa	%	0	7 (MSU Extension, 2004)
Corn			
Plant population of corn	plant/ac	-	25,000-30,000 (IFSM Default)
Relative maturity index of corn	days	101	-
Manure applied to corn	%	70	3 (MSU Extension, 2004)
Irrigation for crops or grazing area	in	0	-

Table A. 3. Animal information collected from confinement farm

	Unit	**Farm**	**Other sources**
Animal type	-	-	Small Holstein
Mature cow body weight	lb	-	1369 (IFSM)
Animal average milk fat content	%	-	3.5 (IFSM)
Animal fiber intake capacity	-	-	1 (IFSM)
Target milk production	lb/cow/ year	29,200	10,000-22,000 (IFSM)
Herd			
First Lactation animals	%	-	25-40% (IFSM)
Calving strategy	-	-	-
Lactating cows	-	131	-
Young stock over one year	-	136	-
Young stock under one year	-	50	-
Labor for milking and animal handling	min/cow/day	-	-

Table A. 4. Livestock expenses information collected from confinement farm

	Unit	**Farm**	**Other sources**
Veterinary and medicine	$/cow	100	118 (TelFarm,2011)
Semen and breeding	$/cow	15	54 (TelFarm,2011)
Animal and milking supplies	$/cow	-	166 (TelFarm,2011)
Insurance of animals	$/cow	11	78 (TelFarm,2011)
Animal hauling	$/cow	0	10 (TelFarm,2011)
DHIA, registration, etc	$/cow	-	40 (TelFarm,2011)

Table A. 5. Animal feeding information collected from confinement farm

	Unit	**Farm**	**Other sources**
Feeding method			
Grain	-	Loader and mixer wagon	-
Silage	-	Loader and mixer wagon	-
Hay	-	Self-fed in hay feeder	-
Ration Constituents			
Minimum dry hay in cow ration	% of forage	0	33 (USDA, 2000)
Phosphorus feeding level	% of NRC recommendation	-	-
Protein feeding level	% of NRC recommendation	-	-
Relative forage to grain ratio	-	High	-
Crude protein supplement	-	Soybean meal 48%	-
Undegradable protein	-	Distillers Grain	-
Energy supplement	-	Dry Corn	-

Table A. 6. Animal facilities information collected from confinement farm

	Unit	Farm
Milking center[a]		
Type	-	Double 5 parlor
Structure cost	$	136,000
Equipment cost	$	-
Cow housing[a]		
Type	-	Free Stall Barn, naturally ventilated
Structure cost	$	200,000
Heifer housing[a]		
Type	-	Bedded pack barn
Structure cost	$	50,000
Feed facility[a]		
Type	-	Commodity shed
Structure cost	$	-

[a] No information collected from other sources

Table A. 7. Manure information collected from confinement farm

	Unit	Farm	Other sources
Manure Characteristics			
Type	% DM	12-14	-
Collection and Use			
Collection method	-	Scraper with bucket loading	-
Incorporation by tillage	-	Delayed	-
Average hauling distance	mile	1.5	-
Field application method	-	Broadcast spreading	-
Manure Storage			
Type	-	Top-loaded earthen basin	Top-loaded concrete tank (MI Gov., 2012)
Storage period	months	-	-
Capacity	ton	4150	-
Storage initial cost	$	-	-
Bedding			
Type of bedding	-	Saw dust	-
Amount of bedding	lb/cow/day	4	-
Import/Export of manure			
Import	-	no	-
Export	-	no	-

Table A. 8. Storage structures information collected from confinement farm

	Unit	Farm
Storage 1[a]		
Type of storage	-	Sealed silo
Type of forage or grain stored		High quality forage (Haylage)
Quantity	-	1
Capacity	ton DM	525
Initial cost	$	-
Storage 2[a]		
Type of storage	-	Sealed silo
Type of forage or grain stored	-	High moisture grain
Quantity	-	1
Capacity	ton DM	22,000
Initial cost	$	-
Storage 3[a]		
Type of storage	-	Bunker silo
Type of forage or grain stored	-	Grain crop silage
Quantity	-	1
Capacity	ton DM	1900
Initial cost	$	-
Storage 4[a]		
Type of storage	-	Pressed bag
Type of forage or grain stored	-	High quality forage (Haylage)
Quantity	-	1
Capacity	ton DM	12,700
Initial cost	$	-

[a]No information collected from other sources

APPENDIX B: DATA COLLECTED FROM FARM VISITS ON SEASONAL PASTURE AND PASTURE-BASED DAIRIES

Table B. 1. Land information collected from seasonal pasture and pasture-based farms

	Unit	Farm 1	Farm 2	Farm 3	Farm 4	Other sources
Total land	ac	315	226	205	879	-
Owned land	ac	245	120	140	844	379 (TelFarm, 2007)
Rented land	ac	70	106	65	35	237 (TelFarm, 2007)
Total crop area	ac	210	0	0	377	525 (TelFarm, 2007)
Alfalfa area	ac	120	66	60	131	-
Grass area	ac	55	160	65	175	42 (TelFarm, 2007)
Corn area	ac	50	0	0	245	-
Small grain area	ac	0	0	0	132	-
Soybeans area	ac	0	0	0	0	-
Grazing area	ac	55	226	128	206	-

Table B. 2. Crop information collected from seasonal pasture and pasture-based farms

	Unit	Farm 1	Farm 2	Farm 3	Farm 4	Other sources
Alfalfa						
Stand life for alfalfa	years	3	5	5	5	-
Manure applied to alfalfa	%	10	0	0	34	7 (MSU Extension, 2004)
Grass						
Stand life for grass	years	-	10	12	10	-
Initial Sward dry matter of grass	lb/ac	-	-	-	1447	418 (IFSM Default)
Initial Sward composition of grass	%	70% CS and 30% L	67% CS and 33% L	70% CS and 30% L	60% CS and 40% L	-
Manure applied to grass	%	0	100	100	0	-
Corn						
Plant population of corn	plant/ac	30,000	-	-	25,000	25,000-30,000 (IFSM Default)
Relative maturity index of corn	days	95	-	-	103	-
Manure applied to corn	%	90	-	-	10	3 (MSU Extension, 2004)

[a] CS= Cool-season grass; L=Legume

Table B. 3. Animal information collected from seasonal pasture and pasture-based farms

	Unit	Farm 1	Farm 2	Farm 3	Farm 4	Other sources
Animal Characteristics						
Animal type		Small Holstein	Small Holstein	New Zealand Friesian	Small Holstein	Small Holstein
Mature cow body weight	lb	1000	-	1000	1300	1369 (IFSM)
Animal average milk fat content	%	-	-	-	3.5	3.5 (IFSM)
Animal fiber intake capacity	-	-	-	-	0.8	1 (IFSM)
Target milk production	lb/cow/ year	15,000	18,000	15,000	24,000	10,000-22,000 (IFSM)
Herd						
First Lactation animals	%	-	-	-	-	25-40% (IFSM)
Calving strategy	-	-	-	-	year round	-
Lactating cows	-	100	90	100	120	-
Young stock over one year	-	40	-	30	35	-
Young stock under one year	-	60	35	60	35	-
Labor for milking and animal handling	min/ cow/ day	2.4	3.3	0.5	1	-

Table B. 4.Livestock expenses information collected from seasonal pasture and pasture-based farms

	Unit	Farm 1	Farm 2	Farm 3	Farm 4	Other sources
Veterinary and medicine	$/cow	5	40	16	137	118 (TelFarm,2011)
Semen and breeding	$/cow	20	no	16	40	54 (TelFarm,2011)
Animal and milking supplies	$/cow	-	130	-	130	166 (TelFarm,2011)
Insurance of animals	$/cow	no	-	-	0	78 (TelFarm,2011)
Animal hauling	$/cow	10	17	-	10	10 (TelFarm,2011)
DHIA, registration, etc.	$/cow	-	-	-	77	40 (TelFarm,2011)

Table B. 5. Animal feeding information collected from seasonal pasture and pasture-based farms

	Unit	Farm 1	Farm 2	Farm 3	Farm 4	Other sources
Feeding method						
Grain	-	Loader and mixer wagon	Individual computer feeder	Individual computer feeder	Loader and mixer wagon	-
Silage	-	No	No	No	Loader and mixer wagon	-
Hay	-	Hand fed	Self-fed in hay feeder	Self-fed in hay feeder	Self-fed in hay feeder	-
Ration Constituents						
Minimum dry hay in cow ration	% of forage	80	-	-	0	33 (USDA, 2000)
Phosphorus feeding level	% of NRC recom.	-	-	-	107	-
Protein feeding level	% of NRC recom.	-	-	-	109	-
Relative forage to grain ratio	-	High	High	-	High	-
Crude protein supplement	-	No	No	Soybean meal 48%	Soybean meal 44%	-
Undegradable protein	-	Roasted soybean	Distillers grain	-	Distillers grain	-
Energy supplement	-	Grain	Grain	Grain	Grain	-

Table B.6. Animal facilities information collected from seasonal pasture and pasture-based farms

	Unit	Farm 1	Farm 2	Farm 3	Farm 4
Milking center[a]					
Type	-	Double 12 parlor	Pipeline system	Automatic Robotic System, multi stall	Automatic Robotic System, multi stall
Structure cost	$	60,000	57,000	150,000	600,000
Equipment cost	$	30,000	42,000	310,000	400,000
Cow housing[a]					
Type	-	Free stall barn, naturally ventilated	Bedded pack barn	Bedded pack barn	Free stall barn, naturally ventilated
Structure cost	$	45,000	-	-	1,000,000
Heifer housing[a]					
Type	-	Free stall barn, naturally ventilated	Bedded pack barn	Calf hutches and dry lot	Free stall barn, naturally ventilated
Structure cost	$	-	-	35,000	300,000
Feed facility[a]					
Type	-	Short term storage of premix	Short term storage of premix	Short term storage of premix	Short term storage of premix
Structure cost	$	200	-	-	200,000

[a] No information collected from other sources

Table B. 7. Manure information collected from seasonal pasture and pasture-based farms

	Unit	Farm 1	Farm 2	Farm 3	Farm 4	Other sources
Manure Characteristics						
Type	% DM	12-14	12-14	12-14	12-14	-
Dry matter content	%	-	-	-	-	10 (ASABE, 2013a)
Nitrogen content	% DM	-	-	-	-	3.8 (ASABE, 2013a)
Organic nitrogen content	% total N	-	-	-	-	70 (ASABE, 2013a)

Table B.7 (cont'd)

Phosphorus content	% DM	-	-	-	-	0.8 (ASABE, 2013a)
Potassium content	% DM	-	-	-	-	2.4 (ASABE, 2013a)
Collection and Use						
Collection method	-	Scraper with bucket loading	Scraper with ramp loading	Scraper with slurry pump	Scraper with bucket loading	-
Incorporation by tillage	-	No	No	No	No	-
Average hauling distance	mile	2	1	1	9	-
Field application method	-	Broadcast spreading	Broadcast spreading	Broadcast spreading	Broadcast spreading	-
Manure Storage						
Type	-	Top-loaded concrete tank	Top-loaded concrete tank	Bottom-loaded tank or basin	Top-loaded concrete tank	Top-loaded concrete tank (MI Gov., 2012)
Storage period	months	None	1	3	6	-
Capacity	ton	124	357	309	3000	-
Storage initial cost	$	4000	15000	-	103000	-
Bedding						
Type of bedding	-	Sand	Straw	Saw dust	Chopped straw	-
Amount of bedding	lb/cow/day	3	18	0.60	3	-
Import/Export of manure						
Import	-	No	No	No	No	-
Export	-	No	No	No	25%	-

Table B. 8. Storage structures information collected from seasonal pasture and pasture-based

	Unit	Farm 1	Farm 2	Farm 3	Farm 4
Storage 1[a]					
Type of storage	-	Sealed silo	Sealed silo	Stave silo	Sealed silo
Type of forage or grain stored		High quality forage (Dry corn)	Grain for milk cows	High moisture grain	Grain crop silage (Dry grain)
Quantity	-	4	2	1	1
Capacity	ton DM	432	12	203	76
Initial cost	$	7,000	1,100	42,000	-
Storage 2[a]					
Type of storage	-	-	Bale	-	Pressed bag
Type of forage or grain stored	-		hay	-	Low and high quality forage
Capacity	ton DM	-	0.3/bale	-	70
Initial cost	$	-	40/bale	-	20
Annual cost	$/ ton DM	-	500	-	-
Storage 3[a]					
Type of storage	-	-	Sealed silo	-	Bunker silo
Type of forage or grain stored	-		Grain for calves	-	Grain crop silage (corn and alfalfa)
Quantity	-		1	-	1 for corn silage and 3 for alfalfa
Capacity	ton DM	-	8	-	270
Initial cost	$	-	100	-	55,625
Initial cost	$/ton DM	-	12.5	-	206
Storage 4[a]					
Type of storage	-	-	-	-	Inside a shed
Type of forage or grain stored	-	-	-	-	Dry hay
Quantity	-	-	-	-	1
Capacity	ton DM	-	-	-	300
Initial cost	$	-	-	-	50,000
Initial cost	$/ton DM	-	-	-	167

[a]No information collected from other sources

Table B. 9. Economic information collected from seasonal pasture and pasture-based farms

	Unit	Farm 1	Farm 2	Farm 3	Farm 4	Other sources
General rates						
Diesel fuel	$/gal	-	-	-	-	3.68(U.S Energy, 2013)
Electricity	$/KWh	-	-	-	-	0.13 (MI Public Service, 2012)
Grain drying	$/pt/ ton DM	-	-	-	-	1.6 (MSU custom machine, 2013)
Labor wage	$/h	-	-	-	30	11.3 (MI AEWR, 2013)
Land rental	$/acre	-	-	-	70	50.98 (TelFarm, 2011)
Property tax	%	-	-	-	0	2.5 (IFSM default)
Fertilizer prices						
N	$/lb	-	-	-	0.61	0.53 (Purdue Extension, 2011)
P	$/lb	-	-	-	1.68	0.56 (Purdue Ext.,2011)
K	$/lb	-	-	-	0.59	0.47 (Purdue Ext.,2011)
Lime	$/ton					0.01 (Purdue Ext.,2011)
Annual seed and chemicals						
New forage stand	$/acre	200	200	200	133	84 (Iowa State University, 2012)
Established forage stand	$/acre	0	0	0	7	-
Corn land	$/acre	200	-	-	100	223 (NASS,2010)
Oats land	$/acre	-	-	-	-	-
Soybean land	$/acre	-	-	-	58	104.39 (NASS,2010)
Additional for corn following corn rotation	$/acre	-	-	-	5	
Buying prices						
Soybean meal 44%	$/ ton DM	-	-	-	184	365 (MSU, 2013)
Distillers grain	$/ ton DM	-	-	-	-	150 (IFSM, 2012)
Corn grain	$/ ton DM	-	-	376	-	145(USDA, 2013)
Hay	$/ ton DM	-	500	320	-	180 (USDA, 2013)
Fat	$/ ton	-	-	200	184	-
Minerals / vitamins	$/ ton	-	2,345	200	184	-

Table B.9 (cont'd)

Bedding material	$/ ton	6	0	170	100	-
Custom operations		No	No	No	No	-

Table B. 10. Grazing information collected from seasonal pasture and pasture-based farms

	Unit	Farm 1	Farm 2	Farm 3	Farm 4	Other sources
Grazing area	ac	55	226	128	206	1 ac/cow* (NRCS)
Grazing management costs						
Investment in perimeter fence	$	10,000	12,600	1,600	14,500	$29/ac* (Iowa State U, 2012)
Investment in temporary fence	$	2,000	1,400	-	8,000	$17/ac* (Iowa State U, 2012)
Investment in watering system	$	no	2,500	1,770	15,000	$25/ac* (NRCS)
Added annual cost of seed and chemical	$/ac	54.5	82	135	10	-
Grazing strategy						
Labor for grazing management	h/ week	10	10	10	6	-
Types of animals grazed	-	all	all	all	all	-
Time on pasture	h	22	22	22	22	-

* The cost of perimeter fence is $0.89 /ft and temporary fence is $0.2/ft(Iowa State Extension, 2012). To convert the cost per feet to cost per acre it was assumed each paddock area is 3 ac (from where is obtained the perimeter of all paddocks). Total number of paddocks were calculated based equations 1,2 and 3 and data from Table B.11.

*Watering system were calculated with equations 4, 5 and 6, and based on data from Table B.12.

$$\text{Days of stay in paddock} = \frac{\begin{matrix}\text{Height of}\\ \text{cool season}\\ \text{grass to start}\\ \text{grazing}\end{matrix} * \begin{matrix}\text{Estimated dry}\\ \text{matter yield}\\ \text{of cool season}\\ \text{grass mix}\end{matrix} * \begin{matrix}\text{Paddock}\\ \text{acres}\end{matrix} * \begin{matrix}\text{Grazing efficiency}\\ \text{for paddock}\\ \text{system}\end{matrix}}{\begin{matrix}\text{Animal}\\ \text{weight}\end{matrix} * \begin{matrix}\text{Daily forage}\\ \text{dry matter intake}\\ \text{for lactating}\\ \text{dairy cow}\end{matrix} * \begin{matrix}\text{Number of animals}\\ \text{per paddock}\end{matrix}} \tag{1}$$

$$\text{Number of paddocks} = \frac{\text{Rest period for cool season grass}}{\text{Days of stay in paddock}} + 1 \tag{2}$$

Paddocks acres* Number of paddocks (3)

Table B. 11. Data for calculations for fence investments

Data for calculations for fence investments

	Recommended by NRCS (Purdue Extension AY-328)	**Data used**
Forage species of cool season grass	70% of Orchadgrass, Tall fescue, perennial ryegrass	-
Forage species for legume	30 % of white clover	-
A: Height of cool season grass to start grazing (in)	6-8	7
Height of legume to start grazing (in)	6-10	7
Rest period for cool season grass (days)	30-45	30
Rest period for legume (days)	24-32	30
Estimated dry matter yield of cool season grass mix (lb/ac/in)	200-300	250
Daily forage dry matter intake for lactating dairy cow (%)	3-4	3
Grazing efficiency for 8 paddock system (%)	60%	60
Paddock acres	-	3
Animal weight	-	1000
Number of animals per paddock	-	25

$$\text{Big pipe and small tank cost} = \begin{array}{c}\text{Distance to}\\ \text{water source}\end{array}\ \text{ft} * \text{Pipe cost} + 10\%\ \text{fittings} + \begin{array}{c}\text{Small}\\ \text{tank cost}\end{array} \quad (4)$$

$$\text{Small pipe and large tank cost} = \begin{array}{c}\text{Distance to}\\ \text{water source}\end{array}\ \text{ft} * \text{Pipe cost} + 10\%\ \text{fittings} + \begin{array}{c}\text{Large}\\ \text{tank cost}\end{array} \quad (5)$$

$$\text{Watering system cost} = \begin{array}{c}\text{Big pipe and}\\ \text{small tank cost}\end{array} * \text{Pipe cost} + 10\%\ \text{fittings} + \begin{array}{c}\text{Large}\\ \text{tank cost}\end{array} \quad (6)$$

Table B. 12. Data for calculations for investment in watering system

Investment in Watering system (NRCS, MSU Extension)		
	Recommended by NRCS	**Data used**
System	Intensive Grazed Pastures	Intensive Grazed Pastures
Animals	Dairy cow	175
Distance to water on paddock (ft)	600-900	700
Distance to water source (ft)	-	1200
Gallons of water for Dairy (gallons/cow/day)	15-25	25
Daily water consumption (gallons/day)	-	4375
Tank refill (h)	-	8
Tank refill rate (gallons/min)	Maximum 10	9.1
Pipe size	-	first 40% of distance with 1-1/4in and last 60% of distance with 1in pipe
Pipe price	Price obtained from commercial store	1-1/4 in = $1.18/ft 1 in = $0.87/ft
Small tank price (305 gallons)	Price obtained from commercial store	$2,80
Large tank price (5000 gallons)	Price obtained from commercial store	$2,670

APPENDIX C: DATA SELECTED FOR THE FIVE REPRESENTATIVE DAIRY PRODUCTION SYSTEMS

Table C. 1. Representative farms

Scenario	Characteristics
F1	Confinement
F2	Confinement with AD
F3	Seasonal 140 cows
F4	Seasonal pasture with imported manure, cash crop and AD
F5	Annual pasture-based
F6	Confinement 500 cows

Table C. 2. Land information selected for farms F1, F2, F3, F4, F5, F6

	Unit	F1	F2	F3	F4	F5	F6
Total land	ac	275	275	275	2000	275	1270
Owned land	ac	175	175	175	175	175	175
Rented land	ac	100	100	100	1825	100	1095
Total crop area	ac	275	275	275	1875	0	1270
Alfalfa area	ac	90	90	25	25	100	450
Grass area	ac	0	0	125	125	175	0
Corn area	ac	185	185	125	925	0	820
Soybeans area	ac	0	0	0	925	0	0

Table C. 3. Crop information for farms F1, F2, F3, F4, F5, F6

	Unit	**F1**	**F2**	**F3, F4**	**F5**	**F6**
Alfalfa						
Stand life	year	4	4	4	4	4
Yield adjustment factor	%	100	100	100	100	100
N application rate	lb/ac	0	0	0	0	0
P application rate	lb/ac	0	0	0	0	0
K application rate	lb/ac	0	0	0	0	0
Manure applied[a]	%	0	0	0	20	0
Corn						
Plant population	plant/ac	28,000	28,000	28,000	-	28,000
Relative maturity index	days	100	100	100	-	100
Yield adjustment factor	%	100	100	100	-	100
N application rate, pre-planting	lb/ac	0	0	0	-	0
N application rate, post-planting	lb/ac	25	25	25	-	25
P application rate	lb/ac	0	0	0	-	0
K application rate	lb/ac	0	0	0	-	0
Manure applied	%	100	100	100	-	100
Grass						
Stand life	years	-	-	10	10	-
Initial Sward dry matter	lb/ac	-	-	418	418	-
Initial Sward composition of	%	-	-	70% CS and 30% L[b]	70% CS and 30% L[b]	-
Yield adjustment factor	%	-	-	110	110	-
N application rate	lb/ac	-	-	0	0	-
P application rate	lb/ac	-	-	0	0	-
K application rate	lb/ac	-	-	0	0	0
Manure applied[a]	%	-	-	0	80	0

[a] The amount of manure applied is the percentage of the amount of manure collected on the milking center

[b]CS =Cool-Season grass; L=Legume

Table C. 4. Grazing information for farms F3, F4 and F5

	Unit	**F3, F4**	**F5**
Grazing area			
Spring	ac	75	100
Summer	ac	125	175
Fall	ac	100	150
Grazing management costs			
Investment in perimeter fence	$	3,625	5,075
Investment in temporary fence	$	2,125	2,975
Investment in watering system	$	3,125	4,375
Added annual cost of seed and chemical	$/ac	30	30
Grazing strategy			
Labor for grazing management	h/week	10	10
Grazed forage yield adjustment factor	%	120	120
Types of animals grazed	-	All cows	All cows
Time on pasture	h	Full days during grazing season	Full days during grazing season

Table C. 5. Animal information for farms F1, F2, F3, F4, F5, F6

	Unit	**F1**	**F2**	**F3, F4**	**F5**	**F6**
Animal Characteristics						
Animal type	-	Large Hols[a]	Large Hols	Medium Hols	Small Hols	Large Hols
Mature cow body weight	lb	1600	1600	1300	1000	1600
Animal average milk fat content	%	3.5	3.5	3.8	4.2	3.5
Animal fiber intake capacity	-	1	1	1	1	1
Target milk production	lb/cow/ year	24,000	24,000	20,000	16,000	24,000
Herd						
First Lactation animals	%	35	35	25	30	35
Calving strategy	-	Year round	Year round	Year round	Year round	Year round
Lactating cows	-	100	100	142	160	500
Young stock over one year	-	38	38	54	61	190
Young stock under one year	-	42	42	60	67	210
Labor for milking and handling	min/cow/day	5.25	5.25	3.0	3.0	5.25
Livestock Expenses						
Veterinary and medicine	$/cow	118	118	85	101	118
Semen and breeding	$/cow	54	54	39	46	54
Animal and milking supplies	$/cow	166	166	107	143	166
Insurance of animals	$/cow	78	78	78	78	78
Animal hauling	$/cow	10	10	10	10	10
DHIA, registration	$/cow	40	40	40	40	40

[a] Hols = Holstein

Table C. 6. Animal feeding information for farms F1, F2, F3, F4, F5, F6

	Unit	F1, F2, F3, F4	F5, F6
Feeding method			
Grain	-	Loader and mixer wagon	Loader and mixer wagon
Silage	-	Loader and mixer wagon	Loader and mixer wagon
Hay	-	Bale grinder	Bale grinder
Ration Constituents			
Minimum dry hay in cow ration	% forage	5	0
P feeding level	% NRC recom.	100	100
Protein feeding level	% NRC recom.	100	100
Relative forage: grain	-	High	High
Crude protein supplement	-	Soybean meal 48%	Soybean meal 48%
Undegradable protein	-	Distiller Grain	Distiller Grain
Energy supplement	-	Grain	Grain

Table C. 7. Animal facilities information for farms F1, F2, F3, F4, F5, F6

	Unit	F1, F2	F3, F4	F5	F6
Milking center					
Type	-	Double 6 parlor	Double 6 parlor	Double 6 parlor	Double 12 parlor
Structure cost	$	182,000	182,000	137,000	274,000
Equipment cost	$	233,600	233,600	175,000	350,000
Cow housing					
Type	-	Free Stall Barn, naturally ventilated	Free Stall Barn, naturally ventilated	None	Free Stall Barn, naturally ventilated
Structure cost	$	140,000	196,000	-	700,000
Heifer housing					
Type	-	Calf hutches and dry lot	Calf hutches and dry lot	Calf hutches and dry lot	Calf hutches and dry lot
Structure cost	$	26,700	37,450	42,650	133,500
Feed facility					
Type	-	Short term storage premix	Short term storage premix	Short term storage premix	Short term storage premix
Structure cost	$	4,500	6,300	7,200	22,500

Table C. 8. Manure information for farms F1, F2, F3, F4, F5, F6

	Unit	F1	F2	F3, F4	F5	F6
Manure Characteristics						
Type	% DM	12-14	12-14	12-14	12-14	12-14
Dry matter content	%	10	10	10	10	10
Nitrogen content	% DM	3.8	3.8	3.8	3.8	3.8
Organic nitrogen content	% total N	70	70	70	70	70
Phosphorus content	% DM	0.8	0.8	0.8	0.8	0.8
Potassium content	% DM	2.4	2.4	2.4	2.4	2.4
Collection and Use						
Collection method	-	Scraper with slurry pump	Scraper with slurry pump	Scraper with slurry pump	Scraper with bucket loading	Scraper with slurry pump
Incorporation by tillage	-	Within 2 days	Within 2 days	Within 2 days	No	Within 2 days
Average hauling distance	mile	0.5	0.5	0.75	0.5	1.0
Manure Storage						
Type	-	Top-loaded lined earthen basin	Top-loaded lined earthen basin	Top-loaded lined earthen basin	Slab with buckwall	Top-loaded lined earthen basin
Storage period	months	6	6	6	0	6
Capacity	ton	1,882	1,882	1,699	0	9,227
Storage initial cost	$	45,224	45,224	44,322	0	81,223
Bedding						
Type of bedding	-	Chop Straw	Chop Straw	Chop Straw	None	Chop Straw
Amount of bedding	lb/cow/day	3	1	1[a]	0	3
Import/Export of manure						
Import	ton	0	0	14,200	0	0
Export	ton	0	0	0	0	0

[a]Farm F3 has an amount of bedding of 3 lb/cow/day

Table C. 9. Storage structure information for farms F1, F2, F3, F4, F5, F6

	Unit	F1	F2	F3, F4	F5	F6
Storage 1						
Type of storage	-	Bunker silo	Bunker silo	Bunker silo	Bale	Bunker silo
Type of forage or grain stored	-	High quality forage	High quality forage	High quality forage	High quality forage	High quality forage
Capacity	ton DM	423	423	202	423	2028
Initial cost	$	56,982	56,982	32,567	56,982	198,470
Annual cost	$/ ton DM	2.0	2.0	2.0	2.0	2.0
Storage 2						
Type of storage	-	Bunker silo	Bunker silo	Bunker silo	-	Bunker silo
Type of forage or grain stored	-	Grain crop silage	Grain crop silage	Grain crop silage	-	Grain crop silage
Capacity	ton DM	476	476	476	-	2,168
Initial cost	$	61,637	61,637	61,637	-	204,508
Annual cost	$/ ton DM	2.0	2.0	2.0	-	2.0
Storage 3						
Type of storage	-	Stave silo	Stave silo	-	-	Sealed silo
Type of forage or grain stored	-	High moisture grain	High moisture grain	-	-	High moisture grain
Capacity	ton DM	191	191	-	-	979
Initial cost	$	38,910	38,910	-	-	90,547
Storage 4						
Type of storage	-	Inside a shed	Inside a shed	Inside a shed	Inside a shed	Inside a shed
Type of forage or grain stored	-	Dry hay	Dry hay	Dry hay	Dry hay	Dry hay
Capacity	ton DM	120	120	120	120	200
Initial cost	$	25,960	25,960	25,960	25,960	50,000
Annual grain storage	$/ ton DM	12	12	12	12	12

Table C. 10. Machine information for farms F1, F2, F3 and F4

	F1,F2			F3, F4		
Operation	**Number**	**Machine type/size**	**Tractor size**	**Number**	**Machine type/size**	**Tractor size**
Harvest/ Feeding						
Mowing	1	Mower conditioner 14 ft	134 hp	1	Mower conditioner 9 ft	87 hp
Raking	1	Tandem rake 18 ft	47 hp	1	Single rake 9 ft	47 hp
Baling	1	Small round baler	108 hp	1	Medium round baler	108 hp
Bale wrapping	0	0	0	1	Large round bale wrapper	87 hp
Forage chopping	1	Medium forage harvester	134 hp	1	Medium forage harvester	134 hp
Grain harvesting	1	Medium corn combine 8 row	none	2[a]	Medium corn combine 8 row	none
Feed mixing	1	Large mixer 13 ton	87 hp	1	Large mixer 13 ton	87 hp
Silo filling	1	Forage blower/ bunker packing	108 hp	1	Forage blower/ bunker packing	108 hp
Tillage / Planting						
Manure handling	1	Medium slurry tank spreader	134 hp	1	Medium slurry tank spreader	134 hp
Plowing	1	Coulter-chisel plow 12 ft	134 hp	1	Coulter-chisel plow 12 ft	134 hp
Field cultivation	1	Seedbed conditioner 19 ft	134 hp	1	Seedbed conditioner 19 ft	134 hp
Row crop planting	1	Corn planter 8 row	108 hp	1	Corn planter 8 row	108 hp
Drill seeding	1	Grain drill 12 ft	47 hp	1	Grain drill 12 ft	47 hp
Spraying	1	Sprayer 50 ft	87 hp	1	Sprayer 50 ft	87 hp

[a]Farm F3 uses 1 medium corn combine of 8 row.

Table C. 11. Machine information for farms F5 and F6

	F5			F6		
Operation	**Number**	**Machine type/size**	**Tractor size**	**Number**	**Machine type/size**	**Tractor size**
Harvest/ Feeding						
Mowing	1	Disc mower conditioner 10ft	108 hp	2	SP[a] mower conditioner 16ft	none
Raking	1	Tandem rake 18 ft	87 hp	1	0	0
Baling	1	Medium round baler	108 hp	2	Windrow merger 32ft	134hp
Bale wrapping	1	Large round bale wrapper	87 hp	1	Medium round baler	108 hp
Forage chopping	0	0	0	1	Large SP forage harvester	none
Grain harvesting	0	0	0	1	Medium corn combine 8 row	none
Feed mixing	1	Large mixer 13 ton	87 hp	2	Large mixer 13 ton	108hp
Silo filling				2	Forage blower/ bunker packing	220hp
Tillage / Planting						
Manure handling	1	Small V- tank spreader	108 hp	2	Large slurry tank spreader	220 hp
Plowing	1	Coulter-chisel plow 12 ft	134 hp	1	Coulter-chisel plow 20ft	220hp
Field cultivation	1	Seedbed conditioner 15ft	87hp	1	Seedbed conditioner 19 ft	134 hp
Row crop planting	0	0	0	1	Corn planter 8 row	108 hp
Drill seeding	1	Grain drill 8ft	47 hp	1	Grain drill 16ft	108hp
Spraying	0	0	0	1	Sprayer 50 ft	108hp

[a]SP = self-propelled

Table C. 12. Miscellaneous information for farms F1, F2, F3 and F4

	F1,F2			**F3, F4**		
Operation	**Number**	**Machine type/size**	**Miles transport**	**Number**	**Machine type/size**	**Miles transport**
Transport tractors	3	47 hp	-	3	47 hp	-
Feed/ Manure loader	1	Medium skid-steer loader	-	1	Medium skid-steer loader	-
Round bale loader	1	87 hp	-	1	87 hp	-
Manure pump/ agitator	-	108 hp	-	-	108 hp	-
Auxiliary manure pump	-	No	-	-	No	-
Initial machine shed cost	-	$25,000		-	$25,000	
Custom operations	-	Grain Harvest	-	-	Grain Harvest / Grain crop planting	-
Transport of feed						
Hay	1	Round bale wagons	0.5	1	Round bale wagons	0.5
Hay crop silage	2	Dump wagons	0.5	2	Round bale wagons and wrappers	0.5
Grain crop silage	2	Dump wagons	0.5	2	Dump wagons	0.5[a]
Grain	3	Grain wagons	0.5	3	Grain wagons	0.5[a]

[a]Farm F3 uses 0.75 miles of hauling distance for grain crop silage and grain

Table C. 13. Miscellaneous information for farms F5 and F6

	F5			F6		
Operation	**Number**	**Machine type/size**	**Miles transport**	**Number**	**Machine type/size**	**Miles transport**
Transport tractors	2	47 hp	-	5	67 hp	-
Feed/ Manure loader	1	Small skid-steer loader	-	2	Large skid-steer loader	-
Round bale loader	1	108hp	-	1	67 hp	-
Manure pump/ agitator	-	No	-	-	134hp	-
Auxiliary manure pump	-	No	-	-	No	-
Initial machine shed cost	-	$20,000		-	$50,000	
Custom operations	-	Forage crop tillage/planting	-	-	Grain Harvest	-
Transport of feed						
Hay	1	Round bale wagons	0.5	2	Round bale wagons	0.5
Hay crop silage	2	Round bale wagons and wrappers	0.5	6	Dump wagons	1.0
Grain crop silage	2	Dump wagons	0.5	6	Dump wagons	1.0
Grain	2	Grain wagons	0.5	3	Grain wagons	1.0

Table C. 14. Tillage and planting information for farms F1, F2, F3, F4, F5, F6

	Operation	Start date
Alfalfa		
Operation 1	Moldboard /Chisel plow	15-Oct
Operation 2	Field cultivator/ conditioner	10-Apr
Operation 3	Field cultivator/ conditioner	10-Apr
Operation 4	Alfalfa seeding	15-Apr
Corn		
Operation 1	Moldboard /Chisel plow	10-Sept
Operation 2	Field cultivator/ conditioner	10-Apr
Operation 3	Field cultivator/ conditioner	25-Apr
Operation 4	Corn planting	01-May
Operation 5	Sprayer	10- May
Grass		
Operation 1	No operation	-
Operation 2	Field cultivator/ conditioner	15-Apr
Operation 3	Field cultivator/ conditioner	20-Apr
Operation 4	Grass seeding	20-Apr
Soybean		
Operation 1	Field cultivator/ conditioner	10- Apr
Operation 2	Field cultivator/ conditioner	25- Apr
Operation 3	Soybean planting	01- May
Operation 4	Sprayer	10- May

Max simultaneous operations: 2
Time available for tillage and planting: 8h/day

Table C. 15. Corn harvest information for farms F1, F2, F3, F4, F5, F6

Starting date	
Corn Silage	1-Sep
High moisture corn	1-Oct
Dried corn	21-Oct
Harvest detail	
Maximum silage moisture content	68%
Corn silage cutting high	6 in
Corn silage processing	Rolled with greater chop length
High moisture corn type	Grain w/ little or no cob and husk

Table C. 16. Alfalfa harvest information for farms F1 and F2

	Harvest 1	**Harvest 2**	**Harvest 3**	**Harvest 4**
Drying Treatment	Mechanical conditioning, wide swath	Mechanical conditioning, wide swath	Mechanical conditioning, narrow swath	Mechanical conditioning, narrow swath
Tedding treatment	No	No	No	No
Raking treatment	Before harvest	Before harvest	Before harvest	Before harvest
Harvest type	Wilted silage harvest by chopping	Hay harvest by baling	Wilted silage harvest by chopping	Wilted silage harvest by chopping
Chemical conditioning application rate (g/ac)	0	0	0	0
Maximum moisture content at harvest (%)	68	20	68	68
Critical NDF for high quality storage (%)	42	42	42	42
Schedule for Alfalfa	4 cuttings- Bud first 2 cuttings, early flower last 2			

Table C. 17. Alfalfa and grass harvest information for farms F3 and F4, F5

	Alfalfa				Grass
	Harvest 1	**Harvest 2**	**Harvest 3**	**Harvest 4**	**Harvest 1**
Drying Treatment	Mechanical conditioning, wide swath	Mechanical conditioning, wide swath	Mechanical conditioning, narrow swath	Mechanical conditioning, narrow swath	Mechanical conditioning, wide swath
Tedding treatment	No	No	No	No	No
Raking treatment	Before harvest	Before harvest	Before harvest	Before harvest	Before harvest
Harvest type	Round bailing for silage	Hay harvest by baling	Round bailing for silage	Round bailing for silage	Round bailing for silage
Chemical conditioning application rate (g/ac)	0	0	0	0	0
Maximum moisture content at harvest (%)	60	20	60	60	60
Critical NDF for high quality storage (%)	42	42	42	42	42
Schedule for Alfalfa	4 cuttings- Bud first 2 cuttings, early flower last 2				1 cutting- early head

Table C. 18. Alfalfa harvest information for farm F6

	Harvest 1	**Harvest 2**	**Harvest 3**	**Harvest 4**
Drying Treatment	Mechanical conditioning, wide swath	Mechanical conditioning, wide swath	Mechanical conditioning, narrow swath	Mechanical conditioning, narrow swath
Tedding treatment	No	No	No	No
Raking treatment	Before harvest	Before harvest	Before harvest	Before harvest
Harvest type	Wilted silage harvest by chopping	Wilted silage harvest by chopping	Wilted silage harvest by chopping	Wilted silage harvest by chopping
Chemical conditioning application rate (g/ac)	0	0	0	0
Maximum moisture content at harvest (%)	68	65	68	68
Critical NDF for high quality storage (%)	42	42	42	42
Schedule for Alfalfa	4 cuttings- Bud first 2 cuttings, early flower last 2			

Table C. 19. Hauling costs for imported manure in seasonal pasture system (F4)

Pumping and trucking from farm to AD	
Custom work	
Labor hours (h)	301
Custom cost ($/h)	90
Total custom cost ($)	27,090
Hauling from AD to field	
Tractor 100 kW	
List price ($)	108,000
Purchase price ($)	97,000
Labor hours per tractor (h)	148
Machinery rate ($/h)	25.36
Fuel and lubrication rate ($/h)	26.83
Total tractor cost ($)	15,448
Spreader	
List price ($)	44,000
Purchase price ($)	39,600
Machinery rate ($/h)	43.26
Labor hours per spreader (h)	148
Total spreader cost ($)	12,805
Labor	
Hours	296
Labor rate ($/h)	16.13
Total labor cost ($)	4,775
Total cost ($)	33,028

APPENDIX D: RESULTS FROM IFSM OF THE FIVE REPRESENTATIVE DAIRY PRODUCTION SYSTEMS

Table D. 1. Development of seasonal pasture farm with 142 medium-frame Holsteins, cash crop, imported manure and AD

	Unit	Confine [a]	Confine AD [a]	Confine AD-Confine	Seasonal [b]	Seasonal AD [b]	Seasonal AD-Seasonal	Seasonal CC/ Import [c]	Seasonal CC/Import/ AD[d]
		Mean	Mean	%	Mean	Mean	%	Mean	Mean
Nutrients available, used, and lost to the environment									
Nitrogen lost by leaching	lb/ac	12.3	10.9	-11%	45.8	41.7	-9%	11.6	**10.3**
Nitrogen lost by denitrification	lb/ac	8.7	7.3	-16%	36.2	32.9	-9%	7.2	**6.0**
Potassium loss through runoff	lb/ac	5.7	5.2	-9%	8.6	8.2	-5%	2.9	**2.6**
Soil potassium depletion	lb/ac	3	13.1	337%	0	0	0%	0	**0.0**
Crop removal over that available on farm	%	90	99	10%	76	80	5%	76	**80.0**
Annual manure production and handling cost									
Manure handled	ton	17193	16897	-2%	3187	3150	-1%	3179	**16897**
Manure applied to corn land	ton	17193	16897	-2%	3187	3150	-1%	3179	**16897**
Machinery cost	$	52790	48297	-9%	18763	16315	-13%	29854	**25361**
Fuel and electric cost	$	10777	9458	-12%	1771	1543	-13%	8154	**6835**
Storage cost	$	7081	99463	1305%	3864	19961	417%	3864	**96246**
Labor cost	$	21004	32078	53%	4115	20162	390%	4775	**15849**
Annual crop production and feeding costs and the net return over those costs									
Equipment cost	$	340664	336864	-1%	95937	95225	-1%	94772.6	**92017**
Facilities cost	$	243555	335916	38%	84918	101014	19%	85031	**177392**
Energy cost	$	121078	39560	-67%	20196	7340	-64%	41613	**13292**
Land rental cost	$	57707	57707	0%	5270	5270	0%	96178	**96178**
Return to	$	705603	714655	1%	86442	73227	-15%	472633	**420348**

Table D.1 (cont’d)

management and unpaid factors									
Annual emissions									
Ammonia									
Housing facility	lb	48889	47934	-2%	14921	14959	0.3%	14950	**14988**
Manure storage	lb	22343	23935	7%	10020	11119	11%	10228	**11350**
Methane									
Manure storage	lb	122905	91039	-26%	15573	15724	1%	15530	**15681**
Biogenic Carbon Dioxide									
Manure storage	lb	463194	2629466	468%	59301	469126	691%	59156	**467979**
Combustion Carbon Dioxide	lb	474590	414113	-13%	65780	52019	-21%	56737	**44868**
Environmental footprints									
Water Use									
Production of purchased feed and inputs	ton	684185	490677	-28%	359740	321983	-10%	362208	**362208**
Not allocated to milk production	ton	-644537	-615283	-5%	-176419	-172232	-2%	-226226	**-220857**
Water footprint with rainfall	lb/lb FPCM	568	538	-5%	630	603	-4%	946	**905**
Water footprint without rainfall	lb/lb FPCM	95	65	-32%	195	169	-13%	197	**171**
Reactive Nitrogen Loss									
Ammonia emission	lb	96413	99351	3%	40650	42884	5%	60511	**63836**
Nitrate leaching	lb	15641	13869	-11%	12591	11462	-9%	23291	**21203**
Nitrous oxide emission	lb	3459	3327	-4%	1310	1280	-2%	2442	**2386**
Fuel combustion	lb	1522	1330	-13%	207	164	-21%	812	**710**

Table D.1 (cont'd)

emissions									
Reactive nitrogen footprint	lb/cwt FPCM	0.92	0.92	0%	1.85	1.88	2%	2.93	**3.0**
Energy Use									
Manure handling	MBtu	389961	342256	-12%	64096	55845	-13%	291200	**244107**
Production of resource inputs	MBtu	8591305	5410426	-37%	2046323	1545287	-24%	3098770	**2355065**
Not allocated to milk production	MBtu	-2127975	-1585832	-25%	-505640	-442520	-12%	-616518	**-542536**
Energy footprint	MBtu/lb FPCM	0.94	0.66	-30%	0.82	0.62	-24%	1.17	**0.89**
Greenhouse Gas Emissions (CO$_{2e}$)									
Manure emissions	lb	4372728	3539654	-19%	795756	796061	0.04%	844711	**845035**
Emission during feed production	lb	403339	375736	-7%	213438	203133	-5%	153939	**146507**
Net biogenic carbon dioxide emission	lb	-4031126	-3942799	-2%	-930755	-931179	0.05%	3226541	**3228011**
Fuel combustion emissions	lb	474590	414113	-13%	65780	52019	-21%	56737	**44868**
Production of resource inputs	lb	2170564	1442038	-34%	579850	463668	-20%	740470	**592105**
Not allocated to milk production	lb	-2134571	-1884921	-12%	-538999	-524117	-3%	-555418	**-540083**
Carbon footprint without biogenic CO$_2$	lb/lb FPCM	0.97	0.84	-13%	1.04	0.99	-5%	1.09	**1.0**
Carbon footprint with biogenic CO$_2$	lb/lb FPCM	0.66	0.53	-20%	0.72	0.68	-6%	2.18	**2.1**

[a] Confinement farm with 500 large-frame Holsteins, [b] Seasonal pasture farm with 140 medium-frame Holsteins, [c] Seasonal pasture farm with 140 medium-frame Holsteins, with cash crop and imported manure, [d]Target farm: Seasonal pasture farm with 140 medium-frame Holsteins, with cash crop, imported manure and AD.

Table D. 2. Average postharvest yield for crops of F1, F2, F3, F4, F5

	Unit	**F1**	**F2**	**F3**	**F4**	**F5**
Alfalfa yield	ton DM/ac	5.26	5.26	5.19	5.18	5.2
Corn silage yield	ton DM/ac	5.69	5.64	5.77	6.15	0
HM Corn yield	ton DM/ac	2.73	2.72	0	0	0
Dry Corn yield	ton DM/ac	2.88	2.86	2.67	2.76	0
Grass yield	ton DM/ac	-	-	1.69	1.84	1.71
Soybean yield	ton DM/ac	-	-	-	1.02	0

Table D. 3. Annual feed production and utilization of F1, F2, F3, F4, F5 (Average)

	Unit	**F1**	**F2**	**F3**	**F4**	**F5**
High-quality hay production	ton DM	51	51	18	17	62
Low-quality hay production	ton DM	31	31	5	5	27
High-quality silage production	ton DM	257	257	106	111	377
Grain crop silage production	ton DM	412	412	409	413	0
High moisture grain production	ton DM	166	166	0	0	0
Dry grain production	ton DM	90	87	110	3185	0
Cash crop grain sold	ton DM	0	0	0	939	0
Grazed foraged consumed	ton DM	0	0	320	337	310
Forage sold	ton DM	45	48	11	48	45
Forage purchased	ton DM	0	0	0	0	0
Grain sold	ton DM	20	17	41	2248	0
Grain purchased	ton DM	0	0	0	0	126
Soybean meal 48% purchased	ton DM	18	19	277	281	225
Distillers grain purchased	ton DM	133	135	155	163	150
Mineral and vitamin mix purchased	ton DM	8	8	7	7	6
Milk production	lb/cow	23731	23745	19276	19268	14594
Fat and protein corrected milk production	lb/cow	21908	21921	18683	18676	15042

Table D. 4. Nutrients available, use and lost to the environment of F1, F2, F3, F4, F5 (Average)

	Unit	**F1**	**F2**	**F3**	**F4**	**F5**
Nitrogen imported to farm	lb/ac	174	174	291	189	305.2
Nitrogen exported from farm	lb/ac	74.4	74.6	70.5	110	67.5
Nitrogen available on farm	lb/ac	266	262	427.1	209	446.4
Nitrogen lost by volatilization	lb/ac	68.1	69.9	147.8	31.1	139.9
Nitrogen lost by leaching	lb/ac	10.8	9.9	45.8	10.3	17.3
Nitrogen lost by denitrification	lb/ac	7.2	6.4	36.2	6.0	10.9
Average nitrogen concentration in leachate	ppm	8.8	8.1	37.7	8.1	12.2
N crop removal over that available	%	60	61	46	60	46
Phosphorous imported to farm	lb/ac	10.5	10.3	20.4	14.2	20
Phosphorous exported from farm	lb/ac	12.2	12.2	12.2	14.2	9.9
Phosphorous available on farm	lb/ac	17.2	17.2	27.8	15	26.4
Phosphorous loss in runoff and leachate	lb/ac	0.3	0.3	0.2	0.5	0
Soil phosphorous build up	lb/ac	0	0	8	0	10
Soil phosphorous depletion	lb/ac	2.0	2.2	0	0.24	0
P crop removal over that available	%	115	117	76	105	64
Potassium imported to farm	lb/ac	23.1	13.5	64.6	36.6	46.2
Potassium exported from farm	lb/ac	24.6	24.6	18.5	28.1	24.5
Potassium available on farm	lb/ac	96.5	86.8	172.4	52.8	174.2
Potassium loss through runoff	lb/ac	4.8	4.3	8.6	2.6	8.7
Soil potassium build up	lb/ac	0	0	37.4	9.1	13
Soil potassium depletion	lb/ac	6.3	15.9	0	0	0
K crop removal over that available	%	101	112	76	80	83
Carbon imported to farm	lb/ac	6711	6557	5953	9388	7984
Carbon exported from farm	lb/ac	998	995	929	1478	789
Carbon loss as carbon dioxide	lb/ac	5525	5391	4800	7902	7019
Carbon loss as methane	lb/ac	186	169	223	28.1	175
Carbon loss through runoff	lb/ac	1.2	1.2	1.2	1.4	0.3

Table D. 5. Annual manure production, nutrient availability and handling cost of F1, F2, F3, F4, F5 (Average)

	Unit	**F1**	**F2**	**F3**	**F4**	**F5**
Manure handled	ton	3478	3419	3187	16897	2865
Manure applied to alfalfa land	ton	0	0	0	0	573
Manure applied to grass land	ton	0	0	0	0	2292
Manure applied to corn land	ton	3478	3419	3187	16897	0
Manure nitrogen over crop requirement	%	51	48	109	58	101
Manure phosphorous over crop requirement	%	89	88	136	99	163
Manure potassium over crop requirement	%	101	90	135	127	125
Machinery cost	$	16468	14097	18762	25360	8562
Fuel and electric cost	$	1947	1677	1771	6836	1790
Storage cost	$	3943	24062	3864	96246	0
Labor cost	$	4561	20473	4114	15848	5617
Bedding cost	$	8306	2768	8084	2695	0
Total manure handling cost	$	35226	63078	36596	146984	15969
Total cost per mature animal	$/cow	352	631	258	1035	100

Table D. 6. Annual crop production, feeding costs and net return over those costs of F1, F2, F3, F4, F5 (Average)

	Unit	**F1**	**F2**	**F3**	**F4**	**F5**
Equipment cost	$	85551	87070	80469	164334	45092
Fuel and electric cost	$	9709	9697	6998	17583	6108
Feed and machinery facilities cost	$	21983	21993	15865	15978	10866
Labor cost	$	17867	17839	18379	28084	18702
Seed, fertilizer and chemical cost	$	51111	51112	38949	340373	17128
Grain drying and roasting cost	$	559	522	654	13049	0
Land rental	$	5270	5270	5270	96178	5270
Purchased feed cost	$	38609	39015	130124	129987	128774
Income from feed sales	$	25125	24369	17234	931877	7901
Net feed cost	$	205534	208148	279474	-128050	224037
Net cost per unit of milk	$/cwt	8.66	8.77	10.21	-	9.59
Net cost as portion of milk income	%	45.6	46.1	53.8	-	50.5
Income from milk sales	$	450900	451160	520062	-	443650
Net return over feed costs	$	245366	243011	240588	-	219613
Net return per cow	$/cow	2454	2430	1694	-	1373

Table D. 7. Annual production costs and net return to management of F1, F2, F3, F4, F5 (Average)

	Unit	**F1**	**F2**	**F3**	**F4**	**F5**
Equipment cost	$	98926	98090	95937	92017	51273
Facilities cost	$	84452	104581	85262	177623	57599
Energy cost	$	21871	5348	20196	13293	15998
Labor cost	$	73943	89828	64294	81912	71418
Custom operation cost	$	3093	3078	3295	97677	2380
Seed, fertilizer and chemical cost	$	51111	51112	38949	340373	17128
Land rental cost	$	5270	5270	5270	96178	5270
Net purchased feed and bedding cost	$	21791	17414	120973	-799143	120873
Animal purchase and livestock expense	$	46600	46600	50978	50978	66880
Milk hauling and marketing fees	$	23730	23744	27370	27359	23348
Property tax	$	5173	5173	5214	5214	3727
Income from milk sales	$	450900	451160	520062	519862	443650
Income from animal sales	$	61655	61655	83810	83810	80407
Return to management and unpaid factors	$	73594	62578	86133	420192	88162

Table D. 8.Crop production costs and feed costs of F1, F2, F3, F4, F5 (Average)

	Unit	**F1**	**F2**	**F3**	**F4**	**F5**
Crop Production costs						
Hay	$/ton DM	176	178	289	283	126
Hay crop silage	$/ton DM	172	173	252	237	135
Grain crop silage	$/ton DM	159	160	189	160	0
High-moisture grain	$/ton DM	202	203	0	0	0
Dry grain	$/ton DM	165	166	204	178	0
Grazed forage	$/ton DM	0	0	62.2	59	87
Feed costs						
Hay	$/ton DM	253	269	339	327	208
Hay crop silage	$/ton DM	208	209	283	261	173
Grain crop silage	$/ton DM	192	193	223	189	0
High-moisture grain	$/ton DM	215	216	0	0	0
Dry grain	$/ton DM	166	167	200	187	158
Grazed forage	$/ton DM	0	0	80	76	106

Table D. 9. Annual emissions of important gaseous compounds of F1, F2, F3, F4, F5 (Average)

	Unit	**F1**	**F2**	**F3**	**F4**	**F5**
Ammonia						
Housing facility	lb	9493	9288	14918	14986	33370
Manure storage	lb	4784	5100	10019	11351	0
Field application	lb	8499	9001	15752	42083	5087
Grazing	lb	0	0	8729	8822	8313
Total farm	lb	22776	23389	49419	77242	46771
Hydrogen Sulfide						
Housing facility	lb	77	75	65	64	87
Manure storage	lb	139	135	110	108	0
Field application	lb	502	481	406	2124	0
Grazing	lb	0	0	1	1	1
Total farm	lb	717	690	582	2297	88
Methane						
Housing facility	lb	43369	43307	44306	44577	42945
Manure storage	lb	24833	18415	15572	15679	0
Field application	lb	83	88	157	448	87
Grazing	lb	0	0	21885	22075	21229
Total farm	lb	68285	61810	81920	82779	64261
Nitrous Oxide						
Housing facility	lb	450	437	747	825	716
Manure storage	lb	324	314	535	592	0
Farmland	lb	296	278	776	2244	671
Total farm	lb	1070	1030	2058	3661	1387
Biogenic Carbon Dioxide						
Housing facility	lb	1510026	1509904	1223542	1220864	1110190
Manure storage	lb	93567	531874	59298	467938	0
Assimilated in feed	lb	-2409483	-2830159	-2752647	1618090	-2355195
Grazing animal	lb	0	0	538938	538066	480428
Net emission	lb	-805891	-788382	-930869	3844958	-764576
Combustion Carbon Dioxide	lb	78598	66542	65779	44870	53068

Table D. 10. Table of environmental footprints of water, nitrogen, energy and carbon for F1, F2, F3, F4, F5 (Average)

	Unit	**F1**	**F2**	**F3**	**F4**	**F5**
Water Use						
Feed production, rainfall	ton	645706	645876	645670	1111121	644806
Drinking	ton	3098	3098	4622	4613	4384
Animal cooling	ton	252	252	357	357	403
Parlor and equipment cleaning	ton	1006	1006	1428	1428	1609
Production of purchased feed and inputs	ton	141444	102164	359683	362089	369910
Not allocated to milk production	ton	-134981	-129020	-176406	-220842	-159448
Water footprint with rainfall	lb/lb FPCM*	600	569	630	905	716
Water footprint without rainfall	lb/lb FPCM	99	68	195	170	244
Reactive Nitrogen Loss						
Ammonia emission	lb	18730	19235	40641	63836	38463
Nitrate leaching	lb	2961	2732	12588	21201	4771
Nitrous oxide emission	lb	681	656	1310	2386	883
Fuel combustion emissions	lb	260	220	207	710	168
Production of resource inputs	lb	945	776	2320	2140	2503
Not allocated to milk production	lb	-4024	-4028	-8133	-11703	-6713
Reactive nitrogen footprint	lb/cwt FPCM	0.89	0.89	1.85	3	1.67
Energy Use						
Feed production	MBtu	204712	204588	133990	181040	109217
Animal feeding	MBtu	144480	144035	115955	114529	105202
Manure handling	MBtu	70449	60700	64088	244129	64762
Milking and milk cooling	MBtu	220185	147002	253959	170087	216645
Animal housing ventilation and lighting	MBtu	54782	54782	53622	53622	17147
Production of resource inputs	MBtu	1806638	1184093	2046170	2354809	1927342
Not allocated to milk production	MBtu	-427475	-320825	-505605	-542463	-412267
Energy footprint	MBtu/lb FPCM	0.95	0.67	0.82	0.91	0.84

Table D.1 (cont’d)

Greenhouse Gas Emissions (CO_{2e})						
Animal emissions	lb	1061739	1061285	1634396	1646297	1580343
Manure emissions	lb	875962	708044	795678	844959	239604
Emission during feed production	lb	78141	73297	213429	146502	182560
Net biogenic carbon dioxide emission	lb	-805891	-788382	-930868	3227514	-764578
Fuel combustion emissions	lb	78598	66542	65779	44870	53068
Production of resource inputs	lb	455884	313506	579791	592051	613756
Not allocated to milk production	lb	-427506	-377880	-538952	-540033	-421879
Carbon footprint without biogenic CO_2	lb/lb FPCM	0.97	0.84	1.04	1	0.93
Carbon footprint with biogenic CO_2	lb/lb FPCM	0.66	0.54	0.72	2.1	0.65

*FPCM is fat and protein corrected milk (4.0% fat and 3.3% protein)

REFERENCES

REFERENCES

Acock, B., and Trent, A. (1991). *The soybean crop simulator, GLYCIM: documentation for the modular version 91*. Moscow, Idaho: Department of Plant, Soil and Entomological Sciences, University of Idaho.

ADIAC. (2009). Anaerobic Digestion Initiative Advisory Committee of BC. Retrieved from Environmental Impacts: http://www.bcfarmbiogas.ca/ad_info/environmental_impacts

Allan, D., Katovich, E., and Nelson, C. (2003). Fertilizer Value and Weed Seed Destruction Potential of Digested Manure. *Anaerobic Digester Technology Applications in Animal Agric ulture: A National Summit.* Raleigh, North : Water Environment Federation.

Archer, D. (1985). *Uncoupling of Methanogenic from Growth of Mecthanosarica barkeri by Phosphate Limitation.* Norwich: Applied and Environmental Microbiology: American Society for Microbiology.

Arora, S. M. (2011). *Poultry Manure: The New Frontier for Anaerobic Digestion.* S3N Consulting, LLC.

ASABE. (2013a). *American Society of Agricultural Engineers.* Retrieved from Manure production and characteristics: http://evo31.ae.iastate.edu/ifafs/doc/pdf/ASAE_D384.2.pdf

ASABE. (2013b). *American Society of Agricultural Engineers.* Retrieved from Agricultural Machinery Management: http://www3.abe.iastate.edu/ast330/Project/AESE496.3.pdf

ASABE. (2013c). *American Society of Agricultural Engineers.* Retrieved from Agricultural Machinery Management Data: http://www3.abe.iastate.edu/ae340/2006/ASAE_D497.4.pdf

ASABE. (2008). *American Society of Agricultural Engineers.* Retrieved from Manure production and characteristics: http://cnmp.unl.edu/D384.2.pdf

Belflower, J. B., Bernard, J. K., Gattie, D. K., Hancock, D. W., Risse, L. M., and Rotz, C. A. (2012). A case study of the potential environmental impacts of different dairy production systems in Georgia. *Agricultural Systems*, 108: 84-93.

Benbrook, C., Carman, C., Clark, E. A., Daley, C., Fulwider, W., Hansen, M., et al. (2010). *A Dairy Farm's Footprint: Evaluating the impacts of conventional and organic farming systems.* The organic center.

Betts, C., and Ling, C. (2009). *Cooperative Approaches for Implementation of Dairy Manure Digesters.* Washington: USDA: Rural Development.

Binkley, D. F. (2010). *The economics of anaerobic digestion under different electricity purchase agreements.* East Lansing: Michigan State University.

Biogas Energy Inc. (2008). *Biogas Energy Inc.* Retrieved September 2012, from Key Elements of Biogas Energy Anaerobic Digesters: http://www.biogas-energy.com/site/BiogasEnergy.pdf

Bishop, C. P., and Schumway, C. R. (2009). The Economics of Dairy Anaerobic Digestion with Coproduct Marketing. *Review of Agricultural Economics*, 31: 394- 410.

Burke, D. (2001). *Washington: Environmental Energy Company.* Retrieved from Dairy Waste Anaerobic Digestion Handbook: http://makingenergy.com/newsite/publications/Dairy%20Waste%20Handbook%20doc.pdf

Center for Climate and Energy Solutions. (2011, June). *Center for Climate and Energy Solutions.* Retrieved June 2013, from Anaerobic Digesters: http://www.c2es.org/docUploads/AnaerobicDigesters.pdf

Chen, Y., and Hashimoto, A. (1978). Kinetics of methane fermentation. *Biotech and Bioeng*, 8:269.

Chen, Y., Yang, G. H., Sweeney, S., and Feng, Y. Z. (2010). Household biogas use in rural China: A study of opportunities and constraints. *Renewable and Sustainable Energy Reviews*, 14: 545- 549.

Chianese , D. S., Rotz , C. A., & Richard, T. L. (2009c). Simulation of methane emissions from dairy farms to asses greenhouse gas reduction strategies. *ASABE*, 52(4), 1313-1323.

Chianese, D. S., Rotz, C. A., & Richard, T. L. (2009b). Simulation of nitrous oxide emissions from dairy farms to assess greenhouse gas reduction strategies. *ASABE*, 52(4), 1325-1335.

Chianese, D. S., Rotz, C. A., & Richard, T. L. (2009a). Simulation of carbon dioxide emissions from dairy farms to assess greenhouse gas reduction strategies. *ASABE*, 52 (4), 1301-1312.

Chynoweth, D., and Isaacson, R. (1987). Anaerobic Digestion of Biomass. *Elsevier Applied Science*, 248-250.

Colorado State University. (undated). *Colorado State University*. Retrieved from Anaerobic Digestion at Colorado Cattle Operations: http://www.engr.colostate.edu/~jlabadie/Decision%20Tree/intro.cfm

Department of Natural Resources and Environment. (2009, January 3). Retrieved from Organic residuals exemption on farm (Anaerobic Digestion): http://www.michigan.gov/documents/deq/DEQ-WHMD-On-Farm-Anaerobic-Digestion_266497_7.pdf

Dupchak, K. (2001). *Potassium in dairy cow diets*. Retrieved October 28, 2013, from Monitoba Agriculture, Food and Rural Initiatives: http://www.gov.mb.ca/agriculture/livestock/nutrition/bza15s00.html

Edwards, W. (2007, September). *Department of Economics, Iowa State University*. Retrieved July 3, 2013, from FARMSIM explanation : http://www2.econ.iastate.edu/classes/econ330/edwards/farmsim/Farmsim_explantion.pdf

El-Mashad, H., and Zhang, R. (2007). Co-Disgetion of food waste and dairy manure for biogas production . *ASABE*, Vol. 50(5): 1815-1821.

EPA. (2012a). *Environmental Protection Agency*. Retrieved June 5, 2013, from Dairy Production: http://www.epa.gov/agriculture/ag101/printdairy.html#back

EPA. (2004, February). *U.S Environmental Protection Agency*. Retrieved from A Manual for Developing Biogas Systems at Commercial Farms in the United States: http://nepis.epa.gov/Exe/ZyNET.exe/

EPA. (2005, January Ireland). *Environmental Protection Agency*. Retrieved from Anaerobic Digestion: Benefits for Waste Management, Agriculture, Energy, and the Environment: http://www.epa.ie/downloads/consultation/epa_discussion_paper_anaerobic_digestion.pdf

EPA. (2010). *EPA.* Retrieved June 10, 2013, from Introduction to the Livestock Analysis Model: http://www.epa.gov/ruminant.html/library/lam/manual.pdf

EPA. (2011, June 2). *United States Environmental Protection Agency*. Retrieved June 30, 2013, from Animal Waste: What's the problem?: http://www.epa.gov/region9/animalwaste/problem.html

EPA. (2012b). *Food Scrap Recycling: A Primer for Understanding Large-Scale Food Scrap Recycling Technologies for Urban Areas.* EPA.

EPA. (2013, May). *U.S. Environmental Protection Agency.* Retrieved from Operational Anaerobic Digester Projects at U.S. Dairy Farms: http://www.epa.gov/agstar/projects/

EPA-AgStar. (2004). *A Manual For Developing Biogas Systems at Commercial Farms in the United States.* Florida: U.S Environmental Protection agency.

EPA-AgSTAR. (2007). *AgSTAR Energy and Pollution Prevention.* Retrieved July 20, 2012, from Anaerobic Digesters Continue Growth in U.S. Livestock Market: 11/2007b. http://www.epa.gov/agstar/pdf/2007_digester_update.pdf

EPA-AgSTAR. (2010a, October). *U.S Environmental Protection Agency.* Retrieved from U.S Anaerobic Digester Status Report: http://www.epa.gov/agstar/documents/digester_status_report2010.pdf

EPA-AgSTAR. (2010b, May). *U.S Environmental Protection Agency.* Retrieved from Anaerobic Digestion Capital Costs for Dairy Farms: http://www.epa.gov/agstar/documents/digester_cost_fs.pdf

EPA-AgSTAR. (2011a). *Protocol for Quantifying and Reporting the Performance of Anaerobic Digestion Systems for Livestock Manures* . Massachusetts: EPA.

EPA-AgSTAR. (2011b). *AgSTAR.* Retrieved from U.S Anaerobic digester status: A 2011 snapshot: http://www.epa.gov/agstar/documents/2011_digester_update.pdf

EPA-AgSTAR. (2012b, September 27). *AgSTAR.* Retrieved June 7, 2013, from Permitting Practices for Co-digestion Anaerobic Digester Systems: http://www.epa.gov/agstar/tools/permitting.html

FAO. (2010). *Greenhouse Gas Emissions from the Dairy Sector. A Life Cycle Assessment.* Food and Agriculture Organization of the United Nations.

Gerardi, M. (2003). *The Microbiology of Anaerobics Digesters.* New York: Wiley InterScience.

Ghafoori, E., and Flynn, P. C. (2007). Optimizing the size of anaerobic digesters. *ASABE*, 50: 1029- 1036.

Goodrich, P. (2005). *The Minnesota Project.* Retrieved June 2013, from Anaerobic Digester Systems for Mid- Sized Dairy Farms: http://www.mnproject.org/pdf/agstar%20report%20full%20update.pdf

Gourley, C. J., Aarons, S. R., and Powell, J. M. (2011). Nitrogen use efficiency and manure management practices in contrasting dairy production systems. *Agriculture, Ecosystems and Environment*, 147:73-81.

Hadrich, J. C., and Wolf, C. A. (2010). Citizen complaints and environmental regulation of Michigan livestock operations. *Journal of Animal Science*, 89:277-286.

Hamilton, S. W., DePeters, E. J., McGarvey, J., McGarvey, J. A., Lathrop, J., & Mitloehner, F. M. (2010). Greenhouse gas, animal performance, and bacterial population structure responses to dietary Monensin to dairy cows. *Environmental Quality*, 39:1-9.

Hoard's Dairyman. (2012, March 10). *Hoard's Dairyman.* Retrieved June 29, 2013, from Fewer dairy farms left the business: http://www.hoards.com/sites/default/files/Fewer%20dairy%20farms%20left%20the%20business.pdf

Hoeksma, P., Mosquera, J., & Melse, R. W. (2012). *Monitoring methane and nitrous oxide reduction by manure treatment.* Wageningen UR, The Netherlands: Livestock Research, Report 627.

IEA Bioenergy. (2006, December 31). *biogasmax.* Retrieved from Biogas production and utilisation: http://www.biogasmax.eu/media/2_biogas_production_utilisation__068966400_1207_19042007.pdf

Intergovernmental Panel on Climate Change (IPCC) . (2007). *IPCC.* Retrieved 7 28, 2013, from Climate change 2007: The physical science basis. Contribution of Working Group I to the

Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Chapter 2, Changes in atmospheric constituents and in radiative forcing: http://www.ipcc.ch/pdf/assessment-report/ar4/wg1/ar4-wg1-chapter2.pdf

Iowa State University. (2010). *i-farmtools*. Retrieved June 11, 2013, from Short I-FARM description: http://i-farmtools.iastate.edu/i-farm/I-FARM_short_description.asp

IPCC. (1995). *Intergovermental Panel on Climate Change.* Retrieved from Second Assesment Report: http://www.ipcc.ch/pdf/climate-changes-1995/ipcc-2nd-assessment/2nd-assessment-en.pdf

IPCC. (2006). *Emissions from livestock and manure management.*

PCC. (2007). *Chapter 2: Changes in atmospheric constituents and in radiative forcing.* Retrieved 11 2013, from Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change: http://www.ipcc.ch/publications_and_data/ar4/wg1/en/ch2.html

Jarvis, S. C., Lovell, R. D., & Panayides, R. (1995). Patterns of methane emission from excreta of grazing animals. *Soil Biol. Biochem*, 27(12):1581 – 1588.

Kirk, D., and Faivor, L. (2011). *The impact of dairy housing and manure managment on anaerobic digestion.* East Lansing, Michigan: Michigan State University.

Krich, K., Augenstein, D., Batmale, J., Benemann, J., Rutledge, B., and Salour, D. (2005). *Biomethane from Dairy Waste* . California: USDA Rural Development.

Kriegl, T., and McNair, R. (2005). *Pastures of plenty: Financial performance of Wisconsin grazing dairy farms.* Madison: University of Wisconsin-Madison.

Lake-Brown, N. (2012). Financial feasibilty of biodigester development in Washington State. *Got Manure?* Liverpool: Cornell University- Department of Animal Science.

Lansing, S., Botero, R. B., and Martin, J. F. (2008). Waste treatment a nd biogas quality in small - scale agricultural digesters. *Bioresource Technology*, 99: 5881 - 5890.

Lazarus, W. F. (2008). *Farm-Based Anaerobic Digesters as an Energy and Odor Control Technology*. USDA.

Lazarus, W. F. (2009). *The Minnesota Project*. Retrieved June 6, 2013, from Economic Analysis ofthe Jer-Lindy Farms Anaerobic Digester: http://mnproject.org/pdf/LCMR_Digester_factsheet_economics.pdf

Lazarus, W. F., and Rudstrom, M. (2007). The economics of anaerobic digester operation on a Minnesota dairy farm. *Review of Agricultural Economics*, 29:349- 364.

Leggett, J., Graves, R. E., and Lanyon, L. E. (Undated). *Anaerobic Digestion: Biogas Production and Odor Reduction from Manure.* Retrieved June 6, 2013, from Agricultural and Biological Engineering. Penn State Extension: http://pubs.cas.psu.edu/freepubs/pdfs/g77.pdf

Lindemann, W. C., & Glover, C. R. (2003, May). *Nitrogen Fixation by Legumes. Guide A-129.* Retrieved October 28, 2013, from New Mexico State University, Agronomy publications: http://aces.nmsu.edu/pubs/_a/A129/

Loucks, D. P., and Beek, E. (2005). Modelling Methods for Evaluating Alternatives. In D. P. Loucks, and E. v. Beek, *Water Resources Systems Planning and Management: An Introduction to Methods, Models and Applications* (pp. 59-77). The Netherlands: United Nations Educational, Scientific and Cultural Organization.

Maria, A. (1997). Introduction to modeling and simulation. *Winter Simulation Conference*, (pp. 7-13).

Mattocks, R., and Wilson, R. (2005). Latest Trends in Anaerobic Digestion in North America. *Biocycle No.46:30.*

MDEQ Rector. (2007, January). *Michigan Department of Environmental Quality*. Retrieved from Environmental Regulations Affecting Anaerobic Digesters: http://www.michigan.gov/documents/mda/AD_Regs_221948_7.pdf

Millen, G. (2008). Small- scale digester boosts farm economics. *BioCycle*, 49: 46 - 47.

Möller H.B. (2007). Results from batch digestion. Not published.

Möller , K., and Müller , T. (2012). Effects of anaerobic digestion on digestate nutrient availability and crop growth: A review. *Eng. Life Sci.*, No. 3, 242–257.

Moser, M. A. (2011). *W. D. Hoard and Sons Company*. Retrieved October 2012, from Is a Digester Right for Your Farm?: http://www.rcmdigester.com/publications/Hoards Dairyman.pdf

Mott, G. O. (1974). Nutrient recycling in pastures. *Forage Fertilization*, 323-339.

Muller, L. D., and Holden , L. A. (1994). Intensive Rotazional Grazing. *Large Animal Veterinarian*, 27-29.

National Research Council. (2003). *National Academy Press, Washington, DC.* Retrieved June 2013, from Air Emissions from Animal Feeding Operations: Current Knowledge, Future Needs: www.national-academies.org.

Nelson, C., and Lamb, J. (2002). *Haubenschild Farms Anaerobic Digester.* Minnesota: The Minnesota Project.

Norman, S., and Jianguo, M. (2004). *A guideline for CoDigestion of food wastes in Farm-based Anaerobic Digesters.* New York: Fact Sheet FW-2, Cornell University.

Nott, S. B. (2003). *Evolution of Dairy Grazing in the 1990's.* East Lansing, Michigan: Department of Agricultural Economics, Michigan State University.

Parton, W. J., Holland, E. A., Del Grosso, S. J., Hartman, M. D., Martin, R. E., Moiser, A. R., et al. (2001). Generalized model for NO_x and N_2O emissions from soils. *Geophys. Res.*, 106 (D15): 17403-17419.

Paul, J. W., & Beauchamp, E. G. (1989). Relationship between volatile fatty acids, total ammonia and pH in manure slurries. *Biol. Wastes*, 29: 313-318.

Pennington, J. A., and VanDevender, K. (undated). *Nutrient and Fertilizer Value of Dairy Manure.* Akansas: University of Arkansas Cooperative Extension Service.

Pennslyvania State University. (2009). *Pennslyvania State University: Biogas.* Retrieved from Biogas and Anaerobic Digestion: http://www.biogas.psu.edu/

Powell, J. M., McCrory, D. F., Jackson-Smith, D. B., and Saam, H. (2005). Manure Collection and Distribution on Wisconsin Dairy Farms. *Journal of Environmental Quality*, 34:2036-2044.

Purdue Extension. (undated extension bulletin). *Managment-Intensive Grazing in Indiana.* Indiana: USDA NRCS.

Ritchie, J. T., Singh, U., Godwin, D. C., and Bowen, W. T. (1998). Cereal growth, development and yield. In G. Y. Tsuji, G. Hoogenboom, and P. Thornton, *Understanting options for agricultural production* (pp. 79-98). Dordrecht, The Netherlands: Kluwer Academic Publishers.

Ritchie, J., Singh, U., Godwin, D., and Hunt, L. (undated). *A User's Guide to CERES-Maize V2.10.* Alabama: International Fertilizer Development Center.

Rotz, A., Corson, M., Chianese, D., Montes, F., Hafner, S., and Coi, C. (2011a). *The Integrated Farm System Model. Reference Manual Version 3.6.* United States Department of Agriculture.

Rotz, C.A. (2004). Management to reduce nitrogen losses in animal production. *J. Anim. Sci.* 82(E. Suppl.):E119-E137.

Rotz, C. A., Chianese, D. S., Montes, F., and Hafner, S. (2012). *Dairy Gas Emissions* Model. *Reference Manual.* USDA.

Rotz, C.A., Hafner, S.D (2011b). Whole farm impact of anaerobic digestion and biogas use on a New York dairy farm. ASABE Annual International Meeting. Paper No. 1111194.

Rotz, C. A., Soder, K. J., Skinner, R. H., Dell, C. J., Kleinman, P. J., Schmidt, J. P., and Bryant, R. B. (2009). Grazing Can Reduce the Environmental Impact of Dairy Production Systems. *Forage and Grazinglands*, doi:10.1094/FG-2009-0916-01-RS.

Schaber, J. (undated). *Universität Osnabrück* . Retrieved June 10, 2013, from FARMSIM: A dynamic model for the simulation of yields, nutrient cycling and resource flows on Philippine small-scale farming systems: http://www.usf.uni-osnabrueck.de/archive/~jschaber/Farmsim/FARMSIM.html

Scottish Executive Environment and Rural Affairs Department. (2007). *Nutrient Value of Digestate from Farm-Based Biogas.* Scotland: ADAS and SAC.

Sendich, E. D. (2008). *Modeling and analysis of the biorefinery integrated with the agricultural landscape.* Michigan: Michigan State University.

Shaver, R., & Hoffman, P. (2010). *Use of straw in dairy cattle diets.* Wisconsin: University of Winsconsin Board of Regents.

Sheffield, R., Barker, J., and Rashash, D. (2008). *BAE.NCSU.* Retrieved from Solids Separation of Animal Manure: http://www.bae.ncsu.edu/programs/extension/manure/technologies/solids.pdf

Simpkins, D. (2005). *Anaerobic Digester FAQs.* Michigan: Michigan Biomass Energy Program. Michigan Department of Labor and Economic Growth.

Soder, K. J., and Rotz, C. A. (2001). Economic and environmental impact of four levels of concentrate supplementation in grazing dairy herds. *Journal Dairy Sci*, 84:2560–2572.

Stokes, J. R., Rajagopalan, R. M., and Stefanou, S. E. (2008). Investment in a Methane Digester: An Application of Capital Budgeting and Real Options. *Review of Agricultural Economics*, 30: 664- 676.

The Minnesota Project. (2010). *Anaerobic Digesters: Farm Oportunities and Pathways.* Minnesota: Minnesota Department of Commerce.

The University of Tasmania. (2013). *Dairy Greenhouse gas Abatement Strategy calculator. User Manual.* The Department of Agriculture, Fisheries and Forestry.

Totzke, D. (2009). Tapping the Potential of Codigestion. *Biocycle*, 50 (6).

Tyrell, H. (2002). Nitrogen flow through livestock production systems: Unmanaged loss to the environment. USDA–ARS, Penn State Univ. Dairy and Animal Science Seminar

U.S Department of Energy. (2012, May 09). *Energy Efficency and Renewable Energy.* Retrieved from Energy basics: Anaerobic Digestion: http://www.eere.energy.gov/basics/renewable_energy/ anaerobic_digestion.html

U.S. Census Bureau. (2012). *U.S.Department of Commerce.* Retrieved May 2013, from Statistical Abstract of the United States: Section 17 Agriculture: http://www.census.gov/compendia/statab/2012edition.html

UDIM. (2013). *United Dairy Industry of Michigan.* Retrieved July 5, 2013, from Michigan Dairy facts:

http://www.michigandairynewsbureau.org/index.php?option=com_content&view=article&id=5&Itemid=7

Ündeğer, Ç. (2008). *Bilkent Üniversitesi Bilgisayar Mühendisliği Bölümü.* Retrieved June 6, 2013, from Introduction To Modeling and Simulation : http://www.cs.bilkent.edu.tr/~cagatay/cs503/_M&S_02_Introduction.pdf

University of California. (2010, March 23). *University of California Agriculture and Natural Resources*. Retrieved June 10, 2013, from Interactive Tools and Models: ALFALFA 1.4: http://www.ipm.ucdavis.edu/IPMPROJECT/alfalfa.html

University of New Hampshire . (2009). *User's Guide for the DNDC Model (Version 9.3)* . New Hampshire : University of New Hampshire .

USDA. (2003). *United States Department of Agriculture*. Retrieved from Recommended methods for manure analysis: http://learningstore.uwex.edu/pdf/A3769.pdf

USDA. (2012, October 29). *USDA Agricultural Research Service*. Retrieved June 6, 2013, from Integrated Farm System Model: http://www.ars.usda.gov/main/docs.htm?docid=8519

USDA. (2013, 11 12). *Integrated Farm System Model*. Retrieved 11 14, 2013, from United States Department of Agriculture-Agricultural Research Service: http://www.ars.usda.gov/main/docs.htm?docid=8519

USDA-NASS. (2013, February 20). *USDA-NASS*. Retrieved May 2013, from Milk production: http://www.usda.gov/nass/PUBS/TODAYRPT/mkpr0213.pdf

USDA-NRCS. (2007). *Profitable Grazing-Based Dairy Systems*. USDA.

USDOE. (1996). *United States Department of Energy*. Retrieved from Deploying Anaerobic Digesters: Current Status and Future Possibilities: http://www.nrel.gov/docs/legosti/fy96/20558.pdf

Vanhorn, H. H., Wilkie, A. C., Powers, W. J., and Nordstedt, R. A. (1994). Components of Dairy Manure Manage ment Systems. *Journal of Dairy Science*, 77: 2008 -2030.

Walsh, J., Ross, C., Smith, M., Harper, S., and Wilkins, W. (1988). *Handbook on Biogas Utilization.* Georgia: Georgia Institute of Technology, Engineering Technoloy Branch.

Walsh, M. E., and Becker, D. (1996). BIOCOST: A software program to estimate the cost of producing Bionergy crops. *The Seventh National Bioenergy Conference: Partnerships to Develop and Apply Biomass Technologies.* Nashville, Tennessee: Oak Ridge National Laboratory.

Warncke, D., Dahl, J., Jacobs, L., & Laboski, C. (2004). *Nutrients recommendations for field crops.* East Lansing, Michigan: Michigan State University, Extension Bulletin E2904.

Wattiaux, M. A., and Karg, K. L. (2004). Protein level for alfalfa and corn silage-based diets. II. Nitrogen balance and manure characteristics. *Journal Dairy Science*, 87:3492-3502.

Wheatley, A. (1990). Anaerobic Digestion: a Waste Treatment Technology. *Elsevier Applied Science*, 93-138.

Whitehead, D. C. (1995). *Grassland nitrogen.* Wallingford, United Kingdom: CABI.

Wilkie, A. (2005). *Anaerobic Digestion: Biology and Benefits.* New York: Cornell University 63-72.

Winsten, J. R., Parsons, R. L., and Hanson, G. D. (2000). Differentiated Dairy Grazing Intensity in the Northeast. *Journal of Dairy Science* , 83:836-842.

Yadav, S. D., Kumar, B., and Thipse, S. S. (2013, January 9). *SAE International.* Retrieved June 6, 2013, from Effects of Bio-Gas Fuel Composition on Engine Performance: http://papers.sae.org/2013-26-0011/

Yamulki, S., Jarvis, S. C., & Owen, P. (1999). Methane emission and uptake from soils as influenced by excreta deposition from grazing animals. *Environmental Quality*, 28: 676 – 682.

Zhao, L., Rausch, J. N., and Combs, T. L. (2008). Overview of Odor Control for Manure Storage Facilities. *Agriculture and Natural Resources. The Ohio State University Extension.*, pp. AEX-738-08.