EMERGY FROM COMBINED WASTE STREAMS IN A BEEF PRODUCTION AGROECOSYSTEM

by

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Abstract

Wastewater from hydraulic fracturing (HF) and manure from beef cattle production are two of the largest waste streams in the Texas Panhandle. The objectives of this research were to 1) evaluate the potential of generating bio-methane (CH_4), a renewable natural gas, from the combination of HF wastewater and beef manure through anaerobic digestion (AD), 2) simulate the annual amount of energy that can be produced from these two waste streams, and 3) evaluate the environmental impacts and sustainability of biogas through an emergy analysis. The research included a laboratory study and the development of two dynamic systems models. Substrate combinations of manure mixed with produced and flowback water (PFW) were evaluated at four moisture contents (MC; 65, 70, 80, and 90%). Substrate combinations mixed with well water (WW), and a 50/50 mixture of WW and PFW were evaluated at MC of 80 and 90%. Manure was harvested from the WTAMU Research Feedlot. The PFW was collected from a HF operation in the Texas Panhandle. Regression analyses were used to predict bio-methane production based on MC for each water type. The regression model statement for WW was $\hat{y} = -2{,}176 + 59.3\ x$, which indicated that CH_4 volume (ml) increased with increasing MC. Conversely, CH_4 volume decreased with increasing MC for the 50/50 mixture ($\hat{y} = 2.94\text{x}10^9 e^{-0.199x}$) and PFW ($\hat{y} = 343{,}662 e^{-0.118x}$).

Regression model statements from the biogas data were used in the energy estimation model, which simulated feedyard manure production and the amount of diesel and electricity generated from AD. The optimum MC for PFW was 70%, with simulated results of 59,800 L of fuel and 139,200 kWh of electricity. These results were for raw methane and did not account for cleaning/upgrading gains or losses of CH_4. The results from the biogas experiment and the feedlot energy model provided inputs for the emergy model. The emergy model was used with traditional emergy analysis methods to determine the relative sustainability and environmental impact of the transformation of energy from dry-lot beef cattle manure and PFW at the WTAMU Nance Ranch. Three options were evaluated: no AD, AD with WW, and AD with PFW. Several emergy indices were used to compare the three options. The percent renewable index simulated by the model was 0.49 for no AD, 0.50 for AD with PFW, and 0.33 for AD with WW. The environmental sustainability index was 7.25 for no AD, 31.62, for AD with PFW, and 6.14 for AD with WW. These results suggested that AD with PFW was the best long-term option from a sustainability perspective.

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CHAPTER I: INTRODUCTION

Energy Production in Texas

Fossil fuels, which include petroleum, natural gas, and coal, made up 81.5% of total United States (US) energy consumption in 2015 (EIA, 2017). Texas leads the country in both energy production and energy consumption with 37% of crude oil and 24% of natural gas production (EIA, 2013). Annual energy consumption in Texas is 472 million British Thermal Units (BTU's). Half of those are consumed by the industrial sector, which includes refineries and petrochemical plants (EIA, 2017). Concerns that arise from the consumption of fossil fuels are anthropogenic increases of carbon dioxide (CO_2), water use to extract oil and gas, and depletion of the fossil fuels on which we have developed a reliance (Höök and Tang, 2013).

Three oil and natural gas regions exist in the Texas Panhandle, the Anadarko Basin, the Palo Duro Basin, and the Dalhart Basin (Figure 1). The Anadarko Basin is the greatest oil and gas producing basin in the Panhandle. The Anadarko is geographically located in 11 counties northeast of Amarillo, Texas. The basin is also located in the western portion of Oklahoma, southwestern portion of Kansas, and southeast Colorado. The Palo Duro Basin is centrally located in the Texas Panhandle between Amarillo and Lubbock. New Mexico borders to the west and Oklahoma borders to the east. The Dalhart Basin is a small basin in the northwest corner of the Texas Panhandle.

With areas greater than 12 km thick, the Anadarko is the deepest sedimentary basin located on the North American craton (Lee and Deming, 1999). The Anadarko basin is an alluvial and structural basin. The tectonic boundaries are the Amarillo–Wichita uplift on the south, the Nemeha ridge on the east, the Sierra Grande on the west and shelf areas to the north (Rice *et al.*, 1988). The Anadarko is rich in hydrocarbons. According to data generated in September 2019, the Anadarko Basin produces 558 thousand barrels of petroleum, and 213 million m^3 of natural gas per day (EIA, 2019). Estimated cumulative production for the basin is more than 3.54 trillion m^3 of gas and 5.4 billion barrels of oil (Mitchell, 2012).

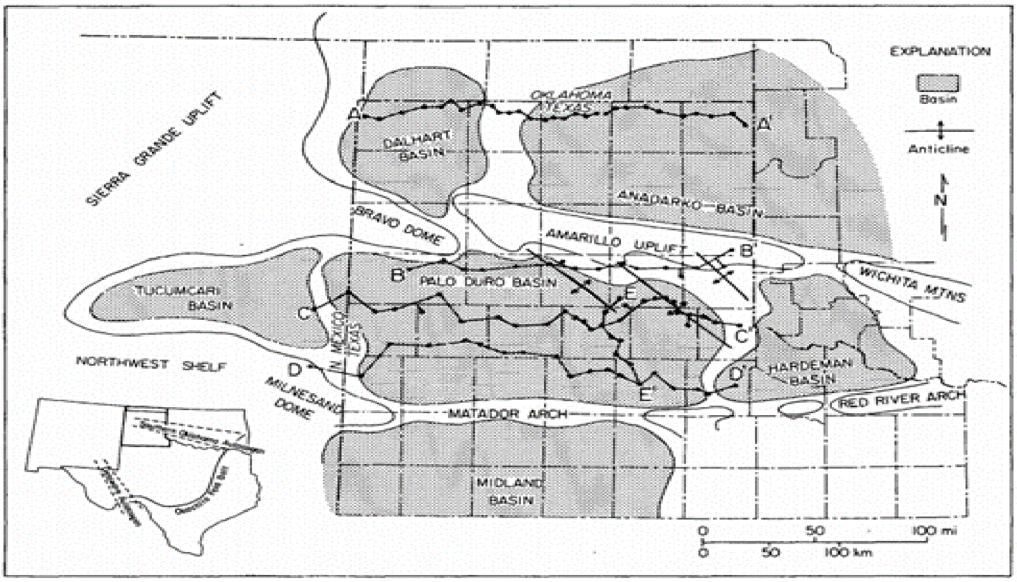


Figure 1: The Dalhart, Anadarko, and Palo Duro Basins in the Texas Panhandle (Handford, 1980)

The Palo Duro Basin is composed of primarily Pennsylvanian, Permian, and Triassic sedimentary rocks (Handford, 1980). The Palo Duro Basin is connected to the Dalhart basin, and merges with the Tucumcari Basin in New Mexico (Handford, 1980).

One of the world's largest gas reserves, the Hugoton-Panhandle Gas Field, is located within the Palo Duro and Anadarko Basins (Figure 2). The Hugoton-Panhandle

Gas Field, which extends 350 km across SW Kansas and the Texas/Oklahoma Panhandle, is the largest conventional gas field in North America (Ballentine and Lollar, 2002; Ha and Marfurt, 2017). The field contains more than 2.3 x 10^{12} m^3 of recoverable natural gas (Ballentine and Lollar, 2002).

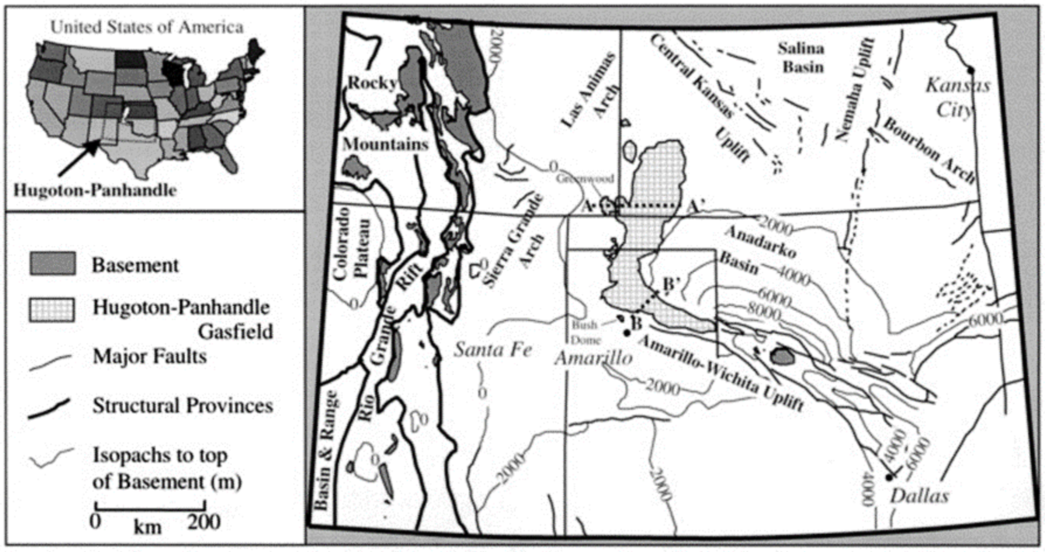


Figure 2: Map of the Anadarko Basin with the Hugoton-Panhandle Gas Field in Kansas, Oklahoma, and Texas and geological/structural features of the area (Ballentine and Lollar, 2002).

Hydraulic Fracturing

Hydraulic fracturing (HF), commonly referred to as "fracking", is an unconventional method of withdrawing natural gas from fissures in shale rock with low permeability. This unconventional method of directional drilling can be performed horizontally or vertically. The HF method requires fracking liquid to be injected at high pressure along shale rock layers to release natural gas through the wellhead. The released gas is then captured at the wellhead, and the pressure is released causing the HF liquid to flow back to the surface. The liquid injected is a mixture of water, proppants, and chemicals. This method of drilling has unlocked huge reserves of shale oil and the gas that were previously believed to be unrecoverable (Rodriguez and Soeder, 2015). Fracturing has improved domestic oil and gas yields allowing the US to decrease its dependence on foreign fossil fuels (Gallegos *et al.*, 2015). Production yield gains have come at a cost to fresh water supplies. Unconventional drilling typically uses 3.79-11.34 million liters of water per gas well, and can exceed 18.9 million liters (Theodori *et al.*, 2014; Ferrer and Thurman, 2015). In areas such as the Texas Panhandle where freshwater availability is diminishing, water use in HF is a critical issue. The Panhandle region relies on available groundwater for municipal and agricultural use. In the Anadarko Basin, 20% of the initial water needs for HF are met by recycled or reused water (Rodriguez and Soeder, 2015).

Two types of wastewater are produced during HF. Flowback water is water that is injected into the well and flows back to the surface after pressure is released. Produced water is the water that is naturally present in the shale formation (Theodori *et al.*, 2014; Ferrer and Thurman, 2015; Lester *et al.*, 2015; Silva *et al.*, 2017). Produced water and flowback water (PFW) both return to the surface, where they must be treated and/or disposed of (Figure 3). Flowback water returns to the surface first, and after approximately one month, the water returning to the surface is primarily produced water. On a ‘by volume' basis, PFW is the largest by-product of oil and gas extraction activities (Silva *et al*., 2017).

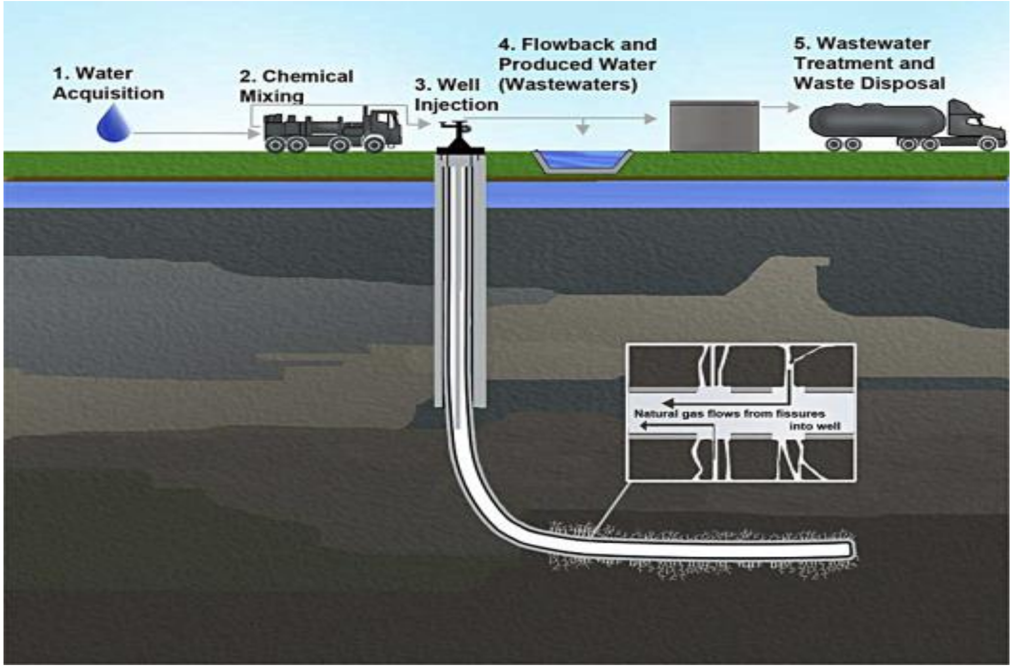


Figure 3: Schematic of Wastewater Production at an Oil and Gas Operation (Engle et al., 2014)

Chemical Composition and Disposal of Produced/Flowback Water

The water produced during HF is considered brackish (Xu *et al.*, 2008). Brackish water is water that is too saline to be considered fresh and not saline enough to be considered saltwater. In estuarine wetlands, a common characteristic is a mixture of fresh and marine water (Tong *et al.*, 2017). The amount of total dissolved solids (TDS) in brackish water is between 1,000 and 10,000 mg L^{-1}. The drinking water threshold in the US is 500 mg L^{-1} TDS (Brown *et al.*, 2016). The World Health Organization (WHO) has established guideline limits of drinking water as 1000 mg L^{-1} TDS and 250 mg L^{-1} chloride concentrations (Abuhabib *et al.*, 2013).

In addition to being brackish, PFW contains heavy metals and naturally occurring radioactive elements. Calcium, potassium, magnesium, sodium, copper, iron, manganese, and zinc are commonly found in PFW. Elemental concentrations will vary depending on the chemicals injected and the geology of the formation (Silva *et al.*, 2017). There are several organic compounds, typically presented as total organic carbon (TOC), present in PFW. The organics present in PFW rarely pose significant health risks; however, some organics can be potentially toxic and should be carefully managed to prevent groundwater contamination (Silva *et al*., 2017).

Approximately 570 million m^3 of wastewater are produced annually from HF (Silva *et al.*, 2017). These oil and gas wastewaters are stored at the surface and then disposed of, or treated, recycled, and reused. Management of PFW poses many challenges due to the sheer volume of water produced. Furthermore, high levels of contaminants present additional concerns for treatment and disposal, particularly in the protection of groundwater quality (Gallegos *et al.*, 2015).

Over 95% of all wastewater from HF is injected into Class II disposal wells (Rodriguez and Soeder, 2015). Four billion liters of fluids are injected into disposal wells in the United States every day (USEPA, 2019). Approximately 180,000 Class II wells are currently in operation in the United States (USEPA, 2019). In Texas, there are thousands of deep disposal wells, where deep-well injection is the preferred method of disposal (Gallegos *et al.*, 2015). Deep disposal wells are typically over 1,609 meters below the surface. This distance allows for the prevention groundwater contamination in the case of well seepage and leaks. Class II disposal wells are regulated by the USEPA. The USEPA has delegated authority for regulation in Texas to the Texas Railroad Commission. According to data released in August 2019, the Texas Railroad Commission is currently monitoring 438,164 active and inactive Class II disposal wells (TRRC, 2019). Texas Administrative Code § 3.13 (Statewide Rule 13) declares that a well’s construction standards require three layers of casing to ensure groundwater is protected. The three layers include surface casing, production casing, and tubing string and packer.

There are some concerns that the practice of disposing wastewater into deep wells is triggering seismic activity in areas with active fault lines or brittle geologic formations (Cooley and Donnelly, 2012; Gallegos *et al.*, 2015; Rodriguez and Soeder, 2015). The potential occurrence of small earthquakes will depend on the volume of water injected into the disposal well, the geology of the deep-well disposal site, and disposal practice (Gallegos *et al.*, 2015).

Class II injection wells can be located on site and operated by the drilling company but are more commonly transported off site where disposal is managed by a third-party (Cooley and Donnelly, 2012). Fresh water and wastewater are typically transported via trucks to and from the well site. Transportation by truck raises several environmental concerns. Some of these concerns include increased noise, dust, congestion, and vehicle accidents. Many operators (Anadarko, Apache, BP, Chesapeake, ConocoPhillips, Devon, Marathon, Newfield, Pioneer, QEP, Southwestern, and Talisman) have transitioned to moving wastewater with pipeline networks (Smith et al., 2017). Wastewater disposal sites can be hundreds of miles away from the HF site, making pipelines more efficient for water transport over long distances (Rodriguez and Soeder, 2015). There are millions of miles of active and abandoned pipelines that deliver natural gas, water, and hazardous materials to various locations throughout the US. Pipelines can exist above ground, but the majority are buried underground making most of the general public unaware of their existence. In 2013, Texas approved transportation of HF wastewater via pipeline to disposal sites and eliminated the legal liability for operators who transport the wastewater for recycle/reuse (Texas HB 2767, 2013; Texas SB 514, 2013; Rodriguez and Soeder, 2015).

Disposal of produced water diverts energy from the economy by removing land from production, threatening water quality, and wasting critical material. Zemlick *et al.* (2018) found that the energy to extract fresh groundwater for HF exceeds the energy that it would require if the same amount of PFW was chemically treated. Additionally, the energy required to transport fresh water and dispose of PFW is far greater than the energy required to move treated PFW to a point of reuse (Zemlick *et al.*, 2018).

High Plains Aquifer

Groundwater resources, which represent about one quarter of freshwater on earth, are the main source of irrigation and drinking water in some arid and semi-arid regions (Balali and Viaggi, 2015). In the Texas Panhandle region, most available moisture is lost to atmospheric demand through evapotranspiration (ET). Mean ET in the Panhandle region exceeds mean annual rainfall (Crosbie *et al*., 2013). The High Plains Aquifer (HPA) is the main source of freshwater for the Texas Panhandle, where few drainage systems exist, and surface water sources are scarce.

The HPA, often referred to as the Ogallala Aquifer, extends across an area of 4.52 x 10^{11} m^2. The HPA lies under portions of Colorado, Kansas, Nebraska, New Mexico, Oklahoma, South Dakota, Texas, and Wyoming (Figure 4; McGuire, 2017). Groundwater from the HPA supports 30% of the irrigated agriculture in the US (Steward and Allen, 2016). Approximately 97% of the water pumped from the aquifer is for irrigation of agricultural crops (Crosbie *et al*., 2013).

The uplifted and tectonically active Rocky Mountains provided source material for deposition of the Ogallala Formation (Steward and Allen, 2016). Valleys and basins that developed by erosion on the surface of Permian, Triassic, Jurassic, and Cretaceous rocks became filled with Ogallala sediments (Steward and Allen, 2016). The HPA is an unconfined aquifer with a saturated thickness of approximately 200 m and a depth to water table that ranges from 5 m to 100 m (Crosbie *et al*., 2013).

Water in the Texas Panhandle portion of the formation generally flows northwest to southeast at an approximate rate of 47.5 m per year (HPGWD, 2009). Northern areas of the HPA recharge at an equal rate to discharge (withdrawal), resulting in minimal water table declines. In the Texas/Oklahoma portion of the aquifer, a caliche layer under topsoil does not allow water to percolate to the water table, impeding recharge of the aquifer. Annual recharge rates for the region range from 0.024 to 2.2 inches per year (McGuire, 2017). The rate of withdrawal in the area significantly exceeds the recharge rate (Crosbie *et al*., 2013). Exceeding the rate of recharge is resulting in a depletion of saturated thickness.

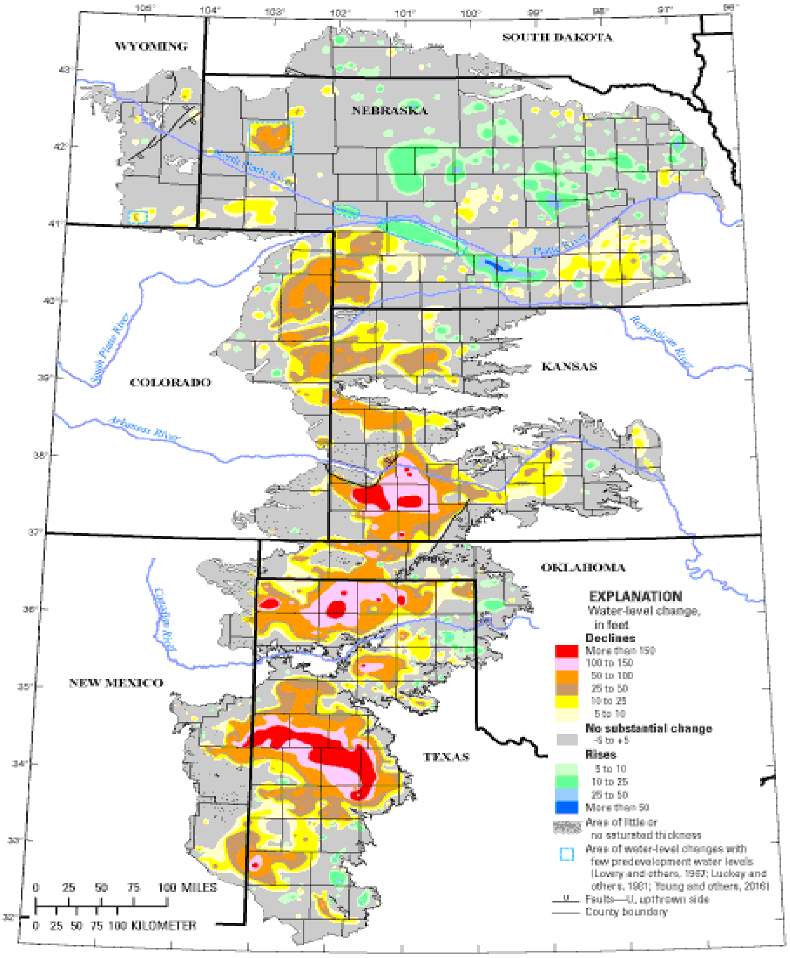


Figure 4: Map of the Geographical Location and Water Level Change of the High Plains Aquifer

Livestock Production in the Texas Panhandle

As of September 2019, there were 2,404,000 cattle on feed in the Texas Panhandle (NASS, 2019). The Texas Panhandle houses 88% of the total cattle on feed in Texas. Texas feeds 28% of the total cattle fed in the US. A consequence of feeding cattle is manure production. A 454 kg beef steer will produce 30 kg of manure daily, which includes urine and feces (NRCS, 1999).

The agriculture sector contributes 10% of total greenhouse gas (GHG) emissions in the US (USEPA, 2019). Nitrous oxide (N_2O) is the primary greenhouse gas produced from the agricultural sector, and those emissions arise as a result of management practices on agricultural soils (USEPA, 2019). The other major contributor to GHG in agriculture is from livestock GHG production. Methane (CH_4) is a natural byproduct of the digestive process in cattle. It is also generated during manure management and storage (USEPA, 2019). Manure management contributes to 14% of total agricultural GHG emissions (USEPA, 2019). Alternative nutrient management research is increasing as a result of public concerns about nutrients lost to the environment as a part of manure management (Achinas & Euverink, 2017).

Biogas Generation

Energy demands increase as the population increases. As a result, alternative energy production has gained popularity in recent years. Biogas offers several advantages as a renewable energy source, as it is energy efficient and environmentally beneficial (Weiland, 2010a). Anaerobic digestion (AD) is the most common method used to generate biogas. Bio-methane is the primary gas produced during the anaerobic digestion process. Bio-methane is a renewable energy source that can be treated or upgraded to supplement or replace electricity, natural gas, and fuel for vehicles (Achinas *et al.*, 2017).

Anaerobic digestion of livestock manures is an effective waste management strategy for several reasons. Biogas production through AD allows for capture and utilization of carbon-based gases from manures, before they enter the atmosphere (Ward *et al.*, 2008). Controlled AD is also a means of odor and pest control, and the remaining slurry can be utilized as a soil amendment for crop growth (Chen *et al.*, 1980; Ward *et al.*, 2008). The bulk of organic matter is reduced during AD making the volume of manure and other agricultural wastes more manageable (El-Mashad *et al.*, 2004). The slurry remaining after digestion can also improve soil nutrient content. There is less biomass remaining after anaerobic digestion when compared to aerobic digestion processes, such as composting (Ward *et al.*, 2008). In both anaerobic and aerobic digestion, there is an opportunity to destroy harmful bacteria present in animal manures (Ward *et al.*, 2008). When the process is carried out at thermophilic temperatures, pathogens such as *E. coli, Salmonella,* and *Mycobacterium paratuberculosis* are destroyed within 24 hours, along with destruction of weed seeds present in manure (El-Mashad *et al.*, 2004). The maximum temperature for pathogenic bacteria to survive is about 45°C, and their optimum temperature is approximately 37.5°C (Bergey, 1919).

While there are many benefits in managing agricultural wastes with AD, there are several disadvantages. Although energy can be generated through AD, energy and heat are required for the AD process. There are also maintenance considerations in the operation of an anaerobic digester. In arid regions, the most important disadvantage is the large amounts of water required to generate biogas with agricultural wastes. By definition, a wet anaerobic digesting system contains no more than 15% total solids (Ward *et al.*, 2008). Depleting amounts of fresh water available in the Texas Panhandle make using fresh water to generate biogas difficult to justify. There are billions of gallons of PFW available that can potentially be utilized as a replacement for fresh water to generate biogas in the Texas Panhandle.

Project Objectives

Produced water and beef cattle manure present an opportunity to combine two waste streams to create a usable product. To date, there have not been any published studies identified that have evaluated the feasibility of biogas generation using wastewater from HF. There are no published studies available that analyze a total system or emergy analysis to evaluate sustainability and environmental impact from using this type of water to produce biogas.

The purpose of this study was to conduct a total systems analysis of using produced and flowback water as an alternative to fresh water in biogas generation through the following objectives:

1) To evaluate the potential of combining produced and flowback water with dry-lot beef cattle manure, in a controlled anaerobic digestion laboratory experiment, for generation of bio-methane.
2) To evaluate the potential energy that can be produced for a feedlot, with data collected from the laboratory bio-methane experiment and through the development of a quantitative dynamic energy model.
3) To conduct an emergy analysis to evaluate the environmental impact and sustainability of generating biogas from combined waste streams through the development of a quantitative dynamic emergy model.

CHAPTER II: BIO-METHANE PRODUCTION WITH WASTEWATER FROM HYDRAULIC FRACTURING AND BEEF CATTLE MANURE

Biogas Generation with Anaerobic Digestion

Biogas is a natural byproduct of anaerobic digestion (AD) from the decomposition of organic matter. Anaerobic digestion is a naturally occurring process that is carried out by microbes that thrive in oxygen-free environments. The AD process occurs in mammal guts during food digestion, in oxygen-depleted water sources such as groundwater, marshes and swamps, and wastewater lagoons (Ward *et al.*, 2008). The process can be replicated in controlled environments from a variety of agricultural and domestic wastes, food wastes, and plant residues as a renewable energy source.

Anaerobic digestion is a complex chemical and biochemical process. There are several different types of microbes responsible for fermentation and biogas production, and the different microbes are present at different phases (Table 1).

Table 1: Major genera of fermentative bacteria in anaerobic digestion (adapted from Li *et al.*, 2011)

Fermentation pathway	Genera	Major products
Acetate fermentation	*Acetobacterium*, *Clostridium*, *Sporomusa*	Acetate, CO_2
Alcohol fermentation	*Saccharomyces*	Ethanol, CO_2
Butyrate fermentation	*Butyribacterium*, *Clostridium*	Buryrate, butanol, isoporpanol, ethanol, CO_2
Lactate fermentation	*Lactobacillus*, *Streptococcus*	Lactic acid, CO_2
Propionate fermentation	*Clostridium*	Propionate, acetate, CO_2

The phases of AD are: 1) hydrolysis/fermentation, 2) acidogenesis, 3) acetogenesis/dehydrogenation, and 4) methanogenesis (Schink, 1997; Amani *et al.*, 2010; Weiland, 2010a; Anukam *et al.*, 2019). Each process has an energy reaction that produces heat as a byproduct. The four phases of AD are presented in Eq. 1-11 (adapted from Anukam *et al.*, 2019).

Hydrolysis (Eq.1) is the splitting of a chemical bond with water, resulting in hydrogen and hydroxide (Anukam *et al.*, 2019). During the hydrolysis phase, hydrolytic microbes are responsible for decomposing organic matter into soluble molecules, and into sugars, fatty acids, volatile fatty acids (VFAs), and amino acids (Weiland, 2010a; Achinas *et al.*, 2017). Hydrolysis is a critical stage in the AD process and is the limiting step for biogas production (Mata-Alvarez *et al.*, 2000).

During acidogenesis (Eq. 2-4), amino acids, sugars, and fatty acids are further broken down into CO_2, hydrogen (H_2), ethanol, and other products by acidogenic bacteria (Amani *et al.*, 2010). Acidogenic bacteria grow rapidly and can survive extreme conditions (Amani *et al.*, 2010). Acetogenic bacteria break the VFAs into acetic acid, CO_2 and hydrogen (Achinas *et al.*, 2017). Bacteria that carry out acetogenesis (Eq. 5-8) produce H_2, CO_2, and acetate by consuming VFA's (Li *et al.*, 2011).

Methanogens (Eq. 9-11) produce CH_4 and CO_2 from acetate and hydrogen, and CO_2 (Amani *et al.*, 2010). Methanogenesis is performed by a specific group of *Archaea* methanogens (Tong *et al.*, 2017). Very few species of bacteria and archaea have been isolated and little is known about the actions of these microorganisms (Weiland, 2010a; Achinas *et al.*, 2017). Methanogenic bacteria are sensitive to small amounts of O_2 and changes in environmental conditions (Anukam *et al.*, 2019).

1) Hydrolysis:

$$C_6H_{10}O_5 + H_2O \rightarrow C_6H_{12}O_6 + H_2 \qquad \text{(Eq. 1)}$$

2) Acidogenesis:

$C_6H_{12}O_6 \leftrightarrow 2CH_3CH_2OH + 2CO_2$ (Eq. 2)

$C_6H_{12}O_6 + 2H_2 \leftrightarrow 2CH_3CH_2COOH + 2H_2O$ (Eq. 3)

$C_6H_{12}O_6 \rightarrow 3CH_3COOHC_6H_{12}O_6 + 2H_2 \rightarrow 2CH_3CH_2COOH + 2H_2O$ (Eq. 4)

3) Acetogenesis/dehydrogenation:

$CH_3CH_2COO- + 3H_2O \rightarrow CH_3COO^- + H^+ + HCO_3^- + 3H^2$ (Eq. 5)

$C_6H_{12}O_6 + 2H_2O \rightarrow 2CH_3COOH + 2CO_2 + 4H_2$ (Eq. 6)

$CH_3CH_2OH + 2H_2O \rightarrow CH_3COO- + 3H_2 + H^+$ (Eq. 7)

$2HCO_3^- + 4H_2 + H^+ \rightarrow CH_3COO^- + 4H_2O$ (Eq. 8)

4) Methanogenesis:

$CH_3COOH \rightarrow CH_4 + CO_2$ (Eq. 9)

$CO_2 + 4H_2 \rightarrow CH_4 + 2H_2O$ (Eq. 10)

$2CH_3CH_2OH + CO_2 \rightarrow CH_4 + 2CH_3COOH$ (Eq. 11)

Byproducts of Anaerobic Digestion and Conversion of Byproducts to Energy

The primary byproducts from the AD process are CH_4, CO_2, hydrogen sulfide (H_2S), nitrogen (N_2), and digested sludge (Ward *et al.*, 2008; Al-Mashhadani *et al.*, 2016; Khan *et al.*, 2017). There are other trace gases present, such as ammonia (NH_3), oxygen (O_2), H_2, carbon monoxide (CO), and water vapor (Ryckebosch *et al.*, 2011; Khan *et al.*, 2017). While the primary gases present in biogas are CO_2 (15-60%) and CH_4 (40-75%), exact concentrations depend on the organic materials used and the conditions present in the anaerobic digester (Ryckebosch *et al.*, 2011).

Bio-methane, also known as renewable natural gas (RNG), is the cleaned or upgraded biogas that has been generated in anaerobic digesters. The cleaned or upgraded product can be used to generate electricity, heat, steam, replace or supplement natural gas, and can be upgraded to biofuel for use in vehicles (Al-Mashhadani *et al.*, 2016; Khan *et al.*, 2017).

Trace gases present must be removed by cleaning, which occurs before introduction to the natural gas grid and/or use in appliances. This method removes H_2S, which is an extremely hazardous gas with a strong "rotten egg" odor at low concentrations, is highly flammable, corrosive, explosive, and can be incapacitating or deadly in high concentrations (NCBI, 2016). The gas is particularly damaging to equipment when moisture is present. The presence of H_2S can lead to rapid and extensive damage to metals including corrosion, pitting, and cracking. Removal of H_2S is essential for minimizing maintenance problems (Ravishanker and Hills, 1984). Digester gas contaminated with H_2S can cause compressor malfunction in engines and lessen the value of lubricating oil (Ravishanker and Hills, 1984).

Biogas upgrading removes CO_2 to improve the calorific value and relative density of the gas to meet the Wobbe index specifications (Ryckebosch *et al.*, 2011). The Wobbe index is the gas quality criterion used for gas appliances and interchanging gaseous fuels in engines, and measures its ability to provide energy (Klimstra, 1986). The fuel grade for good engine performance, assigned to a gas from the Wobbe Index, depends on ignitability, combustion velocity, a high knock resistance, and sufficient energy of the mixture (Klimstra, 1986). Gas engines drive electric generators, pumps, compressors, electric energy, and heat production (Klimstra, 1986). Bio-methane, after upgrading, typically is made up of 95-97% CH_4 and 1-3% CO_2 (Ryckebosch *et al.*, 2011).

There are several methods for removing biogas impurities. The method of removal depends on the type of impurity and the intended use of bio-methane. The cost of removing impurities is dependent on the method of treatment and the gas to be removed. There are at least 13 methods available for H_2S removal alone. The methods vary from biological removal by using air in a filter or scrubber to chemical absorption with water (H_2O), sodium hydroxide (NaOH), or iron compounds such as iron hydroxide ($Fe(OH)_3$). In addition, compounds such as iron chloride ($FeCl_2$) can be added to the digester. Biological filters and adsorption using activated carbon can also be used (Ryckebosch *et al.*, 2011).

Produced and Flowback Water from Hydraulic Fracturing

The composition of PFW is variable depending on the well location, type of extraction, and the types of materials used to operate the HF rig (Silva *et al.*, 2017). Because flowback water returns to the surface first, the wastewater at an HF site begins to assume the chemical composition of the formation rock type it is being extracted from, and fewer injected chemicals are present after a month of recycled use (Silva *et al.*, 2017). In areas with limited access to freshwater sources, brackish water is used as an alternative source water to mix with fracturing additives (Smith *et al.*, 2017). In the Anadarko region, the brackish water is obtained from the Santa Rosa aquifer. The use of brackish groundwater minimizes competition with local fresh water demands (Smith *et al.*, 2017).

Produced and flowback water has a typical salt content of 3.0-5.0 g L^{-1} (Pang *et al.*, 2010). The pH of PFW can range from 1.21 to 9.87, and electrical conductivity (EC) can range from 94.8 to 586,000 $\mu S\ cm^{-1}$ (Silva *et al.*, 2017). The chemistry of brackish PFW is dominated by Na, Ca, and HCO_3 (Frape *et al.*, 1984). Typically, there are heavy metals, naturally occurring radioactive elements (NORM), proppants, HF chemicals, TOC, oil, and grease in PFW. Prior to being recycled on-site or moved for disposal/reuse, many of these constituents must be removed or reduced. Typical treatment processes include disinfection, desalinization to reduce salinity, membrane treatment to reduce a variety of dissolved constituents, and removal of NORM (Smith *et al*., 2017).

Water analysis for PFW in the Anadarko region in scarce. Results for composite water samples of PFW are presented in Table 2 (Thiel and Lienhard, 2014) for the Permian Basin (West Texas) and Marcellus Shale (Pennsylvania).

Table 2: Composition of water samples from the Permian and Marcellus Shales (Thiel and Lienhard, 2014)

	Concentration			
	Permian Basin		Marcellus	
Analyte	mg L^{-1}	mM	mg L^{-1}	mM
Br^-	1,393	18.8	1,202	15.4
$Ba_2{}^+$	0.45	0.0	0.27	0.0
$Ca_2{}^+$	13,000	350	12,575	322
Cl^-	111,000	3378	86,457	2500
$Co_2{}^+$	–	–	6.0	0.10
CT	120	2.12	48	0.81
$Fe_2{}^+$	–	–	54	1.0
K^+	837	23.1	253	6.63
Li^+	–	–	169	25
$Mg_2{}^+$	1,743	77.4	1,106	46.7
$Mn_2{}^+$	35	1.51	6.0	0.25
Na^+	53,550	2513	37,939	1692
SO_4^{2-}	596	6.69	779	8.32
$Sr_2{}^+$	763	9.4	4,153	48.6
TDS	183,037	6379	144,748	4667

– below detectable levels

Water collected for the Thiel and Lienhard (2014) study was analyzed for elements commonly found in PFW including: aluminum (Al), arsenic (As), barium (Ba), beryllium (Be), bicarbonate (HCO_3^-), boron (B), bromide (Br^-), cadmium (Cd), calcium (Ca), chloride (Cl^-), chromium (Cr), cobalt (Co), copper (Cu), iron (Fe), lead (Pb), lithium (Li), magnesium (Mg), manganese (Mn), mercury (Hg), molybdenum (Mo), nickel (Ni), K, selenium (Se), silver (Ag), sodium (Na), strontium (Sr), and sulfate (SO_4^{2-}). Analytes not listed in the table were below the detection threshold.

Conditions for Optimum Biogas Production

Despite the advantages of AD, such as reducing anthropogenic CO_2 and CH_4 emissions, it is a process that is complex, sensitive, and has a high rate of failure even when perfect conditions exist (Amani *et al.*, 2010). The choice of substrates, environmental, and operational conditions can all predict success or failure of digester performance (Esposito *et al.*, 2012). The AD process is considered successful if the headspace concentration of gases is 65-70% CH_4, and 30-35% CO_2 (Amani *et al.*, 2010; Weiland, 2010a). Although there are established guidelines to promote successful AD; it remains a complex process as evidenced by numerous contradictory study findings, especially regarding mixing, pretreatment, and moisture content (MC; Amani *et al.*, 2010). The optimum conditions examined in this section are for conditions established for AD with cattle manure and freshwater. There is no literature available to reference for AD with PFW and cattle manure.

Volatile Solids and B_0

The VS content in manure is the driving variable for methane production, and will vary with cattle diet (Hashimoto *et al.*, 1981; Dustan, 2002). Methane B_0 (m^3 CH_4 kg VS^{-1}) is defined as the ultimate methane yield that can be produced per mass of volatile solids (VS; Hashimoto *et al.*, 1981; Dustan, 2002). The amount of methane produced is directly proportional to the B_0 (Hashimoto *et al.*, 1980). Hashimoto *et al*. (1981) found that B_0 decreases as the silage content of the diet increases. Silage contains more cellulose and lignin than corn. Lignin and hemicelluloses that can slow the anerobic digestion process (Triolo *et al.*, 2011). Ruminant excreta are high in concentrations of slowly digestible organic matter, as they are efficient in using the carbon components in their feed (Triolo *et al.*, 2011). Methane B_0 also decreases with the amount of time the manure is stored on a dry lot, due to C losses to the atmosphere (Dustan, 2002).

Temperature

Anaerobic digestion can be carried out at psychrophilic (12-16°C), mesophilic (<40°C) and thermophilic (>45°C) temperatures (El-Mashad *et al.*, 2004). Hashimoto *et al*. (1981) reported that that more CH_4 is produced from beef cattle manures, and much higher loading rates of VS could be used, at thermophilic temperatures. Additionally, production of CH_4 is faster at thermophilic temperatures, as it speeds up the rate of hydrolysis, but there is little to no difference in the total production at mesophilic and thermophilic temperatures (Hashimoto *et al.*, 1981; Vindis *et al.*, 2009). Chen *et al.* (1980) found that temperatures above 60°C result in a decrease of CH_4 yield. Daily temperature fluctuation should be controlled as much as possible during the AD process, by <1°C in thermophilic digesters, and 2°C to 3°C in mesophilic digesters (Amani *et al.*, 2010).

Substrate Mixing

The substrate should be mixed regularly to ensure that the mixture is homogenous, solids remain in suspension, and for the prevention of crust formation. Adequate mixing allows for release of produced gas due to the prevention of crust formation (Kaparaju *et al.*, 2008). Inadequate mixing results in stratification and a formation of a floating layer of solids, which does not encourage an equal distribution of microorganisms, solids, and enzymes (Kaparaju *et al.*, 2008).

Substrate pH

Fermentative bacteria can survive and function in a wide range of pH, between 4.0 and 8.5 (Amani *et al.*, 2010). Methanogenic bacteria are extremely sensitive to low pH and acidic inoculum should be buffered before the startup of AD (Amani *et al.*, 2010). The optimum pH range for methane production is 6.5 to 8.2 (Alkaya and Demirer, 2011).

Methane Inhibition by Ammonia

The presence of excess ammonia (NH_3) concentrations either already present in the slurry or produced during the breakdown of organic matter can inhibit the activity of the microbes responsible for AD (Yenigün and Demirel, 2013). Methane formation from H_2 and CO_2 is inhibited by NH_3 during thermophilic AD but has little effect on the methane formation from acetate (Yenigün and Demirel, 2013). There is a greater correlation between high NH_3 concentrations in digesters operated at thermophilic than at mesophilic temperatures, and it is related to the pH of the substrate. An increased+ temperature theoretically leads to an increase in acid-producing and acid-consuming micro-organisms (El-Mashed *et al*., 2014). Certain methanogenic bacteria are more sensitive with 50% inhibition of methanogenesis occurring at 4.2 g/L NH_3-N (Jarrell *et al.*, 1987).

Effect of Salinity on Anaerobic Digestion

The research on salt concentrations and their effect on the AD process widely varies. Wilson *et al.* (2013) observed that hydrolysis rates were severely inhibited or eliminated with increased salinity. Iron salts are commonly used to remove chemical phosphorous and H_2S in wastewater treatment plants. The daily dosing of iron salts reduces the daily production of biogas as compared to untreated sludge (Ofverstrom, 2011). Jin *et al.* (2016) studied the effects of salinity on alkaline sludge at low temperatures; their research suggested that salt increases the hydrolysis rate of the organic matter. De Baere *et al.* (1984) found that while introduction of salts inhibited methane producing bacteria and methane production, the microbes were able to adapt to the environment and recover. The presence of methanogenic species is greater in freshwater sources than in brackish water sources (Tong *et al.*, 2017). Methanogen sensitivity to salts varies depending on the species. Growth and methane production are not inhibited by salt concentrations up to 263.7 mM in some species, while other microbes investigated are more sensitive to concentrations greater than 15.2 mM (Patel and Roth, 1977). *Methanobacterium thermoautotrophicum* use sodium for growth and methane production (Perski *et al.*, 1981). Methanogenic populations are diverse and change constantly in response to varying inhibitors (Williams *et al.*, 2013). Acid-using bacteria are more sensitive to sodium and salt ions than acetoclastic microorganisms (Gebauer, 2004). *Methanosueta* is the most prevalent methanogen at salt concentrations of 5 to 20 g Na L^{-1} (Sudmalis *et al.*, 2018).

Oxidation Reduction Potential

Oxidation reduction potential (ORP) determines the order of utilization that electron carriers such as O_2, NO_3^-, SO_4^{-2}, CO_2, and organic molecules will release or gain electrons. It also the reactions between anaerobic and aerobic limits, in the form of respiration that occurs in these carriers (Amani *et al.*, 2010). Anaerobic conditions are associated with reduction of electrons. Low ORP signals the release of electrons. The AD process will begin once ORP falls below -300 mV (Amani *et al.*, 2010). The optimum ORP range is -520 to -530.

Nutrients Required for Anaerobic Digestion

There are several nutrients required for successful AD. The optimal C:N ratio is 20:1 to 30:1 and relatively large amounts of P are required (Amani *et al.*, 2010; Esposito *et al.*, 2012). Cobalt, iron, nickel, sulfide, tungsten, selenium, barium, sodium, and molybdenum are all micronutrients that are required for microbial activity in AD (Amani *et al.*, 2010). Heavy metals can potentially inhibit acidogenic microbes. Heavy metals are not biodegradable and can accumulate to toxic levels. Acidogenic bacteria are particularly sensitive to bioaccumulation (Amani *et al.*, 2010).

Study Objective

The objective of the laboratory experiment was to evaluate the potential of generating bio-methane from a combination of PFW with dry-lot beef cattle manure in a controlled anaerobic digester laboratory setting.

Materials and Methods

Laboratory analysis of biogas production was conducted in the Environmental Agriculture Laboratory located in the Agricultural Sciences Complex at West Texas A&M University in Canyon, TX. Biogas and methane production potential was evaluated using beef cattle manure in combination with PFW, well water (WW), and a 50/50 mixture of WW and PFW. Produced/flowback water was evaluated at 65, 70, 80, and

90% MC. The WW and 50/50 mixture were evaluated along with PFW at 80 and 90% MC.

Water Collection

The PFW was collected from an oil and gas operation in the Northwestern Texas Panhandle. The exact treatment process of the water was proprietary, however general information was given about the reuse and recycle process for PFW. Wastewater for this operation was treated and reused a maximum of three times. After the third use, the wastewater was treated again, before injection into a Class II disposal well. Water for the study was collected following the final treatment and prior to injection into an offsite disposal well. The PFW was transported to the WTAMU research feedlot manure storage site. The PFW was stored in wastewater totes, until utilized in the anaerobic digesters. The WW was collected from the well at the research plots located on the WTAMU Nance Ranch. The well was purged prior to collection to remove any stagnant water in the line. The WW was not filtered, treated, or preserved prior to use in the project. A sample of the PFW, WW, and the 50/50 mixture was analyzed by B.A.T laboratories in Amarillo, Texas (Table 3). The water analysis on the PFW produced results for Br, Ca, K, Cl, Sr, SO_2^{4-}, and TDS similar to samples of PFW collected from the Marcellus Shale and Permian Basin. The notable differences are that the PFW collected for this study had detectable amounts of Al (1,170 mg L^{-1}) and Ba (16.5 mg L^{-1}) whereas the PFW in the Permian Basin and Marcellus Shale had levels for these elements that were below detectable limits.

Table 3: Water analysis results for the PFW, WW, and 50/50 mixture.

		Water Source		
	Units	**PFW**	**Well**	**Mix**
Ag	mg L^{-1}	ND	ND	ND
Al	mg L^{-1}	1,170	0.1	585
Antimony	mg L^{-1}	ND	ND	ND
As	mg L^{-1}	ND	ND	ND
Ba	mg L^{-1}	16.5	0.1	8.3
Br$^-$	mg L^{-1}	1,100	0.0	550
Ca	mg L^{-1}	5,940	13.0	2,976.5
Cl$^-$	mg L^{-1}	106,000	141.0	53,070.5
Chromium	mg L^{-1}	ND	ND	ND
Fe	mg L^{-1}	132.0	ND	66.0
K	mg L^{-1}	315.0	2.8	158.9
Pb	mg L^{-1}	ND	ND	ND
Mercury	mg L^{-1}	ND	ND	ND
Mg	mg L^{-1}	1,370	10.8	690.4
Mn	mg L^{-1}	11.7	ND	5.9
Na	mg L^{-1}	43,000	270	21,635
Na Absorption Ratio	mg L^{-1}	108.0	15.5	61.8
Silica	mg L^{-1}	ND	24.9	12.5
Sr	mg L^{-1}	2,000	3.4	1,001.7
SO$_4^{2-}$	mg L^{-1}	185.5	127	156.3
Tin	mg L^{-1}	ND	ND	ND
TOC	mg L^{-1}	9.0	ND	4.5
Vanadium	mg L^{-1}	ND	ND	ND
Zn	mg L^{-1}	ND	ND	ND
TDS	mg L^{-1}	151,000	2,870	76,935
Total Solids	mg L^{-1}	161,000	1,160	81,080
Total Alkalinity	mg L^{-1}	100	245	172.5
Carbonate Alkalinity	mg L^{-1}	0.0	80.0	40.0
Bicarbonate Alkalinity	mg L^{-1}	100.0	165.0	132.5
Hydroxide Alkalinity	mg L^{-1}	ND	ND	ND
Biological Oxygen Demand	mg L^{-1}	>98.3	< 2.0	50.1
CBOD	mg L^{-1}	> 94.9	< 2.0	48.5
pH	units	5.7	9.1	6.8
EC	µs cm^{-1}	160.0	114.4	94.0
ORP	mV	-18.40	-	-42.4

*ND, non-detect
- not collected

Beef Cattle Manure Collection

On October 15, 2018, approximately 1,500 kg of manure was harvested from the surface of pen #15 at the WTAMU research feedlot. The cattle housed in the pen were shipped the morning manure was collected. Manure is routinely harvested from the pens between shipping of finished cattle and receiving of new cattle and was done in this case as well. Collected manure was frozen (-20°C) and stored until utilization in the laboratory experiment. Manure MC was determined by the ASTM D 2974-87 method. Briefly, the wet weight basis method requires a minimum of 50 g sample to be weighed wet, then dried at 105°C for at least 16 hours to establish wet weight and dry weight. The MC of the sample was calculated on a wet weight basis (Eq. 12).

$$MC\ (\%) = \frac{Wet\ Weight\ (WW) - Dry\ Weight\ (DW)}{Wet\ Weight}\ x\ 100 \qquad \text{(Eq. 12)}$$

A composite manure sample was analyzed by Servi-Tech laboratories in Amarillo, Texas. The composition of manure was 43% TS, 24.6% VS, 57.2%VS/DM, total nitrogen was 10,000 mg/kg, and the C:N ratio was 14.2:1 (Table 4).

Cattle housed in pen #15 were part of a dietary supplementation study. The diet was analyzed at Servi-Tech Laboratories in Amarillo Texas. The diet fed to steers was 14.70% crude protein (CP). Major components were 37.30% steam-flaked corn and 43.50% Sweet Bran, with 0.98 Mcal/kg net energy maintenance (NEm; Table 5).

Table 4: Laboratory analysis results of manure collected from the WTAMU Research Feedlot.

Parameter	Manure
Total Solids (TS) (%)	43.0
Volatile Solids (VS) (%)	24.6
pH	9.13
Boron (g/kg)	9.0
Calcium (g/kg)	14,950
Cu (g/kg)	27.0
Fe (g/kg)	1,110
K (g/kg)	13,170
Mg (g/kg)	4,110
Mn (g/kg)	88.0
Na(g/kg)	4,540
Total Nitrogen (g/kg)	10,000
Organic Nitrogen (g/kg)	7,410
NH_4-N (g/kg)	2,590
NO_3+NO_2-N (g/kg)	4.3
P (g/kg)	5,870
S (g/kg)	2,900
Zn (g/kg)	132.0
C:N Ratio	14.2

Table 5: Diet composition of cattle fed in WTAMU Research Feedlot.

Ingredient Composition	Feed (%)	Feed	Std. Dev.
Corn Grain, Flaked	37.30		
Sweet Bran	43.50		
Corn Stover	4.30		
Cane Molasses	7.31		
Corn Oil	3.82		
Supplement	3.76		
CP	14.70		0.30
ADF	11.00		6.0
TDN	87.40		0.70
NEm, (Mcal/lb)		0.98	0.01
NEg, (Mcal/lb)		0.68	0.01
DM (TS)	69.90		0.30
P	0.54		0.04
Mg	0.30		0.01
K	1.19		0.08
S	0.32		0.04
Na	0.36		0.01
Zn (mg/kg)		63	16.0
Fe (mg/kg)		237	18.0
Mn (mg/kg)		46	1.0
Cu (mg/kg)		22	2.0

All Results Reported on 100% Dry Basis

Laboratory Anaerobic Digestion Experiments

Potential biogas and methane were evaluated for PFW, WW, and 50/50 mixture at four different moisture contents in three trials (Table 6). The first laboratory trial evaluated PFW, WW, and 50/50 mixture at 90% MC. The second trial evaluated the three water types at 80% MC. The third trial evaluated PFW only at 65% and 70% MC. The manure MC were chosen based on previous research and because of concerns with the use of large amounts of HPA well water required for anaerobic digestion (Posey *et al*., 1999, Parker *et al*., 2002).

Table 6: Trial number, trial start dates, duration (Days), MC, water source, and sample size (N).

Trial #	Trial Start Date	Duration (days)	MC (%)	Water Source	N
1	30-Nov-18	60	90%	WW	6
	30-Nov-18	60	90%	Mixture	6
	30-Nov-18	60	90%	PFW	6
2	29-Mar-19	60	80%	WW	6
	29-Mar-19	60	80%	Mixture	6
	29-Mar-19	60	80%	PFW	6
3	4-Jun-19	60	65%	PFW	8
	4-Jun-19	60	70%	PFW	7*

* There was one Ankom module failure, thus only 7 replications for this treatment

Laboratory Trial No. 1

Laboratory trial number one began on November 30, 2018 and was conducted for 60 days. Well water, PFW, and the 50/50 mixture were combined with 24 g manure (9.36 g VS) to bring the manure and water mixture to 90% MC. Eighteen glass bottles were utilized as anaerobic digesters for the manure and water mixture. There were six replications for each water type. One bottle served as a blank and was filled with deionized (DI) water. A zero module not connected to a bottle was used to measure the ambient temperature of the laboratory.

The total volume of the substrate was 250 ml. The total interior volume of the bottles was 620 ml. Total headspace volume of each digester was 370 ml. A sample was collected from each water type mixture to verify 90% MC with the ASTM D 2974-87 method. Initial pH, EC, ORP, and temperature were measured for each bottle using a Hach® sensION™+ MM 150 (Hach®, Loveland, CO). The pH of all prepared substrate was within acceptable range (7.0 ± 1.0), therefore buffer addition was deemed unnecessary (Alkaya and Demirer, 2011). Bottles were stirred until there was total mixture of solids.

The tops of the bottles were sealed with Ankom^{RF} Gas Production System (ANKOM® Technology, Macedon, NY). Modules to eliminate airflow and promote anaerobic conditions. Bottles were not purged with N_2 or CO_2, to avoid potential interactions with the unknown constituents in the produced water. Some research suggests that it may not be necessary to purge digesters, as O_2 dilutes CH_4 concentration, but does not inhibit production (Sheets *et al.*, 2015). The bottles were placed in a shaker incubator (Figure 5). The incubator temperature was set to 40°C. The shaker was set to maintain constant agitation of the substrate.

Figure 5: Shaker/incubator with Ankom^{RF} modules.

Temperature, absolute pressure, and cumulative pressure were collected every 30 minutes via radio frequency with the Ankom^{RF} module. The Ankom^{RF} system was set to release pressure in the modules once the pressure reached 10 psi. Pressure release was recorded, and cumulative pressures were adjusted accordingly by the software. Greenhouse gas samples were collected weekly from the sampling port on the bottles, with a Pressure Lok® Precision Analytical Syringe (Valco Instruments Co. Inc.®, Houston, TX). Samples were analyzed with an SRI 8610 C Gas Chromatograph (GC; SRI Instruments®, Torrence, CA) for CH_4 and CO_2.

At the conclusion of the experiment, gas concentrations were analyzed with the SRI 8610 GC and the Biogas 5000 (Landtec® North America, QED™ Environmental Systems, Dexter, MI). Gas measurements collected with the Biogas 5000 were CH_4, CO_2, and O_2% volume, static, differential and barometric pressures, H_2S, NH_3, and balance gas. Final pH, ORP, electrical conductivity (EC), and temperatures were collected.

Laboratory Trial No. 2

The second biogas experiment began on March 29, 2019 and was carried out for 60 days. Frozen manure was brought to room temperature for 24 hours prior to preparation of the substrate. Eighteen bottles were utilized as anaerobic digesters. There were 6 replications of each water type mixed with 24 g manure (9.36 g VS) to bring the substrate to 80% MC. The volume of the substrate was 200 ml and a headspace volume of 420 ml. Bottles were topped with Ankom^{RF} modules and, same as in trial number one, were placed inside the incubator shaker. The temperature was set to 40°C and the shaker was set to maintain constant agitation of the substrate. Data was collected as in trial one.

Laboratory Trial No. 3

The third laboratory trial began on June 4, 2019 and was carried out for 60 days. There were 8 replications each for PFW at 65% and 70% MC. After evaluating the amount of biogas and CH_4 produced in the first two experiments, the decision was made to focus solely on the production in PFW in the final trial as there was adequate literature to model WW in biogas production. Frozen manure was thawed for 24 hours at room temperature prior to preparation of the substrate. Substrate was prepared by the same procedure as experiments 1 and 2, by mixing 24 g feedlot manure (9.36 g VS) and water by water type to the desired 65% and 75% MC. The volume of the substrate in the 65% MC bottles was 100 ml and a headspace volume of 520 ml. The substrate volume of the 70% MC bottles was 150 ml, with a total headspace volume of 470 ml. Bottles were topped with Ankom^{RF} modules and, same as in trial number one, were placed inside the incubator shaker. The temperature was set to 40°C and the shaker was set to maintain constant agitation of the substrate. Data was collected as in trial one.

Data Analysis of Laboratory Experiments

Data Compilation and Conversion of Pressure to Gas Produced

For all three trials, average daily pressures and temperatures were compiled from the data collected in 30-minute intervals by the ANKOM ^{RF} system. For each bottle, gas production was calculated from the cumulative pressure recorded by the Ankom^{RF} system using the Ideal Gas Law (Eq. 13) and Avogadro's Law (Eq. 14).

Ideal Gas Law (Eq. 13)

$$n = p\ (V/RT)$$

Where: n = biogas produced in moles (mol)
p = pressure in kilopascal (kPa)
V = Head Space volume in the glass bottle (L)
T = temperature in Kelvin (K)
R = Gas Constant (8.314472 L*kPa*K^{-1}*mol^{-1})

Avogadro's Law (Eq. 14)

$$\text{Biogas produced in ml} = n \times 22.4\ \text{L/mol} \times 1000\ \text{ml/L}$$

Where: n = biogas produced in moles (mol)

Once the total volume of gas produced was calculated, the volume of each gas was determined from the results obtained with the GHG GC and the Biogas 5000. Where headspace gas measurements were recorded in mg L^{-1}, the measurements were converted to percentages to determine the volume of each gas present. Ultimate methane yield (B_0) was calculated for each module based on the measured volume of CH_4 and the mass of VS (equation 15).

$$B_0 = \frac{m^3\ CH_4}{kg\ VS} \qquad \text{(Eq. 15)}$$

Statistical Analysis

Data for all laboratory trials was analyzed with IBM SPSS 24.0 package (SPSS International, Chicago, IL). Descriptive statistics; minimum, maximum, median, means, and standard error of the mean were developed for numerical comparison of water combinations and MC. Regression model statements were developed for each water type to determine the relationship between mean CH_4 (ml) and MC. Mean CH_4 (ml) was the dependent variable and MC was the independent variable. Prior to the development normality of the data was evaluated. The data was not normally distributed; however data was not transformed prior to regression analysis. For the development of the regression model statements, curve estimation was used to determine the best line fit for regression. The greatest R^2 and lowest *p*-value was used to determine the best line fit for the regression equation (Appendix A). Parameter estimates for the regression equations were evaluated at $\alpha = 0.05$.

Results and Discussion

The results of cumulative biogas production were highly variable for every water type. Minimum and maximum values are evaluated for volume of CH_4 and B_0. The greatest amount of biogas was produced in the 50/50 mixture at the 90% MC (24,040 ml; Table 7). The least amount of biogas was in PFW at the 70% MC (322 ml; Table 7).

Table 7: Cumulative biogas (ml) production for PFW, WW, and the 50/50 mixture.

MC %	H_2O Type	Min	Max	Median	Mean	SEM
65	PFW	380	12,225	3,466	5,293	1,841
70	PFW	322	8,383	670	1,726	970
80	Well	494	22,633	11,837	12,170	3,246
	Mix	369	21,840	4,357	6,249	3,231
	PFW	352	14,260	890	3,060	2,252
90	Well	398	12,681	11,147	7,537	2,038
	Mix	459	24,040	2,720	5,008	2,736
	PFW	945	2,824	2,120	1,938	218

The greatest CH_4 headspace percentage (66%) was in PFW at 70% MC (Table 8). The second greatest headspace CH_4 percentage (62%) was in WW at 90% MC. The WW and PFW at 80% MC, PFW at 70% MC, and PFW at 90% all had anaerobic digesters with no detectable CH_4.

Table 8: Headspace CH_4 percentage by MC and water type.

		Headspace CH_4 (%)				
MC%	H_2O Type	Min	Max	Range	Mean	SEM
65	PFW	2	28	26	10.2	3.6
70	PFW	<0.1	66	66	20.6	8.8
80	Well	<0.1	24	24	16.2	3.7
	Mix	3	61	57	18.4	9.0
	PFW	<0.1	38	38	8.0	6.1
90	Well	1	62	60	31.9	6.8
	Mix	1	6	5	2.2	0.6
	PFW	<0.1	18	18	3.3	2.1

The greatest volume of CH_4 produced in all trials was with WW at 90% MC (4,590 ml; Table 9). The lowest volume of CH_4 was in PFW at 80% MC (0.08 ml). As MC increased, the amount of CH_4 present increased in WW digesters (Table 9). The greatest amount of CH_4 for WW was at 90% MC (6,780 ml). For PFW, the greatest CH_4 production was at 70% MC (5,573 ml), with 80% MC following closely behind (5,392 ml). The PFW at 65% MC (3,364 ml) had a greater maximum CH_4 production than at 90% MC (498 ml).

Table 9: Cumulative CH_4 for PFW, WW, and the 50/50 mixture.

		Cumulative CH_4 (ml)				
MC%	H_2O Type	Min	Max	Median	Mean	SEM
65	PFW	6.26	3,364	277	901	464
70	PFW	14.09	5,563	84	985	772
80	Well	0.27	5,525	2,281	2,568	894
	Mix	12.47	3,289	760	1,126	526
	PFW	0.08	5,392	18.6	924	894
90	Well	4.77	6,780	3,573	3,161	989
	Mix	3.67	1,322	51	204	160
	PFW	0.63	498	15	79	61

The greatest mean B_0 value was in WW at 90% MC (0.33 m^3 CH_4 kg VS^{-1}; Table 10). While there is no reference value at this time for B_0 with PFW, the B_0 values for WW were within the range of reference values that have been established in the literature. Hashimoto *et al* (1980) reported mean B_0 for beef cattle manure of 0.33 m^3 CH_4 kg VS^{-1} for fermentation at similar temperatures for this is experiment (40°C). Dustan (2002) reported that there was significant variation in the estimates of B_0 for cattle reported in the literature, with reported values between 0.17 to 0.285 m^3 kg VS^{-1}. Godbout *et al* (2010) reported that typical B_0 values fall between 0.17 to 0.33 m^3 CH_4 kg VS^{-1}. The lowest max B_0 values were in PFW at 90% MC and 50/50 mixture at 90% MC at 0.05 m^3 CH_4 kgVS^{-1} and 0.14 m^3 CH_4 kg VS^{-1} respectively. The greatest max B_0 for PFW was at 70% MC (0.59 m^3 CH_4 kg VS^{-1}).

Table 10: Ultimate methane yield (B_0) descriptive statistics by water type and MC.

		B_0 (m^3 CH^4 kg VS^{-1})					
MC%	H_2O Type	Min	Max	Range	Median	Mean	SEM
65	PFW	<0.01	0.34	0.34	0.03	0.10	0.05
70	PFW	<0.01	0.59	0.59	0.00	0.11	0.08
80	Well	<0.01	0.59	0.59	0.24	0.27	0.10
	Mix	<0.01	0.35	0.35	0.08	0.12	0.06
	PFW	<0.01	0.58	0.58	0.00	0.10	0.10
90	Well	<0.01	0.73	0.73	0.38	0.33	0.34
	Mix	<0.01	0.14	0.14	0.00	0.02	0.02
	PFW	<0.01	0.05	0.05	0.00	0.01	0.01

Model statements were developed in SPSS (Appendix B), on cumulative CH_4 (ml) for each water type to determine the relationship between CH_4 (ml) and MC. Methane (ml) was the dependent variable and MC was the independent variable. Cumulative CH_4 in all water types was not normally distributed across moisture contents. Curve estimation was used to determine the best line fit for regression. The greatest R^2

and lowest *p*-value was used to determine the best line fit regression equation (Appendix B). Parameter estimates for the regression equations were evaluated at $\alpha = 0.05$. The data is not linear or normal for WW; however, there was no improvement to the R^2 or the *p*-value with any non-linear model (Appendix B). The linear model was selected for WW as it is the simplest model ($\hat{y} = -2{,}174 + 59.286x$, $R^2 = 0.015$, $p = 0.676$; Table 11, Figure 6). For 50/50 mixture several models were evaluated. The best fit for the 50/50 mixture was an exponential model ($\hat{y} = 2.94E{+}09e^{-0.199x}$, $R^2 = 0.237$, $p = 0.083$; Table 11, Figure 7). The exponential model was the best fit for PFW ($\hat{y} = 343{,}662e^{-0.118x}$, $R^2 = 0.169$, $p = 0.025$; Table 11, Figure 8). The R^2 is not valid for the non-linear equations (PFW and 50/50 Mixture), and the parameter estimates are not a good indicator of fit (Neter *et al.*, 1996).

The regression statements supported the trend noted in the descriptive statistics for CH_4 volume produced based on MC (Table 11). For WW as MC increased the predicted amount of CH_4 produced increased by 59.30 ml (Table 11).

Table 11: Regression model statements for PFW, WW, and 50/50 mixture.

H_20 Type	Equation	R^2	*p*-value
WW	$\hat{y} = -2{,}174 + 59.30x$	0.015	0.676
Mix	$\hat{y} = 2.94E{+}09e^{-0.199x}$	0.237	0.083
PFW	$\hat{y} = 343{,}662e^{-0.118x}$	0.169	0.025

$\hat{y}$ = predicted methane yield (ml) for 60 days
x = moisture content (%)

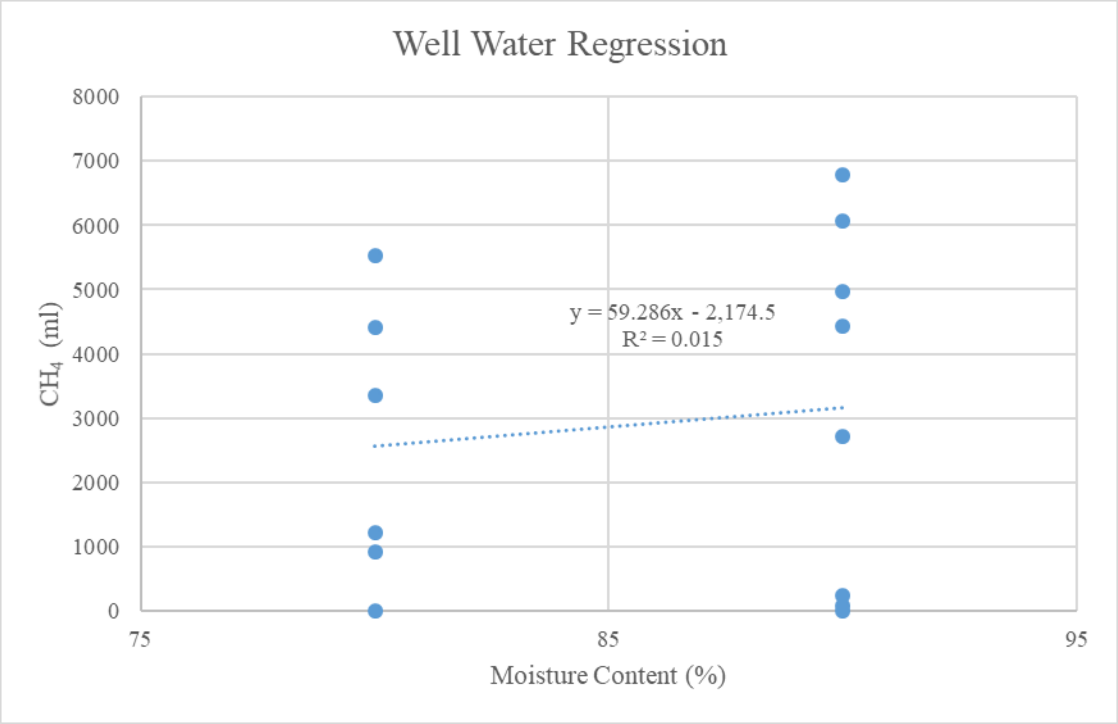


Figure 6: Well Water Regression

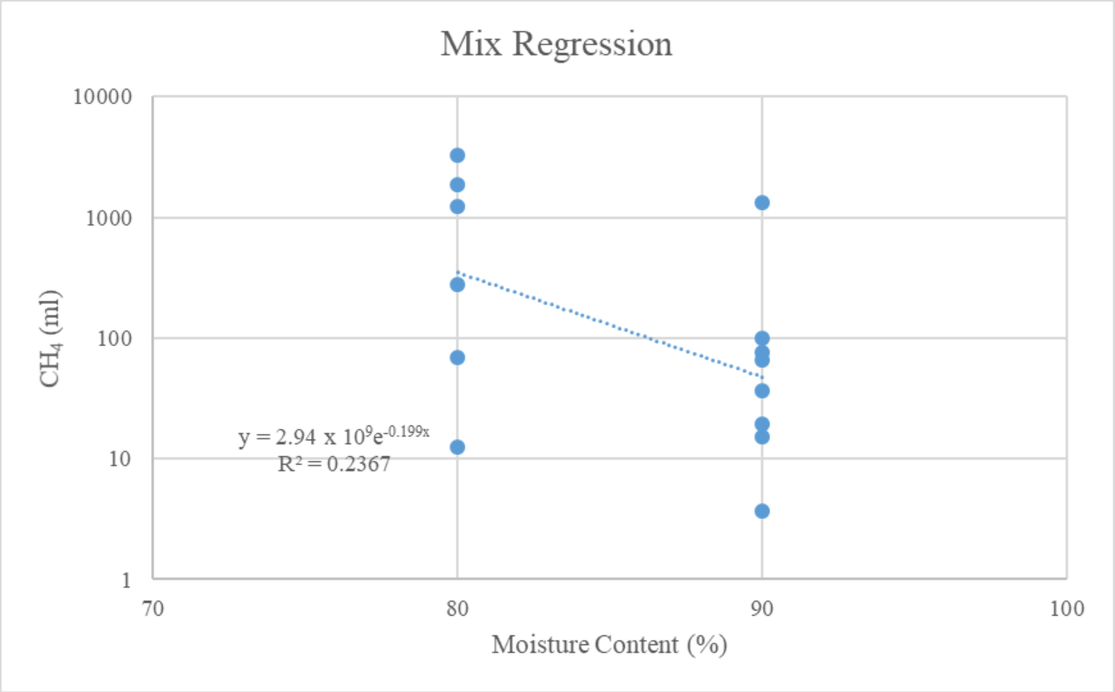


Figure 7: 50/50 Mixture Regression

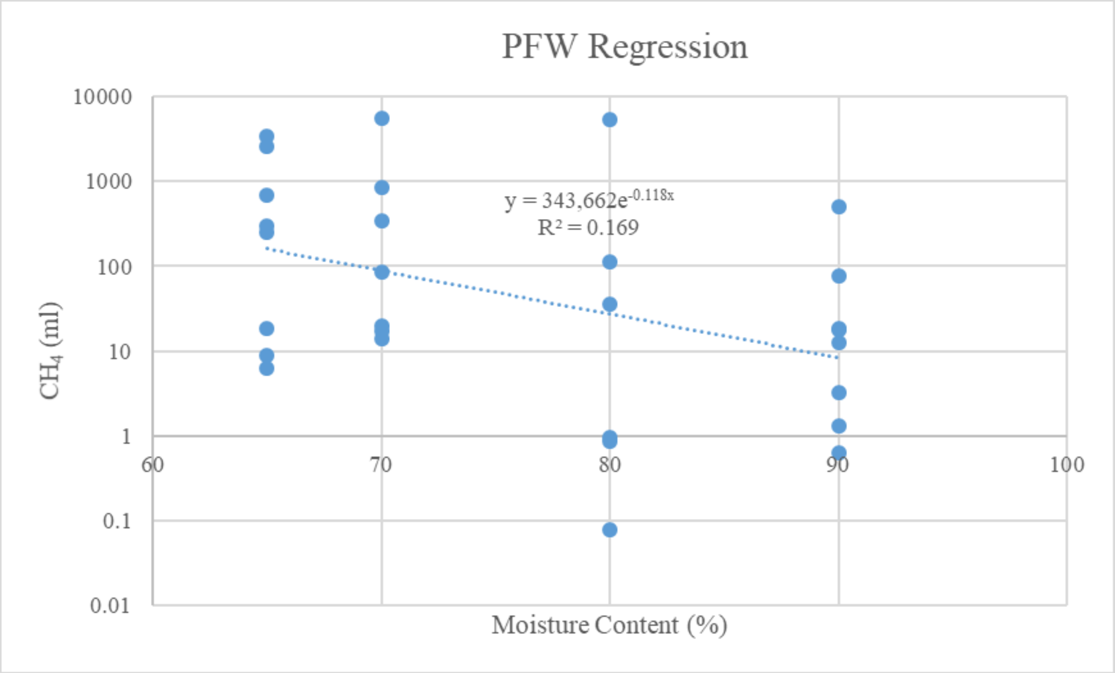


Figure 8: Produced and Flowback Regression

CHAPTER III: FEEDLOT ENERGY ESTIMATION MODEL

Systems Analysis

When a scientist with a specialization in one field carefully evaluates some causal or correlated relationship between isolated phenomena or components, they are potentially missing outside influences that are dynamically affecting the performance of that variable. Empirical studies are unable to fully depict or allow us to deeply understand the complex work and dynamic scenarios that occur within a system (Arnold and Wade, 2015). A system is more than a collection of its parts. A system is an interconnected set of elements that are coherently organized in a way that all the pieces work together (Meadows, 2008). Although many definitions of systems thinking exist, Arnold and Wade (2015) has defined systems thinking as “a set of synergistic analytic skills used to improve the capability of identifying and understanding systems, predicting their behaviors, and devising modifications to them in order to produce desired effects”. Systems thinking provides context for understanding complexity and transformation (Cavana and Mares, 2004).

System Components

Dynamic systems deal with phenomena that change over time and involve several components that interact together to cause a change in system behavior (Deaton and Winebrake, 1999). The major components of a system are state variables, control variables, feedback loops, and converters. State variables are reservoirs, or stocks, within systems. State variables are where the quantities of materials or information in a system are accumulated and can be measured at any given time (Hannon and Ruth, 2001; Meadows, 2008). State variables can act as a delay in a system and control the dynamic rates of a system (Meadows, 2008). Control variables (flows) are the exchange of material or information between stocks. Flows can add to stock material or reduce the amount of material in the reservoir (Hannon and Ruth, 2001). Flows act as controls of inputs or outputs of material or information from the stock. Feedback loops cause behavior that persists over time (Meadows, 2008). Feedback loops have material or information that constantly flow in and out of a steady state. Negative feedbacks lead to balance in a system, and positive feedbacks reinforce behavior (Hannon and Ruth, 2014). Convertors are variables that transform behavior in a system (Hannon and Ruth, 2014).

Causal Loop

The development of a causal loop is typically the initial step in systems analysis. A causal loop is a sequence of events that cause or lead to the next event, and whose last event is one of the causes of the first event. The events that make up a loop are not complete causes of one another, nor do they need to be complete effects of one another (Meyer, 2012). Causal loops are an important tool to help identify the feedback structure of a system (Sterman, 2000). The arrows within a causal loop go in a circular direction, but there might be additional arrows that lead into the circle, or arrows that lead out of it. If there are no arrows leading out of the boundaries of the loop, then it is a closed system (Meyer, 2012). The causal loop compartmentalizes the concepts of the system into something that can be measured and monitored, establishes links between related variables, and leads to the determination of reinforcing or balancing loops (Cavana and Mares, 2004).

The causal loop depicted in Figure 9 illustrates the transfer of energy between agricultural, biological, and ecological systems when using PFW as an alternative to fresh water in conjunction with beef cattle manure in biogas production. The system is open with boundaries established not to evaluate external variables which include economics, social perception, and atmospheric carbon. Arrows with (+) signs attached indicate an increase in the stock (storage) of the variable caused by the variable before the arrow. Arrows with (–) signs indicate a decrease in the stock of the variable caused by the variable before the arrow. The causal loop is based on theory and provides a framework for future empirical and process-based studies.

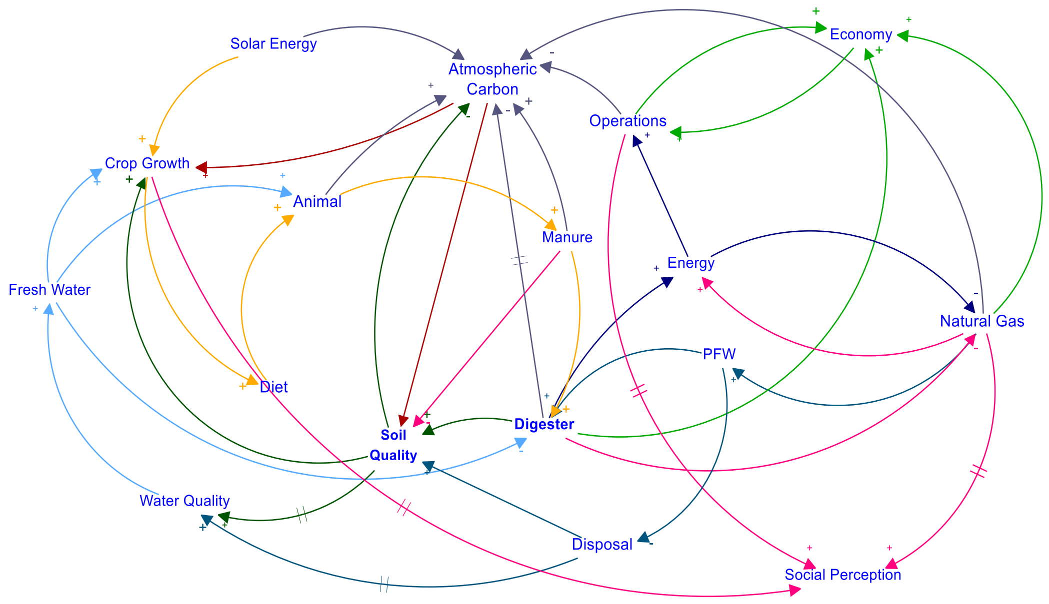


Figure 9: Causal loop of the energy transfer between systems when using PFW as an alternative to fresh water in biogas generation

All energy within a system originates with solar energy. Solar energy is converted to chemical energy through photosynthesis in plants. That energy is then transferred into the organism consuming the plant, and then to the animal or organism consuming that organism. The energy transfer never stops; it continues to transfer between variables in the system. When the manures produced by animals (beef cattle in the case of the feedlot) are immediately utilized for biogas production there will be a decrease in the loss of energy to the atmosphere, soil, and water sources. When PFW water is utilized instead of fresh water, there will be a decrease in deep-well disposal, soil and groundwater contamination, leading to an increase in water quality and a decrease in freshwater use. Decreasing freshwater use for anything other than agricultural or direct human use is imperative to preserve the groundwater resources in the Texas Panhandle.

The energy generated from the AD process increases the energy developed on site for a feedlot and decreases the amount of energy obtained from outside sources, and in turn decreases atmospheric carbon. The potential exists to share excess energy generated in an anaerobic digester with the economy. The captured carbon in the digester can be utilized to increase soil organic matter and provide nutrients for soil amendment, which improves soil quality. The high saline content of the PFW can potentially degrade the soil quality over time. This leads to an important area of future research that should be evaluated prior to using PFW in this manner. Soil quality and the availability of quality irrigation water is imperative for plant growth and crop production. Social perception, atmospheric C, economics, and soil quality are important areas for researchers, with concentrated expertise in those fields, to evaluate. These areas will drive the future potential of utilizing PFW in the generation of energy.

Dynamic Modeling

Dynamic modeling of real-world issues is fundamental to our understanding of how systems work. American physicist Heinz Pagels stated that modeling with computers is to the mind what the telescope and microscope are to the eye (Hannon and Ruth, 2001). Environmental and climate models help to make predictions that shape how decisions are made (Deaton and Winebrake, 1999). Dynamic models help to capture change in real or simulated time (Hannon and Ruth, 2014).

System interactions can be difficult to understand because the world system is made up of subsystems that are complex and interrelated. Models give us a conceptualization of reality that enable us to see structural and dynamic workings within a system (Hannon and Ruth, 2001). Models provide a simulated environment to experiment and run scenarios without the risk of changing a system. Models allow us to bypass risk aversion that may be present in making changes in a real system (Hannon and Ruth, 2014).

Models serve as a space to organize thought and develop a deeper understanding and help to predict or forecast system behavior (Hannon and Ruth, 2014). Models are in a constant state of revision, comparison, and change. Each simulation allows for a fundamental understanding of processes and interactions, and improvement (Hannon and Ruth, 2001).

Study Objective

The objective for this portion of the study was to simulate the potential energy that can be produced for the WTAMU Research Feedlot, with data collected from the laboratory bio-methane experiment and through the development of a quantitative dynamic energy model.

Feedlot Energy Model Development

The model was developed with the intention to be a user-friendly tool for producers to estimate the amount of fuel and/or electricity that can be generated from a digester system at their operation. One m^3 of CH_4 is the equivalent of 1 L (0.264 gallons) of diesel fuel, and 2 kWh of electricity (EIA, 2013). The model simulates the L of fuel and kWh generated from beef cattle manure and PFW, 50/50 mixture, or WW. The feedlot energy model (FEM) was developed with data collected in the biogas generation project, the Agricultural Waste Management Field Handbook (AWMFH), and peer reviewed literature. The model was developed for incorporation into the emergy model in the following chapter. The FEM was developed in Stella® Architect by Isee Systems©, 2019. Stella is a very powerful, yet easy to learn dynamic modeling software program (Hannon and Ruth, 2001). The FEM is a balance between empirical and process-based modeling. The model is simplistic in that the inputs and processes are limited but leave "hooks" for future research areas in collaboration with experts from the engineering, plant science, nutrition, economic, and social fields.

The boundary established for the FEM was limited to include energy production from manure produced by feedlot steers when mixed with WW or PFW. The FEM estimates the potential amount of fuel and/or electricity that can be produced for each water type analyzed in the laboratory study. The model excludes energy transfer to and from cropping systems, the energy required to run the digester, and energy from dietary input to steers.

Model Components

Stella uses some basic components as a conceptual framework to allow the model to input equations and relationships. Stocks, flows, modules, convertors, and connectors are presented in Figure 10. Transforming variables (converters) are represented by circles. Connectors, represented by arrows, provide the flow of information between a converter and a flow. Flows are valves that control variable input or output to the stock. The stock is the capital variable where information or resources are stored.

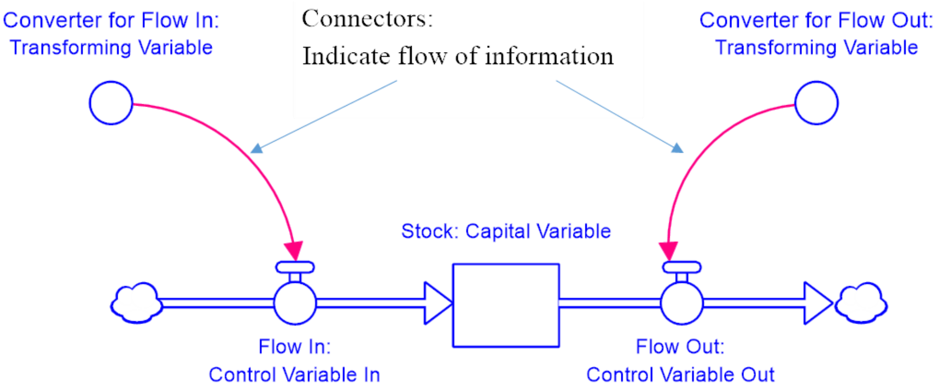


Figure 10: Model Components and Their Representative Figures

The FEM has two modules, the feedlot module and the energy production module. The feedlot module contains the feedlot manure production model. The energy production module contains the energy conversion to fuel and electricity model (Figure 11). Modules allow for compartmentalization of large models for ease of data input and evaluation.

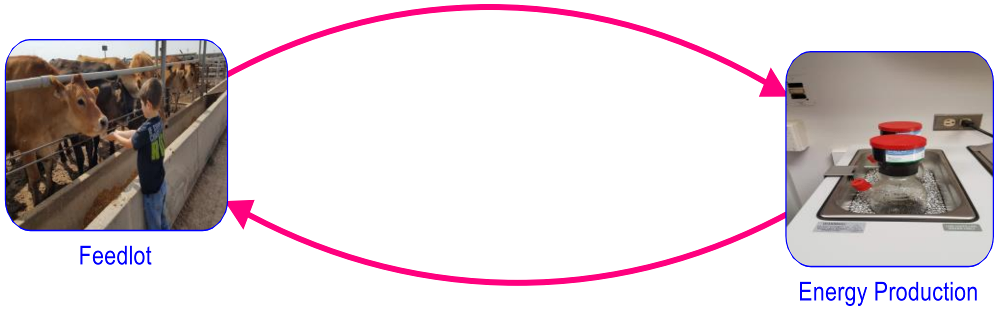


Figure 11: Feedlot Energy Model Depicting the Feedlot and Energy Production Modules

Feedlot Model

The feedlot model simulates the amount of manure produced at the WTAMU Research Feedlot on an annual basis (Figure 12). The WTAMU Research Feedlot is currently a 600 head capacity feedlot with 60 pens. Data on the amount of waste produced by a beef steer was obtained from Table 4-8(d) of the AWMFH (NRCS, 1999).

The model assumes full capacity at the feedyard throughout the year. The average weight of steers in the feedlot is assumed to be 408 kg. The weight is adjusted to an animal unit (454 kg). The daily production is multiplied by the number of days in a year (365) to obtain total annual manure production.

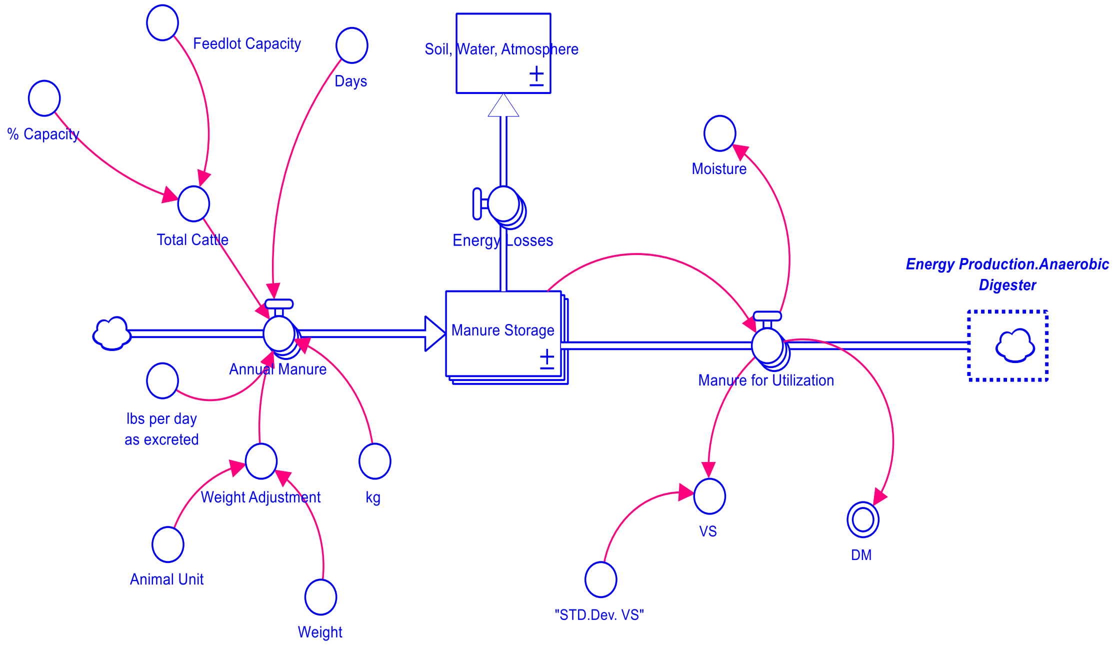


Figure 12: Feedlot Energy Model: Feedlot Manure Production

Exposure to air leads to rapid losses of CO_2 from manure to the atmosphere (Rotz *et al.*, 2014). Storage of manure can also lead to atmospheric losses of CH_4 if conditions become anaerobic. The number of days manure is stored is assumed to be zero for the purpose of the model. This assumption means that when manure is harvested from the pen it is immediately transferred to the digester, in order to capitalize on manure nutrients.

Manure for utilization is the flow of manure that will be utilized in the energy production model. The values for calculation of dry matter (DM) and moisture content are obtained from AWMFH, Table 4-8 (d; 1999). The VS value was obtained from empirical data collected in the biogas experiment. The standard deviation for the VS of the manure was obtained from literature. The manure for utilization flow is connected between the modules to the energy production model. All equations used and citations for equations in the feedlot model are presented in Appendix B.

Energy Production Model

The model provides a safe environment in which to simulate energy production with PFW without causing harm to the ecosystem and economy. The energy production model simulates the potential amount of energy in liters of fuel and/or kWh of electricity from the selected water type and feedlot manure (Figure 13). Regression statements for CH_4 (ml) were obtained from the laboratory biogas trial to simulate the ultimate methane yield in the model (Table 11). The model uses the 60-day data to simulate a year's worth of bio-methane production.

The MC of the manure (31.8%) was obtained from the manure evaluated in the biogas experiment. The empirical moisture content was similar to MC obtained from literature (Sweeten *et al.*, 2003). The standard deviation of the moisture content of the manure was calculated using values obtained from Sweeten *et al.* (2003).

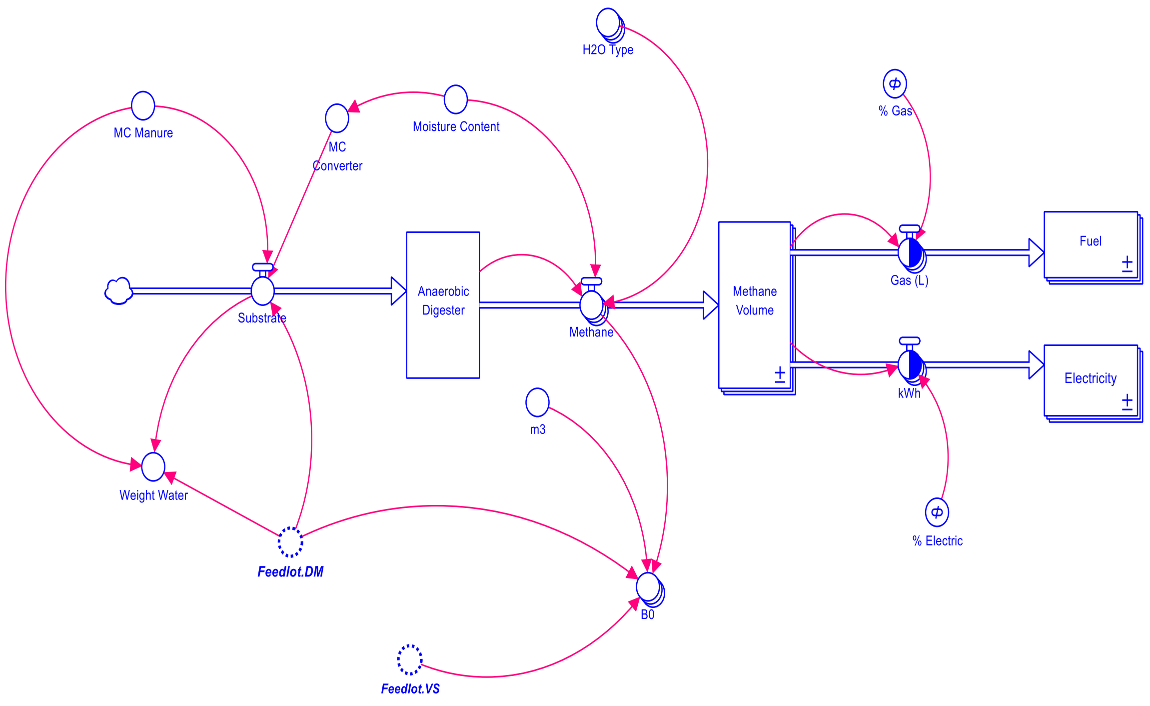


Figure 13: Feedlot Energy Model: Energy Production

The MC variable is adjusted to the desired MC for AD. Water type options are PFW, 50/50 mixture, and WW. An array was set up for the water type as an option that can be selected easily. The simulated amount of CH_4 produced is converted to cubic meters in the CH_4 flow. The B_0 values for each water type and manure calculations are developed from the CH_4 (ml) flow and are designed to be a check of the model based on results obtained in the biogas trials in Chapter 2. The weight of the water converter (Figure 13) calculated the amount of water to add to the digester at the selected MC.

The final product of the model is the potential amount of fuel produced and kWh of electricity in the feedlot with the different water types. The amount of fuel and kWh output can be adjusted for the desired percentage of each energy type. The model is set to simulate 50% electricity and 50% diesel fuel from the bio-methane generated.

Model Results and Discussion

The purpose of the Stella model was to simulate data to aid in managerial decisions related to feedlot management. The model allows for the evaluation of complex relationships with multiple variables. The model simulated manure and energy values for the feedlot for one year. With the model assumptions as described above, simulated rates of 5,180,000 kg of manure, 517,000 kg of DM, and 296,000 kg of VS were generated. The average of 100 simulations from the feedlot energy model are presented in Table 12.

Table 12: Simulated Annual Energy Production from the Feedlot Energy Model (50% Fuel (L) and 50% Electricity (kWh))

	Diesel (L)			Electricity (kWh)		
MC	WW	Mix	PFW	WW	Mix	PFW
60%	26,300	29,200	25,700	52,600	58,500	51,500
70%	37,500	39,600	69,600	71,500	79,200	139,200
80%	53,500	59,800	28,300	107,600	119,600	56,700
90%	71,500	37,200	8,300	143,000	37,200	16,600

These results are for raw CH_4 produced in the digesters and do not account for any cleaning/upgrading of CH_4. Per the simulation, WW at 90% MC, generated the greatest amount of fuel and electricity (71,500 L and 143,000 kWh, respectively). The least amount of energy simulated was from manure combined with the PFW water at the 90% MC (8,300 L of fuel and 16,600 kWh, respectively). Overall, the simulation predicted that the best option for generating CH_4 with the 50/50 mixture is at the 80% MC with 59,800 L of fuel and 119,600 kWh of electricity. According to the simulation, the best scenario for energy generation with the PFW is at the 70% MC. This combination will produce approximately 69,600 L of fuel and 139,200 kWh of electricity.

With 2 kWh of electricity a 100W light bulb can be powered for 20 hours (EIA, 2013). The skid steer currently in operation at the WTAMU feedlot has a 94 L fuel tank. Before cleaning/upgrading, the fuel amount simulated for one year will produce enough diesel to fuel a skid steer 636 times with PFW at 70% MC. Combining WW and manure at 90% MC will fuel the skid steer 760 times.

CHAPTER IV: EMERGY MODEL

Emergy Analysis

The earth's environment provides the necessary life support for society, economy, fertile soils, clean waters, clean air, good climate, healthy ecological systems, and aesthetic surroundings (Odum, 1996b). Energy is the flow of natural systems that links all living things together. Energy provides a common unit with which to assess all flows and materials (Odum, 1971).

The initial source of energy for the earth system is the sun. Emergy quantifies all inputs into a system by converting them to solar energy equivalents. This conversion allows for direct comparison of diverse inputs of renewable energies, human labor and economic goods needed to construct and maintain the energy production systems (Odum, 1996b). Emergy analysis is a holistic method of analyzing energy transfer that yields the greatest benefit to society (Campbell and Brown, 2012). Real wealth products have been generated from items occurring in nature and contain potential energy that can perform work. Emergy analysis is an energetic basis for quantification and assessment of the goods and services produced in an ecosystem (Hau and Bakshi, 2004).

The method uses the first law of thermodynamics to evaluate all forms of energy and materials in the form of a single solar unit, which is measured in Joules (J). The first law of thermodynamics states that energy entering a system can neither be created nor destroyed. Energy entering a system is either stored in state variables or flows outside of the system. Heat is a byproduct of the degradation of organic matter and release of energy (Odum, 1996a). Heat is measured in calories. A calorie is the amount of heat necessary to raise 1g of H_2O 1°C. Solar emergy (seJ) is the available solar energy used up directly and indirectly to make up a service or product (Odum, 1996b).

Emergy Evaluation Procedure

The first step is to very clearly determine the spatial boundary. The boundary provides a window of evaluation and establishes the problem being evaluated (Odum, 1996b). As in traditional systems analysis, the boundary is established with drawing a systems diagram (Figure 9). From this diagram, external variables that provide input into the system and accept output from the system are established. The energy transfer outside the system can be acknowledged but care should be taken to not analyze anything outside the established boundary.

The second step in emergy analysis is to gather the data for all renewable, non-renewable, purchased inputs, and products for the spatial area being analyzed. All data gathered are converted to a single solar energy (J) unit (Odum, 1996b). It is general practice in emergy analysis to leave the variable in weight units when the energy value for that variable is unknown.

The third step is to determine solar transformities for all variables being evaluated. A solar transformity is the amount of emergy required to make 1 J of a service or product. Transformity is the emergy per unit of available energy (seJ/J) (Odum, 1996a). Transformities are a critical link between the energy unit and the dollar value of a flow, and the emergy it took to create the original material (Sweeney *et al.*, 2007). Transformities increase as they move through the system. All transformities were obtained from literature. A complete list and citation information for transformities used in this analysis can be found in appendix C.

Following data collection, the inputs were entered into the emergy model developed in Stella® Architect (Isee Systems, 2018). The components of the model were the same as for the feedlot energy model in Chapter 3 (Figure 7). The general procedure is to include all major renewable flows in the initial analysis, but to use only the largest value for Total Renewable Flow (R; Odum, 1996b). Evapotranspiration and the geopotential of runoff are typically listed as separate line items; however, these items are frequently combined before applying the criteria of largest renewable flow because summing these flows is not considered double accounting (Sweeney *et al.*, 2007).

Once the energy units for all materials being evaluated are entered into the model, the fourth step is to divide the energy units by the transformity for that material. This determines the solar energy for all materials and resources being evaluated. Solar emergy is represented as solar emjoules (seJ).

The final step in emergy analysis is to calculate and evaluate emergy indices that relate emergy flows of the system being evaluated to predict fitness, carrying capacity, or economic viability. Money ($) in emergy analysis is not a representation of actual dollars, rather, it refers to the amount of emergy, environmental resources, and the economic activity that is required to produce a product or service. Emergy value is represented in terms of EmDollars (^{Em}\$). EmDollars are an information flow in an emergy model that is circulating in closed loops. The idea is that by increasing real wealth in the economy the buying power of the circulating currency is increased, and that wealth directly and indirectly comes from environmental resources. (Odum, 1996b). The emergy to money ratio (EMR) attaches the economic activitities of a society for a given year as measured by the Gross Domestic Product (GDP) for that nation (Odum, 1996).

Study Objective

The objective for this portion of the study was to conduct an emergy analysis to evaluate the environmental impact and sustainability of generating biogas from combined waste streams through the development of a quantitative dynamic emergy model.

Materials and Methods

The emergy and environmental accounting technique developed by Howard T. Odum (Odum, 1996b) was used in the development of the emergy model. Emergy evaluation was used to determine the relative sustainability and environmental impact of the transformation of energy from dry-lot beef cattle manure and PFW. The emergy model was used to quantitatively evaluate the primary ecological and economic assets of the WTAMU Nance Ranch area from an environmental perspective.

Spatial and Temporal Boundaries

The ecosystem evaluated (i.e. the spatial boundary) is the West Texas A&M University Nance Ranch (Figure 14), located at latitude 34.9704 N, longitude -101.8029 W. The ranch totals 9,684,127 m^2, and includes the ranch, the WTAMU Research Feedlot, the Small Plot Research Area, and several homes and buildings. The emergy model simulates the environmental sustainability of producing energy and nutrients for the entire ranch area with an anaerobic digester. The impacts of having a digester reach beyond the operations at the feedlot as all entities located within the ranch boundary are connected. Equipment use is shared among all entities of the ranch, the energy produced will be shared with the entire ranch area, and the land application of any slurry produced will occur within the confines of the ranch.

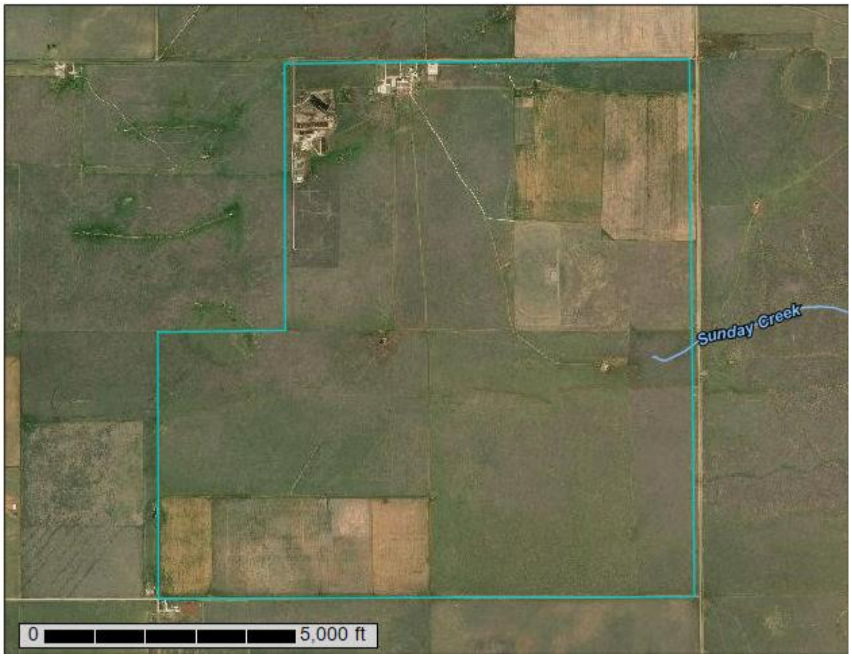


Figure 14: Boundary of Nance Ranch in Green (NRCS, 2009, Web Soil Survey)

Digester Options

The considerations for implementing energy from an anaerobic digester should be whether to replace or supplement natural gas, electricity, or diesel fuel and should include the construction and maintenance of the digester. While the AD process occurring inside the digester will produce energy, the digester will require energy to maintain temperature, operate the stirrer, and to upgrade/and or clean the biogas. There will be lower energy requirements in warm summer months, and greater requirements in the cold winter months. A digester on a dry beef lot will differ from a wet dairy facility in that there is not an opportunity to continuously feed water and manure into the digester. The model assumes that all manure is loaded immediately into the digester following harvest to reduce potential nutrient losses, as in the energy model.

Model Development

The modules of the model include non-renewable inputs, renewable inputs, purchased inputs, products, and WTAMU Nance Ranch (Figure 15). Emergy indices are simulated in the emergy analysis results module. The most recent information available for the inputs and outputs was used where possible. A full list of resources, citations, and calculations is presented in Appendix C.

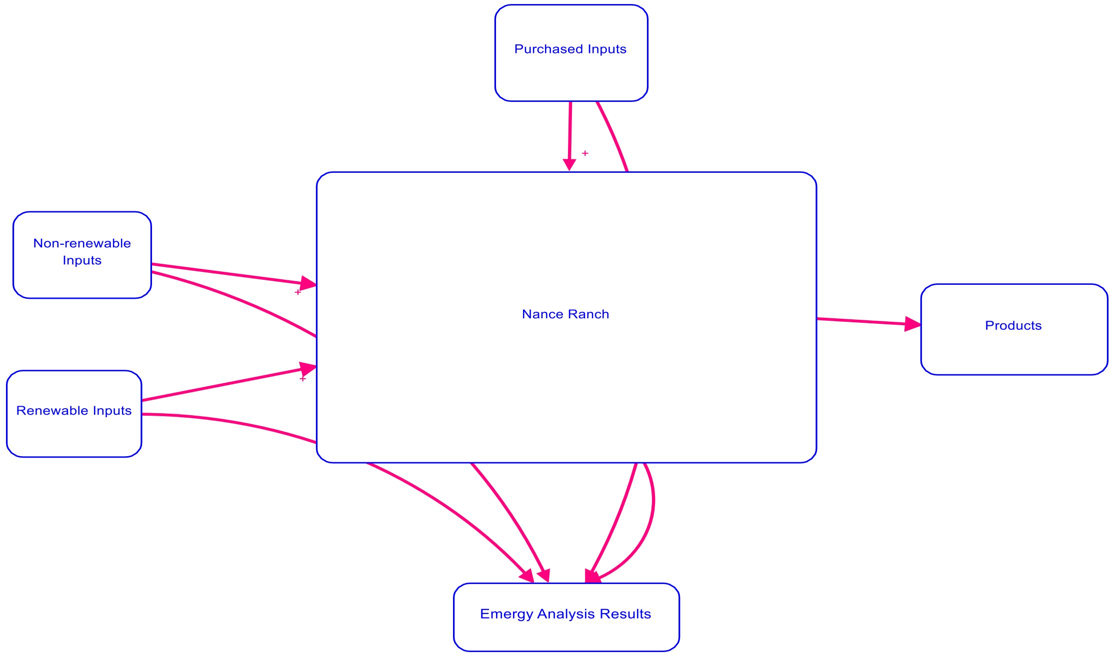


Figure 15: Emergy Model Modules

Renewable Emergy Model

The calculated renewable flows supporting the ranch area included solar insolation, wind, chemical and geopotential energy of rain, potential evapotranspiration (ET_0), and manure produced at the WTAMU Research Feedlot. A full list of data sources for the renewable inputs are presented in the calculation table in appendix C. Solar insolation, and albedo were obtained from NASA (Figure 16), rainfall was obtained from NOAA (NOAA, 2019), wind data was obtained from Weather Underground (Weather Underground, 2019).

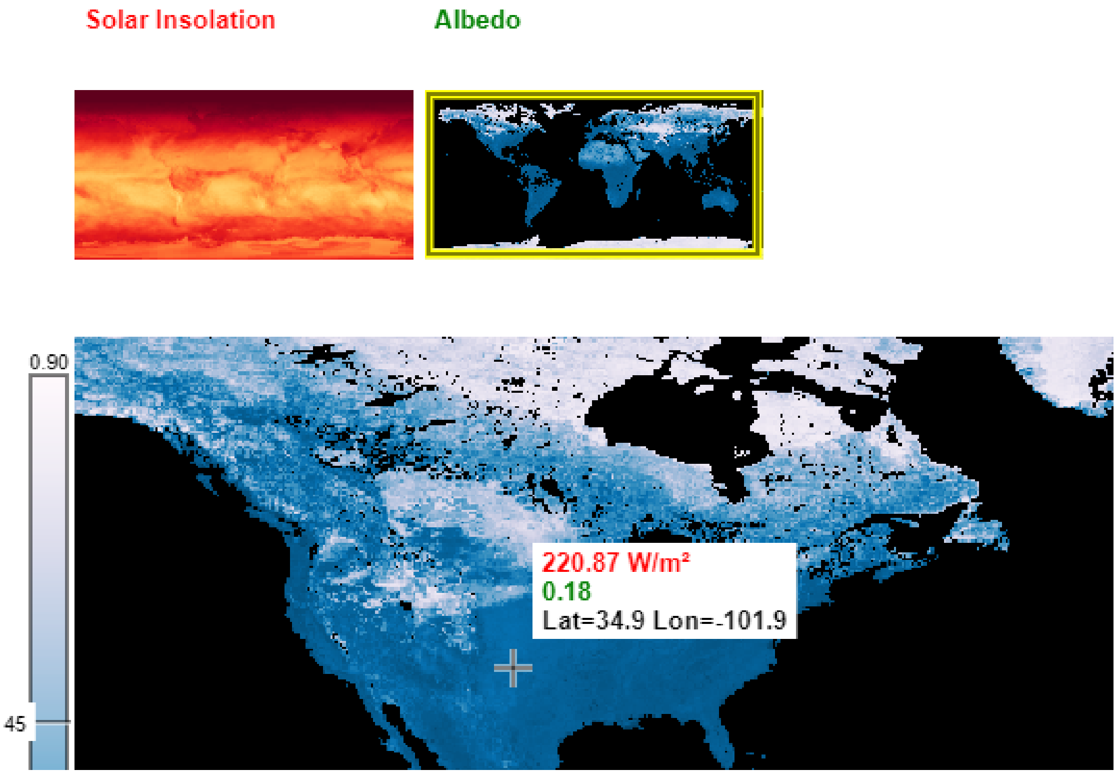


Figure 16: NASA Images of Albedo and Insolation Captured from the Terra/Modis Satellite (NASA, 2017)

Solar insolation is the rate of incoming sunlight (W) falling on every square meter during an indicated time period. When sunlight reaches the Earth's surface, some of it is absorbed and some is reflected. Albedo is the relative amount of light that a surface reflects compared to the total incoming sunlight (NASA, 2019). The solar insolation along with the renewable flow data was entered into the total renewable inputs model (Figure 17).

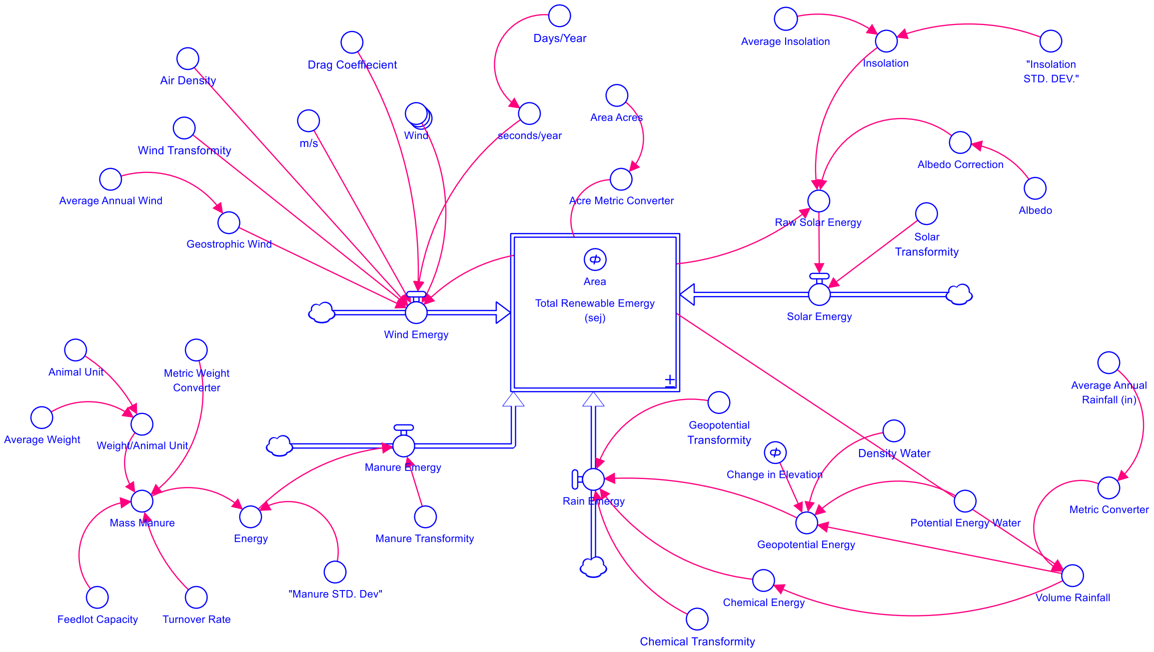


Figure 17: Total Renewable Inputs Model

Manure production data for the WTAMU feedlot was obtained from the FEM model developed in Chapter 3 of this study. Energy values for the manure were determined from literature (Sweeten *et al*., 2013).

Non-Renewable Emergy Model

The non-renewable inputs included soil loss and groundwater for the ranch area (Figure 18). While soil and groundwater can both be renewed over time, they are considered non-renewable for the purposes for the model because it would take to geologic time to replenish these resources. Groundwater is renewable in areas where recharge is equal to recharge, but that is not the case in the study area. Therefore, soil and groundwater are non-renewable for one lifetime. Information on annual soil loss was obtained from the NRCS (2009). The annual soil loss includes the amount of organic matter lost on an annual basis. Available groundwater information was obtained from High Plains Groundwater District (2009).

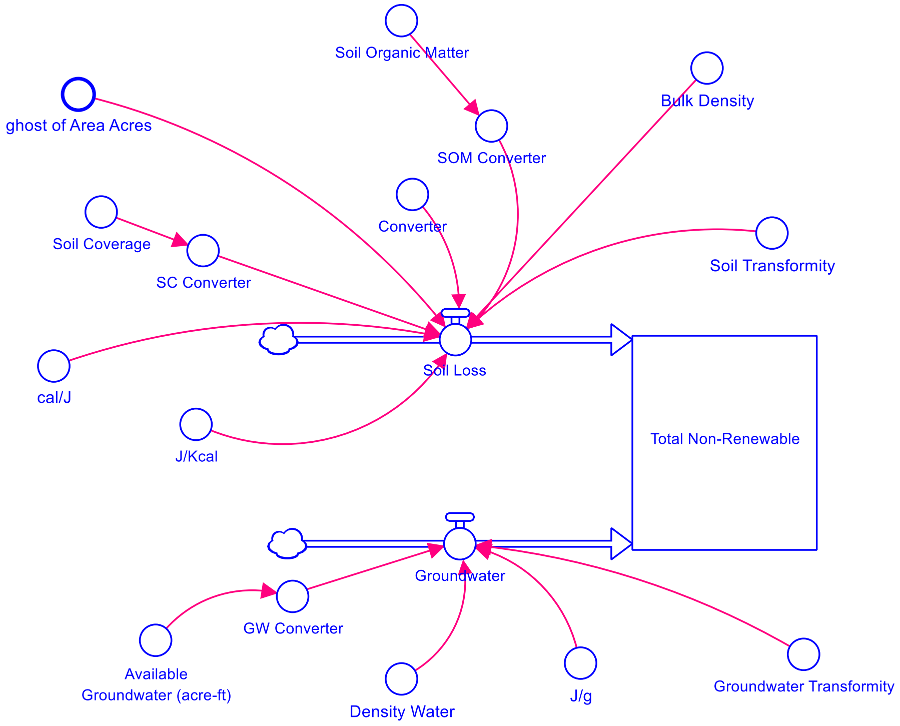


Figure 18: Non-Renewable Inputs Model

Total External Inputs Model

Total external inputs are items that are purchased or must be extracted for use. Total external inputs included petroleum, electricity, cattle, feed, water pumped, PFW, machinery, and digester construction materials (Figure 19). Cattle emergy, feed, and petroleum information was calculated with information obtained from Odum *et al.* (1987). Electricity usage for the ranch was estimated by calculating the average usage annually for a typical business and household for each building located on the within the ranch (EIA, 2019). Water usage for the feedlot was estimated as 40.9 L/head/d from literature (Parker *et al*., 2000). The energy used for irrigation was determined from a previously developed model that estimates energy for pumping groundwater (Campbell *et al*., unpublished data). Petroleum usage was estimated for the ranch by taking inventory of the equipment and researching the amount of fuel necessary to operate the equipment for a year. Digester construction material information was obtained from Ciotola *et al.* (2011). The energy of each external input was divided by its appropriate transformity within the model.

In previous emergy analysis studies, the when energy values were unknown the resource was left in weight units and not converted to energy units. A simple method for calculating the theoretical energy of an object, when the exact calorific value is unknown, is to use Einstein's theory of relativity. Einstein (1905) stated that the mass of a body is a measure of its energy content. A body gives off energy in the form of radiation and that radiation released from the body conveys inertia between the emitting and absorbing bodies. This method of determining energy streamlined several areas of the emergy model. The theory of relativity (Eq. 16) was used to calculate the energy of the equipment and building materials.

Einstein's theory of relativity (Eq. 16):

$$E = mc^2 \qquad \text{(Eq. 16)}$$

Where:

E = kinetic energy in Joules (J)
m = mass in kg
c = speed of light (m/s)

Annual inputs of renewable energy were divided by their appropriate transformity within the model. The transformation of solar energy to emergy (seJ/J) was performed according procedures developed by Odum (1996b). The three natural sources of renewable energy accounted for in the model were solar energy, chemical potential of rainfall, and manure to avoid double accounting of renewable inputs.

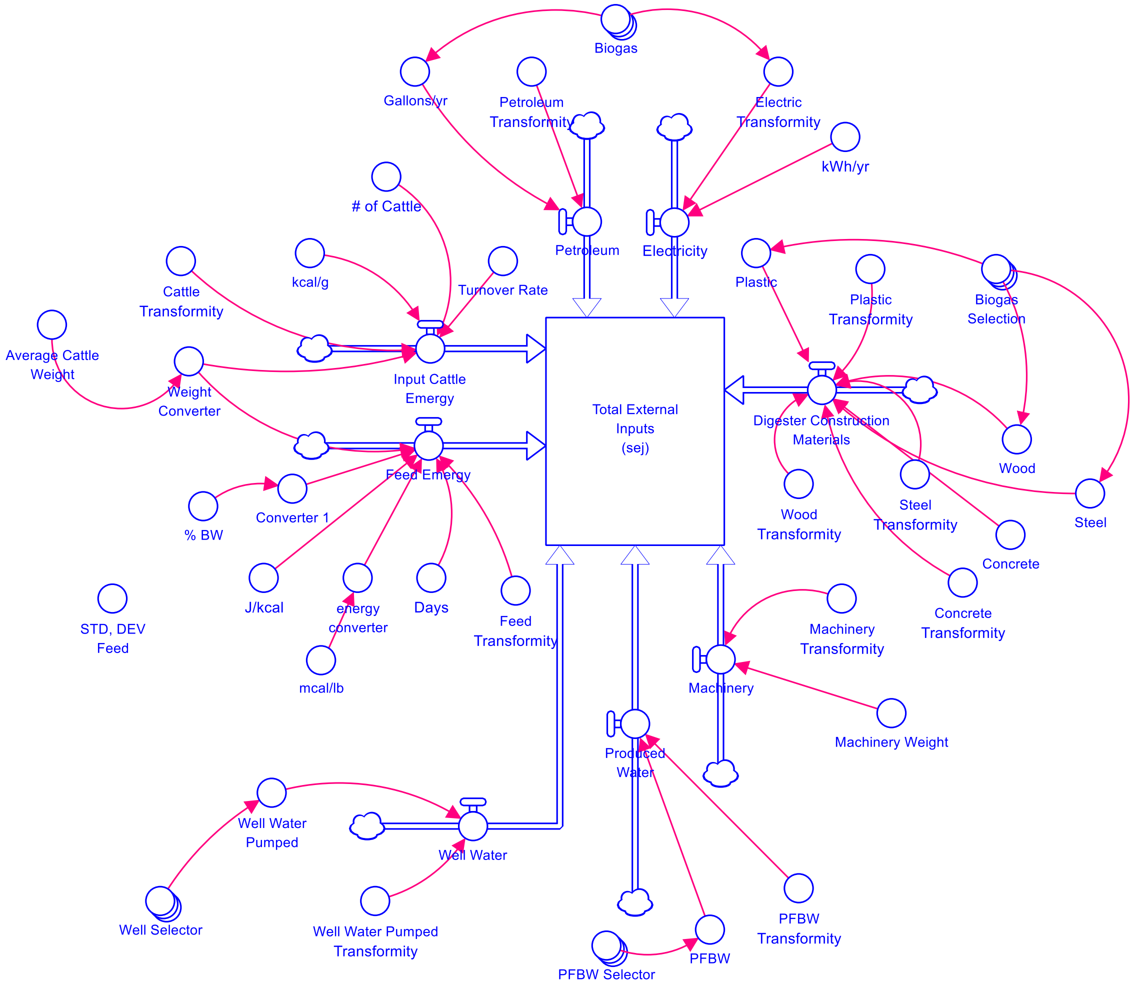


Figure 19: Total External Inputs Model

Total Emergy Outputs Model

Emergy outputs are products of the ranch that are exported. For the purpose of this model, they include fuel and electricity produced from energy production with the anaerobic digester (Figure 20). The energy for fuel and electricity was obtained from the feedlot energy model developed in chapter 3. Sludge nutrients (N & P) were obtained from the biogas generation study (Appendix A). Cattle energy information was obtained from a previous emergy analysis by Odum *et al.* (1987). The energy of each external input was divided by its appropriate transformity within the model.

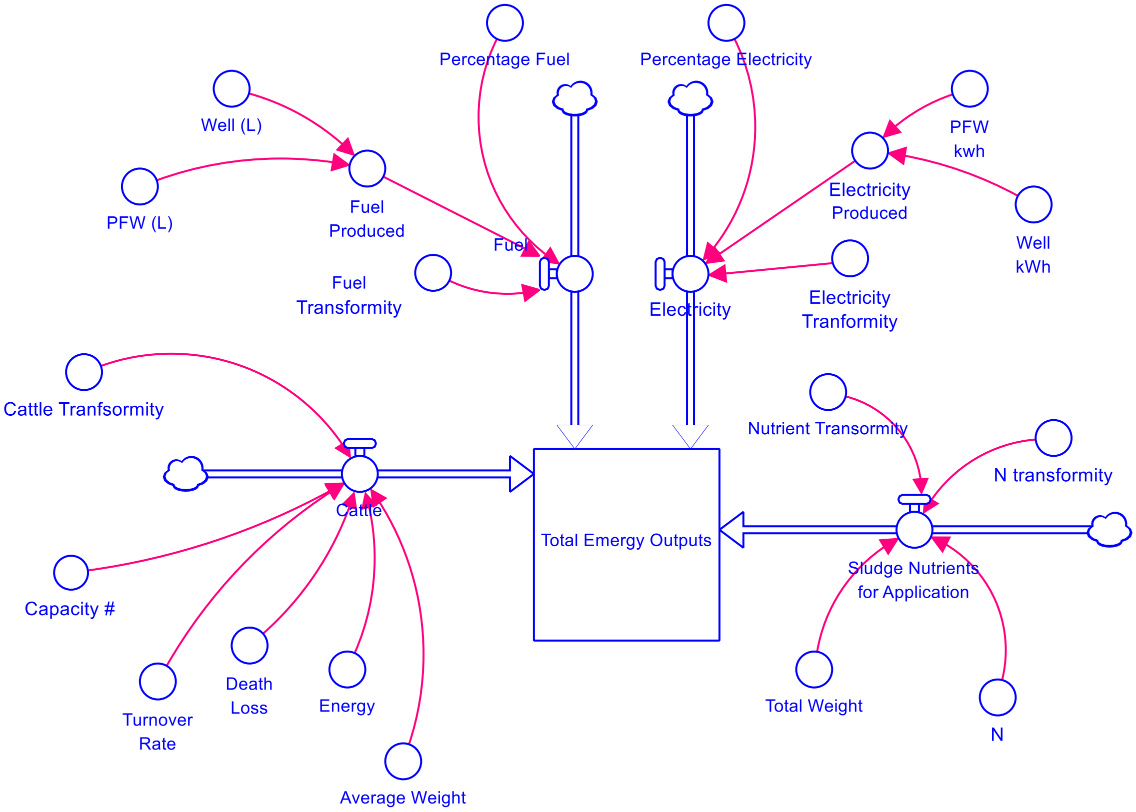


Figure 20: Total Emergy Outputs Model

Nance Ranch Model

Inside of the Nance Ranch module, all data simulated by the renewable, non-renewable, external inputs, and outputs are collected to provide total emergy from inputs minus the total emergy of the output (Figure 21).

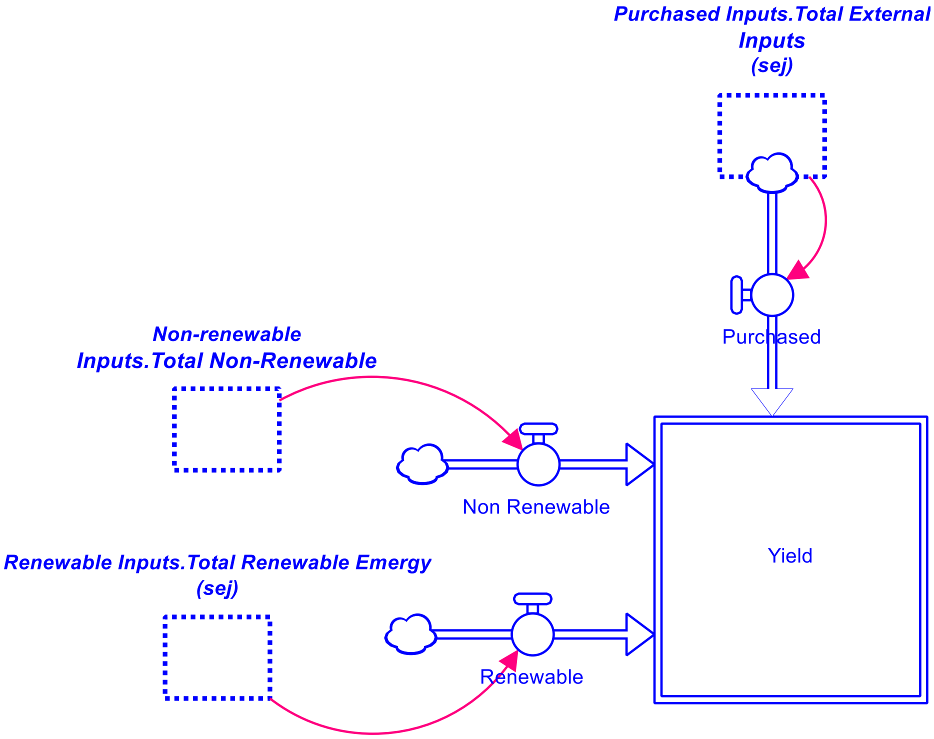


Figure 21: Nance Ranch Model: Total Inputs

Simulation Results

The average of 100 simulation results from the Nance Ranch Model are summarized in Table 13. The emergy/money ratio (EMR) is calculated by dividing the total amount of emergy from all sources for the US for one year, by the gross domestic product (GDP) for the corresponding year in accordance with Odum (1996b; Appendix C). The year 2014 was used in calculating this ratio, as it is the most recent year available for total annual emergy for the US (NEAD, 2019). The ^{em}\$ is calculated by dividing the total solar emergy of a flow, such as manure emergy, by the EMR. In general, as the ^{em}\$ increases the value of the material to the ecosystem increases. Conversely, as the ^{em}\$ decreases, the value of the material to the ecosystem decreases.

There are several line items of interest from the analysis. The manure at the feedlot has a solar emergy value of 6.78 E+12 seJ year^{-1} but has a very low ^{em}\$ value at ^{em}\$4.02E+00. This implies that there is environmental value in manure when it is not in storage. The longer manure remains in storage the more value it loses. The emergy value of cattle is 3.61E+07 seJ year^{-1} and the associated ^{em}\$ value is ^{em}\$2.14E-05. This would indicate that the number of cattle in the feedlot is not sufficient to support the ecosystem alone. The emergy of the groundwater is 7.24E+08 seJ year^{-1}, and the associated ^{em}\$ value is ^{em}\$4.29E-04. It has been stated that groundwater has more *environmental* value in the ground than it does when it is pumped for irrigation (Odum, 1996b). Water from the HPA has 10 times more emergy value than we pay for its extraction (Odum, 1987). The ^{em}\$ value of ^{em}\$4.29E-04 seems reasonable for the area of the WTAMU Nance Ranch given that the annual amount of ET_0 exceeds the annual amount of rainfall in this area, and the amount of discharge from the aquifer exceeds the recharge rate.

The results of the Stella model (Table 14) showed that the emergy value of the ranch without biogas production is 1.52E+14 seJ and the associated ^{em}\$ value is ^{em}\$8.97E+01. The greatest emergy value is the biogas with WW option (2.01E+14 seJ with an associated ^{em}\$ value of ^{em}\$1.19E+02). The emergy value of the ranch with energy production utilizing PFW is 1.58E+14 seJ and the associated ^{em}\$ value is ^{em}\$9.38E+01. The simulation results indicate that adding a digester adds both emergy to the ecosystem and environmental value to the ranch system. The emergy model simulations agree with the results of the energy model in Chapter 3. There is more energy produced in an anaerobic digester with WW, and this would result in greater emergy in the system.

Table 13: Simulated Emergy Results of Select Flows Supporting WTAMU Nance Ranch

Item	Raw Value	Solar Emergy	Emergy Value
	(J)	(seJ)	(^{Em}\$)
Renewable			
Sunlight	1.52E+14	1.52E+14	8.97E+01
Rain Chemical Potential	1.21E+14	1.03E+10	6.07E-03
ET_0	1.52E+14	2.38E+10	1.41E-02
Manure	1.15E+19	6.78E+12	4.02E+00
Non-renewable			
Soil Loss	1.25E+09	7.44E-01	4.40E-13
Groundwater	1.15E+14	7.24E+08	4.29E-04
Purchased inputs			
Petroleum products (oil, gas)	5.92E+11	6.81E+06	4.03E-06
Electricity without digester	1.37E+08	4.69E+02	2.78E-10
Electricity with digester	2.72E+09	9.32E+03	5.52E-09
Machinery Equipment	6.98E+08	6.17E-02	3.66E-14
Feed	6.51E+12	9.57E+07	5.67E-05
PFW	1.13E+12	6.92E+06	4.10E-06
Digester Const. Materials	5.72E+12	1.09E+08	6.48E-05
Well Water Pumped	5.97E+11	3.76E+06	2.22E-06
Outputs			
Cattle	7.23E+12	3.61E+07	2.14E-05
Fuel PFW	9.39E+11	3.78E+06	2.24E-06
Fuel WW	9.64E+11	5.71E+05	3.38E-07
Electricity PFW	5.01E+11	1.72E+06	1.02E-06
Electricity WW	5.15E+11	1.76E+06	1.04E-06

Emergy Analysis Results Model

The emergy indices are calculated using the emergy analysis results model (Figure 22). Emergy indices are used to compare systems, predict trends and find which option will deliver more energy (Odum, 1987). All indices are calculated by procedures established by Odum (1996b). An explanation of the methods employed in the calculations of the indices are provided below with a summary of the results. The options for the WTAMU Nance Ranch were 1) without implementation of an anaerobic digester,

2) with the addition of a digester utilizing WW, and 3) with the addition of a digester utilizing PFW.

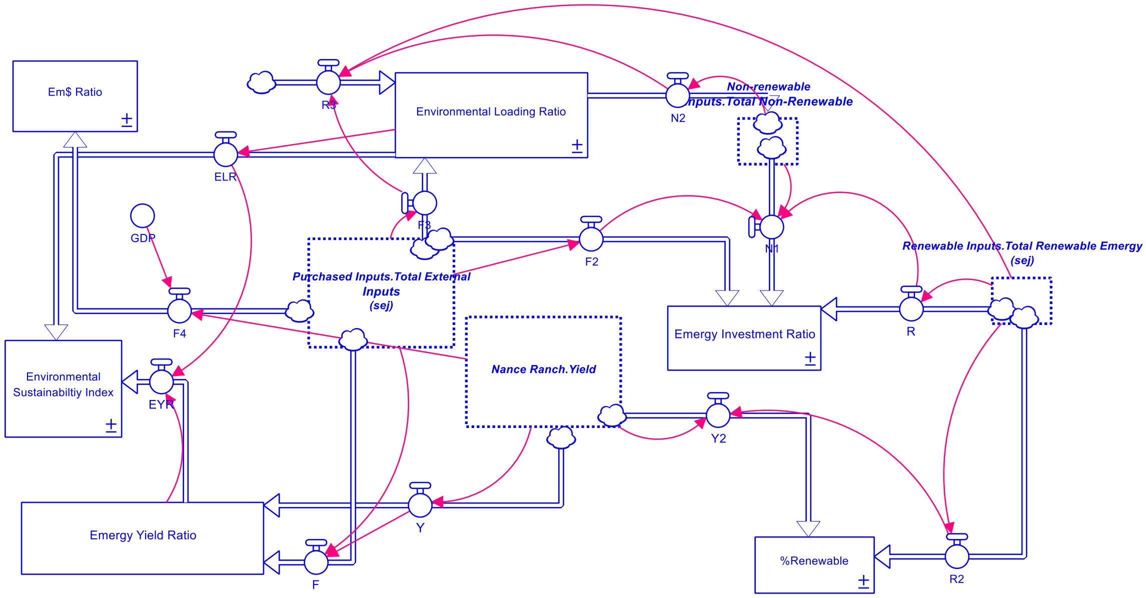


Figure 22: Emergy Analysis Results Model

Figure 23 depicts the flows for an environmental system along with their labels: renewable (R), non-renewable (N), purchased resources and services (F), and yield (Y). The indices can be calculated after the yield is calculated for the system being evaluated. The yield is calculated separately for each option. For example, the yield for biogas with PFW and WW does not include an input of outside petroleum products, and utilizes the manure produced as a renewable resource. The without biogas option does not include electricity with digester, PFW, or digester construction materials.

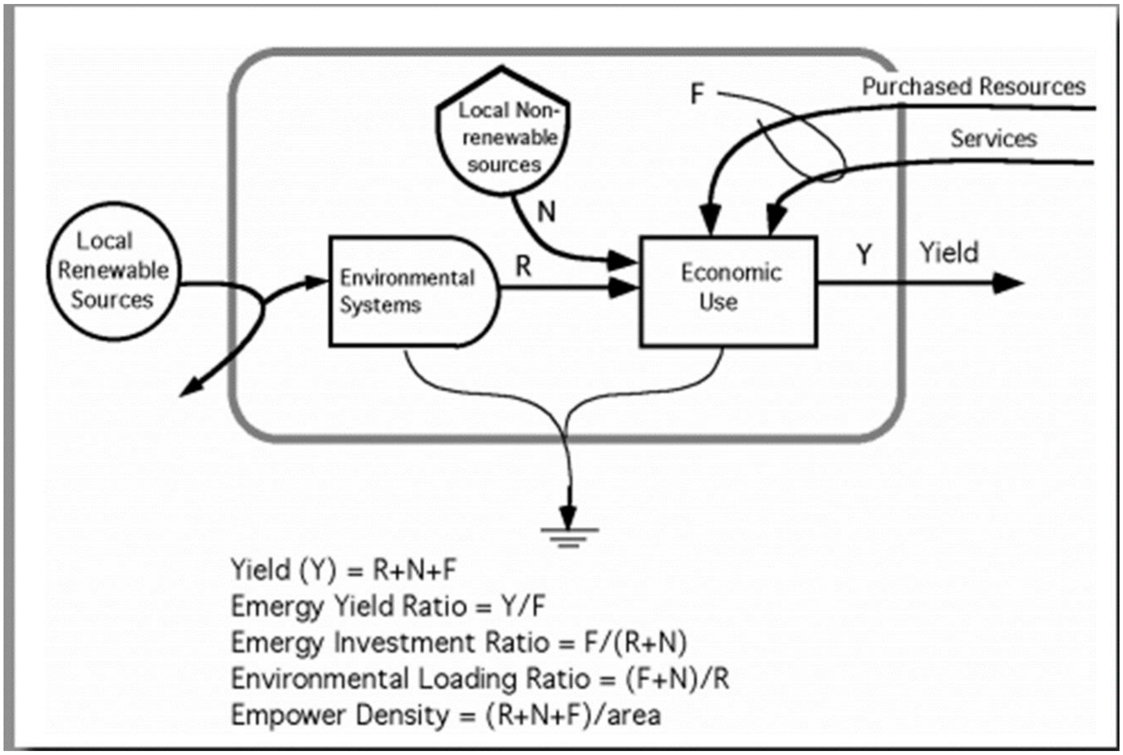


Figure 23: Diagram of Flows in Emergy Analysis and Their Labels (Brown and Ulgiati, 1997)

Percent Renewable

Percent renewable (%Ren) is the ratio of renewable emergy to the total emergy use for a flow. It is the percent of the total energy driving a process that is derived from total renewable sources (R/Y) (Brown and Ulgiati, 1997). The greater the %Ren the more sustainable an option is over time. The %Ren simulated by the model was 0.49 for no digester, 0.50 for a digester with PFW, and 0.44 for a digester with WW (Table 15). The simulated results indicate that an anaerobic digester with PFW is the most sustainable option over time.

Emergy Yield Ratio

The emergy/yield (EYR) measures the net contribution of an output to the economy beyond its own operation (Odum, 1996). The EYR is calculated by dividing the inputs of services and materials by the yield of that process (Y/F). The EYR is an indicator of how much a process can exploit local resources (Brown and Ulgiati, 1997). The greater the EYR the more it contributes emergy to the economy. The greatest EYR is for the digester with PFW option (5.28; Table 15). The lowest EYR is for no digester (1.08) followed closely by digester with WW (1.81). The ratio for no digester and WW digester means that they use almost as much resources from the economy as they produce (Odum, 1996b). A digester with PFW will provide more energy to support other activities.

Environmental Loading Ratio

The environmental loading ratio (ELR) is an indicator of the pressure that a transformation process will have on the environment. The ELR value provides an idea of the amount of stress an ecosystem will experience due to a transformation activity from a production process (Odum, 1996b). It is calculated by adding the non-renewable resources to the purchased services and resources and dividing by the renewable resources (ELR = (F+N)/R)). The ELR was lower for no digester (0.149) than PFW digester (0.166). The greatest ELR was for the WW digester (0.295; Table 15). According to these results the transformation stress to the ecosystem is greatest for having a digester with WW.

Emergy Sustainability Index

The emergy sustainability index (ESI) is the ratio of the emergy yield to the environmental loading ratio (EYR/ELR). Environmental sustainability, according the index, is a mutli-dimensional concept that evaluates the ability to maintain environmental assets over long periods of time. It also provides the ability to identify potential problems that arise from changing environmental conditions (Siche *et al*., 2008). The ESI measures environmental loading to the economy from the contribution of a material. The values of ESI vary between 0 and 100, with 0 being the least sustainable to 100 being the most sustainable (Siche *et al*., 2008). The ESI for no biogas was 7.25, biogas with PFW was 31.62, and biogas with WW was 6.14 (Table 14). Based on the simulation the most sustainable option was biogas with PFW.

Table 14: Simulated Emergy Indices from the WTAMU Nance Ranch Emergy Model

	Option		
Index	**No Biogas**	**Biogas (PFW)**	**Biogas (Well)**
Emergy Yield (seJ)	1.52E+14	1.58E+14	2.01E+14
% Ren	0.49	0.50	0.44
EYR	1.08	5.28	1.81
ELR	0.149	0.166	0.295
ESI	7.25	31.62	6.14

According to the simulation results, the addition of an anaerobic digester to Nance Ranch will improve the value of the ranch from an environmental perspective. While the WW value seemed to provide the most desirable results for the WTAMU Nance Ranch in terms of the amount of energy it produces; it does not provide the best option for sustainability long term. Based on these results the PFW option for a digester is the best long-term option from a sustainability perspective. These are simulated results that do not include an analysis for what environmental/ecosystem effects will be from the disposal of the sludge remaining after digestion. More research needs to occur on the long-term effects of using PFW in an anaerobic digester. A complete emergy analysis of the land application of the PFW sludge should be evaluated to give a more complete picture of the benefits or harms of installing an anaerobic digester using this wastewater.

Model Validation

Model validation is not possible in this study. Validation of the model to compare predicted values against measured values would require a massive data set from a range of environmental conditions (Rotz *et al.*, 2014). A data set of that type was not collected in this study and is not available at the present time. The model was utilized as a less formal tool, and as a guide to evaluate the potential of a new combination of waste streams in the generation of energy.

CHAPTER V: CONCLUSIONS AND RECOMMENDATIONS FOR FUTURE RESEARCH

According to the results from the biogas generation project and the two models developed, there is potential to generate biogas with wastewater from hydraulic fracturing and beef cattle manure. Results from the regression analysis indicate, for PFW, the CH_4 generation decreases as MC increases. The greatest amount of CH_4 with PFW was 5,525 ml. The greatest amount of CH_4 for all trials was in the WW-90% combination with 6,780 ml.

The feedlot energy model simulations predicted that the greatest amount bio-methane energy is generated with WW at 90% MC. According to the model simulations, the best scenario for energy generation with PFW is at 70% MC, and the worst was at 90% MC. This suggests there may be a toxicity effect at high PFW content. There are greater amounts of fuel and electricity produced with WW, but also at a greater cost to groundwater sources. Using PFW to either replace or supplement WW for AD is a viable option that will result in a reduction of freshwater use. Mixing the PFW with fresh water presents an opportunity to reduce freshwater use in AD by at least 50%. Reducing the use of fresh water for anything other than direct or indirect human consumption is imperative to preserving precious groundwater resources.

The emergy model simulation results indicate that the addition of an anaerobic digester to the WTAMU Nance Ranch will improve the value of the ranch from an environmental perspective. While WW produced the most energy, it does not appear to be the most sustainable option long term. The emergy analysis indicates that anaerobic digestion with PFW is the best long-term option from a sustainability perspective.

More research needs to occur to find optimum conditions for biogas production including the determination of optimum temperature ranges, moisture content variations and their impact on CH_4 produced, microbial behavior, and large-scale outdoor studies. This study replicated biogas production studies with optimal conditions for fresh water. Those conditions may not be optimum for biogas generation with this type of wastewater.

A study should be conducted to evaluate the potential long term environmental and ecological impacts that could arise from disposal of the sludge byproduct from AD through land application or other methods. The produced water acquired for this study had been pretreated prior to the use in the biogas experiment. Anyone using this type of water should be mindful of potential chemical reactions that can occur as a result of combining water treated at a municipal treatment facility and the water produced during hydraulic fracturing. Only untreated fresh water directly from a well should be used when mixing with PFW.

A current study is under way to evaluate the nutrients and heavy metals taken up by corn and sunflower. If the plants were successful at reducing salinity and pH of the soils, a thorough evaluation of potential toxic levels should occur to determine if heavy metals can or will impact animals and humans when digested through a life cycle analysis. If there are potential toxicological issues from the consumptions of the plants used to phytoremediate soils, an evaluation of the potential of co-digestion or use in ethanol production should be evaluated. The phytoremediation potential of cotton plants should be evaluated, as this is a crop used in both the agriculture and oil and gas industries.

A total energy analysis should be conducted to evaluate how much energy it will require to run the digester. A complete systems analysis that looks at more of the interactions and flows between cropping systems, oil and gas, range, economic impacts, and other livestock production facilities is imperative.

REFERENCES CITED

Abuhabib, A.A., Ghasemi, M., Mohammad, A.W., Rahman, R.A., El-Shafie, A.H., 2013. Desalination of Brackish Water Using Nanofiltration: Performance Comparison of Different Membranes. Arabian Journal for Science and Engineering 38, 2929-2939.

Achinas, S., Achinas, V., Euverink, G.J.W., 2017. A Technological Overview of Biogas Production from Biowaste. Engineering 3, 299-307.

Al-Mashhadani, M.K., Wilkinson, S.J., Zimmerman, W.B., 2016. Carbon dioxide rich microbubble acceleration of biogas production in anaerobic digestion. Chemical Engineering Science 156, 24-35.

Alkaya, E., Demirer, G.N., 2011. Anaerobic-fed and sequencing-batch treatment of sugar-beet processing wastes: a comparative study. Water Environment Research 83, 247-255.

Amani, T., Nosrati, M., Sreekrishnan, T., 2010. Anaerobic digestion from the viewpoint of microbiological, chemical, and operational aspects—a review. Environmental Reviews 18, 255-278.

Anukam, A., Mohammadi, A., Naqvi, M., Granström, K., 2019. A Review of the Chemistry of Anaerobic Digestion: Methods of Accelerating and Optimizing Process Efficiency. Processes 7, 504.

Arnold, R.D., Wade, J.P., 2015. A definition of systems thinking: A systems approach. Procedia Computer Science 44, 669-678.

Balali, H., Viaggi, D., 2015. Applying a system dynamics approach for modeling groundwater dynamics to depletion under different economical and climate change scenarios. Water 7, 5258-5271.

Ballentine, C.J., Lollar, B.S., 2002. Regional groundwater focusing of nitrogen and noble gases into the Hugoton-Panhandle giant gas field, USA. Geochimica et Cosmochimica Acta 66, 2483-2497.

Bastianoni, S., Marchettini, N., 2000. The problem of co-production in environmental accounting by emergy analysis. Ecological Modelling 129, 187-193.

Bergey, D.H., 1919. Thermophilic bacteria. Journal of bacteriology 4, 301.

Brown, M.T. and Ulgiati, S., 1997. Emergy-based indices and ratios to evaluate sustainability: monitoring economies and technology toward environmentally sound innovation. Ecological engineering, 9(1-2), 51-69.

Brown, C.J., Ward, J., Mirecki, J., 2016. A Revised Brackish Water Aquifer Storage and Recovery (ASR) Site Selection Index for Water Resources Management. Water Resources Management 30, 2465-2481.

Campbell, E.T., Brown, M.T., 2012. Environmental accounting of natural capital and ecosystem services for the US National Forest System. Environment, development and sustainability 14, 691-724.

Campbell, T., Dukes, B., Abdou Kadi, H., Tomczak, D., Wolf, N., 2017. The environmental and economic impacts of converting irrigated acres to dryland acres in the north plains ground water district. Unpublished.

Chen, Y., Varel, V., Hashimoto, A., 1980. Effect of temperature on methane fermentation kinetics of beef-cattle manure. Biotechnol. Bioeng. Symp, pp. 325-339.

Ciotola, R.J., Lansing, S., Martin, J.F., 2011. Emergy analysis of biogas production and electricity generation from small-scale agricultural digesters. Ecological engineering 37, 1681-1691.

Cooley, H., Donnelly, K., Ross, N., Luu, P., 2012. Hydraulic fracturing and water resources: separating the frack from the fiction. Pacific Institute, Oakland.

Crosbie, R.S., Scanlon, B.R., Mpelasoka, F.S., Reedy, R.C., Gates, J.B., Zhang, L., 2013. Potential climate change effects on groundwater recharge in the High Plains Aquifer, USA. Water Resources Research 49, 3936-3951.

De Baere, L., Devocht, M., Van Assche, P., Verstraete, W., 1984. Influence of high NaCl and NH4Cl salt levels on methanogenic associations. Water Research 18, 543-548.

Deaton, M., Winebrake, J.J., 1999. Dynamic modeling of environmental systems. Springer Science & Business Media.

Dustan, A., 2002. Review of methane and nitrous oxide emission factors for manure management in cold climates.

EIA, US, 2013. Annual energy outlook 2013. US Energy Information Administration, Washington, DC, 60-62.

EIA, US, 2017. Annual energy outlook 2015: with projections to 2040. US Energy Information Administration, Washington, DC.

EIA, US, 2019. Drilling activity report September 2019. US Energy Information Administration, Washington, DC.

Einstein, A., 1905. Does the inertia of a body depend upon its energy-content? Annalen der Physik 18, 639-641.

El-Mashad, H.M., Zeeman, G., Van Loon, W.K., Bot, G.P., Lettinga, G., 2004. Effect of temperature and temperature fluctuation on thermophilic anaerobic digestion of cattle manure. Bioresource technology 95, 191-201.

Engle, M.A., Cozzarelli, I.M., Smith, B.D., 2014. USGS investigations of water produced during hydrocarbon reservoir development. US Department of the Interior, US Geological Survey.

Esposito, G., Frunzo, L., Liotta, F., Panico, A., Pirozzi, F., 2012. Bio-methane potential tests to measure the biogas production from the digestion and co-digestion of complex organic substrates. The Open Environmental Engineering Journal 5.

Ferrer, I., Thurman, E.M., 2015. Chemical constituents and analytical approaches for hydraulic fracturing waters. Trends in Environmental Analytical Chemistry 5, 18-25.

Frape, S., Fritz, P., McNutt, R.t., 1984. Water-rock interaction and chemistry of groundwaters from the Canadian Shield. Geochimica et Cosmochimica Acta 48, 1617-1627.

Gallegos, T.J., Varela, B.A., Haines, S.S., Engle, M.A., 2015. Hydraulic fracturing water use variability in the United States and potential environmental implications. Water Resources Research 51, 5839-5845.

Gebauer, R., 2004. Mesophilic anaerobic treatment of sludge from saline fish farm effluents with biogas production. Bioresource Technology 93, 155-167.

Gebremedhin, K., Wu, B., Gooch, C., Wright, P., Inglis, S., 2005. Heat transfer model for plug-flow anaerobic digesters. Transactions of the ASAE 48, 777-785.

Godbout, S., Verma, M., Larouche, J., Potvin, L., Chapman, A., Lemay, S., Pelletier, F., Brar, S., 2010. Methane production potential (B0) of swine and cattle manures–A Canadian perspective. Environmental technology 31, 1371-1379.

Ha, T., Marfurt, K., 2017. Seismic reprocessing and interpretation of a fractured-basement play: Texas Panhandle. Interpretation 5, SK179-SK187.

Handford, C.R., 1980. Lower Permian facies of the Palo Duro Basin, Texas: depositional systems, shelf-margin evolution, paleogeography, and petroleum potential. Texas Univ., Austin (USA). Bureau of Economic Geology.

Hannon, B., Ruth, M., 2001. Dynamic modeling. Springer Science & Business Media.

Hannon, B., Ruth, M., 2014. Modeling dynamic biological systems. Modeling dynamic biological systems. Springer, pp. 3-28.

Hashimoto, A.G., Varel, V., Chen, Y., 1981. Ultimate methane yield from beef cattle manure: effect of temperature, ration constituents, antibiotics and manure age. Agricultural wastes 3, 241-256.

Hau, J.L., Bakshi, B.R., 2004. Promise and problems of emergy analysis. Ecological modelling 178, 215-225.

Höök, M., Tang, X., 2013. Depletion of fossil fuels and anthropogenic climate change—A review. Energy Policy 52, 797-809.

HPGWD, N.P.G., 2009. High Plains Groundwater District. The Ogallala Aquifer.

Jarrell, K.F., Saulnier, M., Ley, A., 1987. Inhibition of methanogenesis in pure cultures by ammonia, fatty acids, and heavy metals, and protection against heavy metal toxicity by sewage sludge. Canadian journal of microbiology 33, 551-554.

Jin, B., Wang, S., Xing, L., Li, B., Peng, Y., 2016. The effect of salinity on waste activated sludge alkaline fermentation and kinetic analysis. Journal of Environmental Sciences 43, 80-90.

Kaparaju, P., Buendia, I., Ellegaard, L., Angelidakia, I., 2008. Effects of mixing on methane production during thermophilic anaerobic digestion of manure: Lab-scale and pilot-scale studies. Bioresource technology 99, 4919-4928.

Khan, I.U., Othman, M.H.D., Hashim, H., Matsuura, T., Ismail, A., Rezaei-DashtArzhandi, M., Azelee, I.W., 2017. Biogas as a renewable energy fuel–A review of biogas upgrading, utilisation and storage. Energy Conversion and Management 150, 277-294.

Klimstra, J., 1986. Interchangeability of gaseous fuels—The importance of the Wobbe-index. SAE transactions, 962-972.

Lee, Y., Deming, D., 1999. Heat flow and thermal history of the Anadarko Basin and the western Oklahoma Platform. Tectonophysics 313, 399-410.

Lester, Y., Ferrer, I., Thurman, E.M., Sitterley, K.A., Korak, J.A., Aiken, G., Linden, K.G., 2015. Characterization of hydraulic fracturing flowback water in Colorado: Implications for water treatment. Science of the Total Environment 512, 637-644.

Li, Y., Park, S.Y., Zhu, J., 2011. Solid-state anaerobic digestion for methane production from organic waste. Renewable and sustainable energy reviews 15, 821-826.

Mata-Alvarez, J., Mace, S., Llabres, P., 2000. Anaerobic digestion of organic solid wastes. An overview of research achievements and perspectives. Bioresource technology 74, 3-16.

McGuire, V.L., 2017. Water-level and recoverable water in storage changes, high plains aquifer, predevelopment to 2015 and 2013–15. US Geological Survey.

Meadows, D.H., 2008. Thinking in systems: A primer. chelsea green publishing.

Mitchell, J., 2012. The Anadarko Basin: Oil and Gas Exploration–Past, Present and Future. Oklahoma Geological Survey. Oklahoma Structural and Stratigraphic Oil and Gas Workshop PowerPoint.

NASA, 2019. NASA Earth Observations. https://neo.sci.gsfc.nasa.gov/view

NASS, 2019. United States Department of Agriculture. National Agricultural Statistics Service, Washington, DC. Available at https://quickstats.nass.usda.gov/

NCBI, 2016. US National Library of Medicine. Bethesda, MD.

NEAD, 2019. National Environmental Accounting Database Center for Environmental Policy, University of Florida. https://cep.ees.ufl.edu/nead/index.php.

Neter, J., Kutner, M. H., Nachtsheim, C. J., & Wasserman, W. 1996. Applied linear statistical models. 4th ed. WCB McGraw-Hill, Boston, MA, 529-552.

NOAA, 2019. National Oceanic and Atmospheric Administration. Climate data and reports. https://www.noaa.gov/climate-data-and-reports

NRCS, U., 1999. Agricultural waste management field handbook. US Department of Agriculture, Natural Resources Conservation Service, Washington, DC. Available at: http://www. nrcs.usda.gov/wps/portal/nrcs/detailfull/national/technical/alphabetical/mnm.

NRCS, U., 2009. Web soil survey. URL http://www.websoilsurvey.ncsc.usda.gov/app/[verified October 29, 2009].

Odum, H., 1996a. Environmental accounting, emergy and decision making: Emergy evaluation. University of Florida 370.

Odum, H., Odum, E., Blissett, M., 1987. Ecology and economy: Emergy analysis and public policy in Texas. policy research project report 78, 178.

Odum, H.T., 1971. Environment, Power and Society, 1971. New York: Wiley Interscience.

Odum, H.T., 1996b. Environmental accounting: emergy and environmental decision making. Wiley New York.

Ofverstrom, S., and Regimantas Dauknys, 2011. The effect of iron salt on anaerobic digestion and phosphate release to sludge liquor. Mokslas: Lietuvos Ateitis 3, 123.

Pang, H.-C., Li, Y.-Y., Yang, J.-S., Liang, Y.-S., 2010. Effect of brackish water irrigation and straw mulching on soil salinity and crop yields under monsoonal climatic conditions. Agricultural Water Management 97, 1971-1977.

Parker, D., Perino, L., Auvermann, B., Sweeten, J., 2000. Water use and conservation at Texas High Plains beef cattle feedyards. Applied Engineering in Agriculture 16, 77.

Parker, D.B., D.L. Williams, N.A. Cole, B.W. Auvermann and W. J. Rogers. 2002. Dry nonheated anaerobic biogas fermentation using aged beef cattle manure. ASAE Paper No. 02-4142. In Proceedings 2002 ASAE International Meeting, Chicago, Illinois, July 28-31, 2002.

Patel, G., Roth, L., 1977. Effect of sodium chloride on growth and methane production of methanogens. Canadian journal of microbiology 23, 893-897.

Perski, H.-J., Moll, J., Thauer, R.K., 1981. Sodium dependence of growth and methane formation in Methanobacterium thermoautotrophicum. Archives of Microbiology 130, 319-321.

Posey, J.S., D.B. Parker, D.L. Williams, B.W. Auvermann, and N.A. Cole. 1999. Production of biogas in landfill cells using beef cattle manure collected in open lots. ASAE Paper No. 99-4084. In Proceedings 1999 ASAE/CSAE International Meeting, Toronto, Canada, July 18-21, 1999.

Ravishanker, P., Hills, D., 1984. Hydrogen sulfide removal from anaerobic digester gas. Agricultural wastes 11, 167-179.

Rice, D.D., Threlkeld, C.N., Vuletich, A.K., 1988. Character, origin and occurrence of natural gases in the Anadarko basin, southwestern Kansas, western Oklahoma and Texas Panhandle, USA. Chemical geology 71, 149-157.

Rodriguez, R.S., Soeder, D.J., 2015. Evolving water management practices in shale oil & gas development. Journal of Unconventional Oil and Gas Resources 10, 18-24.

Rotz, C.A., Montes, F., Hafner, S.D., Heber, A.J., Grant, R.H., 2014. Ammonia emission model for whole farm evaluation of dairy production systems. Journal of environmental quality 43, 1143-1158.

Ryckebosch, E., Drouillon, M., Vervaeren, H., 2011. Techniques for transformation of biogas to biomethane. Biomass and bioenergy 35, 1633-1645.

Schink, B., 1997. Energetics of syntrophic cooperation in methanogenic degradation. Microbiol. Mol. Biol. Rev. 61, 262-280.

Sheets, J.P., Ge, X., Li, Y., 2015. Effect of limited air exposure and comparative performance between thermophilic and mesophilic solid-state anaerobic digestion of switchgrass. Bioresource technology 180, 296-303.

Silva, T.L., Morales-Torres, S., Castro-Silva, S., Figueiredo, J.L., Silva, A.M., 2017. An overview on exploration and environmental impact of unconventional gas sources and treatment options for produced water. Journal of environmental management 200, 511-529.

Smith, A.P., Van De Ven, C.J., Richardson, S.D., 2017. Current Water Management Practices, Challenges, and Innovations for US Unconventional Oil and Gas Development. Current Sustainable/Renewable Energy Reports 4, 209-218.

Steward, D.R., Allen, A.J., 2016. Peak groundwater depletion in the High Plains Aquifer, projections from 1930 to 2110. Agricultural Water Management 170, 36-48.

Sudmalis, D., Gagliano, M., Pei, R., Grolle, K., Plugge, C., Rijnaarts, H., Zeeman, G., Temmink, H., 2018. Fast anaerobic sludge granulation at elevated salinity. Water research 128, 293-303.

Sweeney, S., Brown, M., Cohen, M., 2007. Creation of a global database for standardized national emergy synthesis. Proceedings of Emergy Synthesis Conference, pp. 1-23.

Sweeten, J.M., Annamalai, K., Thien, B., McDonald, L.A., 2003. Co-firing of coal and cattle feedlot biomass (FB) fuels. Part I. Feedlot biomass (cattle manure) fuel quality and characteristics☆. Fuel 82, 1167-1182.

Texas Administrative Code Rule §3.13. Title 16: Economic Regulation. Part 1: Railroad Commission of Texas. Chapter 3: Oil and Gas Division.

TRRC, 2019. Texas Railroad Commission. Class II Injection Wells. https://www.rrc.state.tx.us/

Theodori, G.L., Luloff, A., Willits, F.K., Burnett, D.B., 2014. Hydraulic fracturing and the management, disposal, and reuse of frac flowback waters: Views from the public in the Marcellus Shale. Energy Research & Social Science 2, 66-74.

Thiel, G.P., 2014. Treating produced water from hydraulic fracturing: composition effects on scale formation and desalination system selection. Desalination 346, 54-69.

Tong, C., Cadillo-Quiroz, H., Zeng, Z.H., She, C.X., Yang, P., Huang, J.F., 2017. Changes of community structure and abundance of methanogens in soils along a freshwater–brackish water gradient in subtropical estuarine marshes. Geoderma 299, 101-110.

Triolo, J.M., Sommer, S.G., Møller, H.B., Weisbjerg, M.R., Jiang, X.Y., 2011. A new algorithm to characterize biodegradability of biomass during anaerobic digestion: influence of lignin concentration on methane production potential. Bioresource technology 102, 9395-9402.

USEPA. 2019. Inventory of US Greenhouse Gas Emissions and Sinks 1990 – 2017. Available at: https://www.epa.gov/sites/production/files/2019-04/documents/us-ghg-inventory-2019-main-text.pdf.

Vindis, P., Mursec, B., Janzekovic, M., Cus, F., 2009. The impact of mesophilic and thermophilic anaerobic digestion on biogas production. Journal of achievements in materials and manufacturing Engineering 36, 192-198.

Ward, A.J., Hobbs, P.J., Holliman, P.J., Jones, D.L., 2008. Optimisation of the anaerobic digestion of agricultural resources. Bioresource technology 99, 7928-7940.

Weather Underground. Weather Forecast & Reports Data. 2019. www.weatherunderground.com

Weiland, P., 2010a. Biogas production: current state and perspectives. Applied microbiology and biotechnology 85, 849-860.

Williams, J., Williams, H., Dinsdale, R., Guwy, A., Esteves, S., 2013. Monitoring methanogenic population dynamics in a full-scale anaerobic digester to facilitate operational management. Bioresource technology 140, 234-242.

Wilson, L.P., Loetscher, L.H., Sharvelle, S.E., Susan, K., 2013. Microbial community acclimation enhances waste hydrolysis rates under elevated ammonia and salinity conditions. Bioresource technology 146, 15-22.

Xu, P., Drewes, J.E., Heil, D., Wang, G., 2008. Treatment of brackish produced water using carbon aerogel-based capacitive deionization technology. Water research 42, 2605-2617.

Yenigün, O., Demirel, B., 2013. Ammonia inhibition in anaerobic digestion: a review. Process Biochemistry 48, 901-911.

Zemlick, K., Kalhor, E., Thomson, B.M., Chermak, J.M., Graham, E.J.S., Tidwell, V.C., 2018. Mapping the energy footprint of produced water management in New Mexico. Environmental Research Letters 13, 024008.

APPENDIX A: BIOGAS TRIAL DATA

Table 15: Mean Headspace Gas (%) by Treatment

		Mean Headspace Gas (%) by Treatment					
Water Type	**MC (%)**	**CH_4**	**CO_2**	**O_2**	**NH_3**	**H_2S**	**N_2**
Blank		0.00	4.87	18.48	0.00	0.00	76.42
PFW	65	10.22	9.50	16.20	0.02	0.04	63.70
PFW	70	20.61	28.80	18.14	0.01	0.04	32.22
Well	80	16.16	14.78	14.70	0.01	0.03	53.89
Mix	80	18.37	18.31	17.27	0.00	0.00	45.51
PFW	80	8.00	24.21	18.70	0.00	0.00	48.39
Well	90	31.88	9.13	17.58	0.02	0.03	41.38
Mix	90	2.19	2.53	16.85	0.00	0.00	78.44
PFW	90	3.30	21.71	18.99	0.00	0.00	55.38

Table 16: Initial and Final pH, EC, ORI

	Initial			Final			Δ		
	pH	EC (µs/cm)	ORP (mV)	pH	EC (µs/cm)	ORP (mV)	ΔpH	ΔEC (µs/cm)	ΔORP (mV)
Well	9.09	114.4	-						
Produced	5.65	160.0	-18.4						
Mix	6.79	94.0	-42.4						
DI	8.04	33.1	-31.6						
Manure	9.13	19.2	-326.0						
65% PFW	7.91	125.8	-169.4	8.35	118.38	-164.00	-0.44	7.43	-5.40
70% PFW	7.86	101.8	-165.8	8.25	98.38	-159.58	-0.39	3.42	-6.23
80% Well	9.43	11.4	-330.0	8.89	20.90	-339.00	0.54	-9.54	9.00
80% Mix	7.84	56.6	-121.5	8.15	68.80	-101.50	-0.31	-12.20	-20.00
80% PFW	7.50	112.6	-165.4	7.42	99.60	-166.00	0.08	13.00	0.60
90% Well	8.98	5.6	-346.6	8.32	8.90	-328.00	0.66	-3.29	-18.63
90% Mix	7.14	88.9	-240.1	7.72	92.70	-214.00	-0.58	-3.82	-26.11
90% PFW	6.57	147.0	-183.7	7.56	151.10	-151.10	-0.99	-4.11	-32.55

Table 17: Sludge Nutrients Remaining After AD

	Sludge by Water Type			
Analyte	**DI 90%**	**Well 90%**	**Mix 90%**	**Produced 90%**
Ag	ND	ND	ND	ND
Al	124	103	62.9	ND
Antimony	ND	ND	ND	ND
Arsenic	ND	ND	ND	ND
Barium	ND	ND	7.79	14.1
Chloride	1270	974	49700	93800
Chromium	ND	ND	ND	ND
Fe	153	ND	ND	ND
K	1470	1580	1530	1610
Lead	ND	ND	ND	ND
Mercury	ND	ND	ND	ND
Na	0.058	0.075	2.12	3.98
NO_2-N	ND	ND	ND	ND
NO_3+NO_2-N	ND	ND	ND	ND
NO_3-N	ND	ND	74.7	ND
P	67.2	61.2	32.9	28.2
Tin	ND	ND	ND	ND
Total Kjeldahl nitrogen (TKN)	801	766	536	393
Total Nitrogen	801	766	611	393
Vanadium	ND	9.4	7.47	ND
Zn	36.9	ND	ND	ND

Table 18: Laboratory Trial #1 Headspace Gas Concentrations

			Headspace Gas										
			O_2		NH_3		H_2S		CH_4		CO_2		Bal
MC	Water Source	Module	mg/L	%	mg/L	%	mg/L	%	mg/L	%	mg/L	%	%
90%	Well	25	202000	20.20	61.00	0.01	>500	0.05	12000.00	1.20	18000.00	1.80	76.74
90%	Well	15	163000	16.30	15.00	0.00	>500	0.05	167000.00	16.70	40000.00	4.00	62.95
90%	Well	7	170000	17.00	41.00	0.00	>500	0.05	236000.00	23.60	74000.00	7.40	51.95
90%	Well	2	196000	19.60	0.00	0.00	5.00	0.00	241000.00	24.10	56000.00	5.60	50.70
90%	Well	11	94000	9.40	5.00	0.00	24.00	0.00	388000.00	38.80	96000.00	9.60	42.20
90%	Well	10	188000	18.80	10.00	0.00	44.00	0.00	412000.00	41.20	144000.00	14.40	25.59
90%	Well	20	202000	20.20	156.00	0.02	40.00	0.00	479000.00	47.90	135000.00	13.50	18.38
90%	Well	30	191000	19.10	991.00	0.10	>500	0.05	615000.00	61.50	167000.00	16.70	2.55
90%	Mixed	5	196000	19.60	4.00	0.00	11.00	0.00	8000.00	0.80	11000.00	1.10	78.50
90%	Mixed	18	196000	19.60	5.00	0.00	3.00	0.00	8000.00	0.80	11000.00	1.10	78.50
90%	Mixed	27	193000	19.30	2.00	0.00	1.00	0.00	9000.00	0.90	8000.00	0.80	79.00
90%	Mixed	21	186000	18.60	3.00	0.00	3.00	0.00	15000.00	1.50	11000.00	1.10	78.80
90%	Mixed	9	131000	13.10	8.00	0.00	17.00	0.00	22000.00	2.20	36000.00	3.60	81.10
90%	Mixed	22	190000	19.00	3.00	0.00	5.00	0.00	25000.00	2.50	29000.00	2.90	75.60
90%	Mixed	8	60000	6.00	15.00	0.00	3.00	0.00	33000.00	3.30	65000.00	6.50	84.20
90%	Mixed	19	196000	19.60	5.00	0.00	3.00	0.00	55000.00	5.50	31000.00	3.10	71.80
90%	Produced	28	203000	20.30	0.00	0.00	1.00	0.00	668.83	0.07	353853.50	35.39	44.14
90%	Produced	12	193000	19.30	11.00	0.00	15.00	0.00	1000.00	0.10	4000.00	0.40	79.41
90%	Produced	17	180000	18.00	3.00	0.00	1.00	0.00	2036.94	0.20	232543.41	23.25	57.86
90%	Produced	29	201000	20.10	8.00	0.00	15.00	0.00	6199.59	0.62	223164.18	22.32	56.31
90%	Produced	26	184000	18.40	6.00	0.00	18.00	0.00	7849.65	0.78	231113.13	23.11	57.03
90%	Produced	4	190167	19.02	7.00	0.00	22.00	0.00	32345.74	3.23	219848.32	21.98	55.15
90%	Produced	23	188028	18.80	8.00	0.00	21.00	0.00	37625.23	3.76	197514.13	19.75	56.98
90%	Produced	16	180000	18.00	13.00	0.00	28.00	0.00	176319.46	17.63	274415.72	27.44	36.12
90%	Blank	3	201000	20.10	0.00	0.00	0.00	0.00	0.00	0.00	61000.00	6.10	86.22

Table 19: Laboratory Trial #2 Headspace Gas Concentrations

			Headspace Gas										
			O_2		NH_3		H_2S		CH_4		CO_2		Bal
MC	Water Source	Module	mg/L	%	mg/L	%	mg/L	%	mg/L	%	mg/L	%	%
80%	Well	13	198000	19.80	71.00	0.01	1.00	0.00	552.41	0.06	142729.66	14.27	65.45
80%	Well	18	176000	17.60	13.00	0.00	28.00	0.00	132083.57	13.21	238250.28	23.83	44.67
80%	Well	2	170000	17.00	59.00	0.01	>500	0.05	147760.94	14.78	89059.82	8.91	59.00
80%	Well	9	95000	9.50	100.00	0.01	>500	0.05	216387.77	21.64	100314.75	10.03	58.48
80%	Well	28	131000	13.10	69.00	0.01	>500	0.05	228290.39	22.83	220468.99	22.05	41.32
80%	Well	10	112000	11.20	66.00	0.01	>500	0.05	244119.18	24.41	96138.45	9.61	54.44
80%	Mixed	26	196000	19.60	22.00	0.00	46.00	0.00	33741.18	3.37	134967.14	13.50	63.13
80%	Mixed	16	178000	17.80	17.00	0.00	32.00	0.00	59158.49	5.92	235708.80	23.57	52.02
80%	Mixed	11	192000	19.20	35.00	0.00	50.00	0.01	81416.54	8.14	110979.81	11.10	61.23
80%	Mixed	29	174000	17.40	19.00	0.00	50.00	0.01	85363.22	8.54	234308.24	23.43	49.94
80%	Mixed	1	142000	14.20	4.00	0.00	27.00	0.00	234382.38	23.44	152748.43	15.27	46.64
80%	Mixed	7	154000	15.40	7.00	0.00	39.00	0.00	608334.90	60.83	229836.65	22.98	0.11
80%	Produced	19	175000	17.50	1.00	0.00	3.00	0.00	210.35	0.02	242666.74	24.27	57.50
80%	Produced	4	205000	20.50	1.00	0.00	1.00	0.00	2471.44	0.25	276623.57	27.66	50.78
80%	Produced	5	201000	20.10	36.00	0.00	38.00	0.00	2680.02	0.27	280111.98	28.01	50.80
80%	Produced	17	193000	19.30	0.00	0.00	1.00	0.00	25660.38	2.57	309254.24	30.93	46.31
80%	Produced	21	170000	17.00	1.00	0.00	3.00	0.00	70706.94	7.07	230200.13	23.02	52.24
80%	Produced	3	178000	17.80	13.00	0.00	33.00	0.00	378118.64	37.81	113599.33	11.36	32.69
80%	Blank	6	193000	19.30	0.00	0.00	0.00	0.00	0.00	0.00	34000.00	3.40	84.39

Table 20: Laboratory Trial #3 Headspace Gas Concentrations

			Headspace Gas										
			O_2		NH_3		H_2S		CH_4		CO_2		Bal
MC	Water Source	Module	mg/L	%	mg/L	%	mg/L	%	mg/L	%	mg/L	%	%
65%	Produced	10	105000	10.50	275.00	0.03	>500	0.05	16463.92	1.65	239372.15	23.94	63.14
65%	Produced	28	179000	17.90	315.00	0.03	80.70	0.01	21292.43	2.13	48505.29	4.85	74.94
65%	Produced	27	168000	16.80	56.00	0.01	>500	0.05	35335.01	3.53	57760.31	5.78	73.82
65%	Produced	7	150000	15.00	289.00	0.03	>500	0.05	60238.57	6.02	17450.88	1.75	76.64
65%	Produced	1	168000	16.80	56.00	0.01	>500	0.05	71327.99	7.13	93902.84	9.39	66.35
65%	Produced	2	179000	17.90	551.00	0.06	>500	0.05	88769.63	8.88	93726.18	9.37	63.47
65%	Produced	13	173000	17.30	248.00	0.02	>500	0.05	248842.54	24.88	0.00	0.00	57.74
65%	Produced	16	174000	17.40	31.00	0.00	27.00	0.00	275142.12	27.51	209485.85	20.95	33.52
70%	Produced	30	193000	19.30	276.00	0.03	>500	0.05	0.00	0.00	365698.17	36.57	43.95
70%	Produced	7	176000	17.60	65.00	0.01	>500	0.05	43794.67	4.38	450461.12	45.05	32.79
70%	Produced	9	206000	20.60	8.00	0.00	2.00	0.00	52415.93	5.24	366201.01	36.62	37.43
70%	Produced	29	193000	19.30	56.00	0.01	>500	0.05	54509.90	5.45	511502.67	51.15	23.89
70%	Produced	11	165000	16.50	20.00	0.00	30.00	0.00	87165.30	8.72	414308.53	41.43	33.23
70%	Produced	19	163000	16.30	69.00	0.01	>500	0.05	238918.22	23.89	140890.78	14.09	45.25
70%	Produced	6	179000	17.90	38.00	0.00	>500	0.05	508069.46	50.81	37287.80	3.73	27.40
70%	Produced	3	176000	17.60	65.00	0.01	>500	0.05	663609.80	66.36	17453.44	1.75	13.82
	Blank	18	160491.2	16.05	0.00	0.00	0.00	0.00	0.00	0.00	84887.58	8.49	78.60

Table 21: Produced/Flowback Water Descriptive Statistics

				Methane (ml)	B_0
MC	65	1		6.2564	.0007
		2		8.9800	.0010
		3		18.2821	.0020
		4		696.5225	.0744
		5		254.3083	.0272
		6		298.8093	.0319
		7		2564.9666	.2740
		8		3363.7396	.3593
		Total	Minimum	6.2564	.0007
			Maximum	3363.7396	.3593
			Median	276.558812	.029539
			Mean	901.483091	.096287
			Std. Error of Mean	463.5264771	.0495089
	70	1		14.0887	.0015
		2		16.9670	.0018
		3		20.0232	.0021
		4		84.1087	.0090
		5		342.1690	.0365
		6		847.9912	.0906
		7		5562.8456	.5942
		Total	Minimum	14.0887	.0015
			Maximum	5562.8456	.5942
			Median	84.108659	.008984
			Mean	984.027630	.105103
			Std. Error of Mean	771.6896827	.0824235
	80	1		.0765	.0000
		2		.8698	.0001
		3		.9659	.0001
		4		36.3148	.0039
		5		113.5803	.0121
		6		5392.1331	.5759
		Total	Minimum	.0765	.0000
			Maximum	5392.1331	.5759
			Median	18.640337	.001991
			Mean	923.990076	.098691
			Std. Error of Mean	893.8078509	.0954668
	90	1		.6317	.0001
		2		1.3208	.0001
		3		3.1882	.0003
		4		12.4867	.0013
		5		17.5534	.0019
		6		18.5897	.0020
		7		76.6998	.0082
		8		497.8761	.0532
		Total	Minimum	.6317	.0001
			Maximum	497.8761	.0532
			Median	15.020080	.001604
			Mean	78.543318	.008389
			Std. Error of Mean	60.5382142	.0064660

Table 22: 50/50 Mixture Descriptive Statistics

				Methane (ml)	B_0
MC	80	1		12.4707	.0013
		2		68.6156	.0073
		3		278.3875	.0297
		4		1241.1925	.1326
		5		3289.4332	.3513
		6		1864.3542	.1991
		Total	Minimum	12.4707	.0013
			Maximum	3289.4332	.3513
			Median	759.790042	.081153
			Mean	1125.742318	.120240
			Std. Error of Mean	526.4768160	.0562325
	90	1		3.6688	.0004
		2		15.3254	.0016
		3		19.2578	.0021
		4		36.8303	.0039
		5		65.6569	.0070
		6		75.6181	.0081
		7		100.4291	.0107
		8		1322.1950	.1412
		Total	Minimum	3.6688	.0004
			Maximum	1322.1950	.1412
			Median	51.243576	.005473
			Mean	204.872660	.021882
			Std. Error of Mean	160.0506495	.0170949
	Total	Minimum		3.6688	.0004
		Maximum		3289.4332	.3513
		Median		72.116847	.007703
		Mean		599.531085	.064035
		Std. Error of Mean		263.7147421	.0281671

a. Limited to first 100 cases.

Table 23: WW Descriptive Statistics

				Methane (ml)	B_0
MC	80	1		.2729	.0000
		2		909.4025	.0971
		3		1208.4128	.1291
		4		3353.0509	.3581
		5		4413.5110	.4714
		6		5525.1673	.5901
		Total	Minimum	.2729	.0000
			Maximum	5525.1673	.5901
			Median	2280.731856	.243603
			Mean	2568.302887	.274318
			Std. Error of Mean	893.6759209	.0954527
	90	1		4.7700	.0005
		2		70.3345	.0075
		3		237.7589	.0254
		4		2716.0388	.2901
		5		4430.8152	.4733
		6		4975.9881	.5315
		7		6074.0566	.6488
		8		6779.5011	.7241
		Total	Minimum	4.7700	.0005
			Maximum	6779.5011	.7241
			Median	3573.426999	.381675
			Mean	3161.157907	.337641
			Std. Error of Mean	988.7166229	.1056040
	Total	Minimum		.2729	.0000
		Maximum		6779.5011	.7241
		Median		3034.544865	.324117
		Mean		2907.077184	.310502
		Std. Error of Mean		662.6128566	.0707731

a. Limited to first 100 cases.

WELL WATER REGRESSION

Linear

Model Summary

R	R Square	Adjusted R Square	Std. Error of the Estimate
.123	.015	-.067	2560.975

The independent variable is MC.

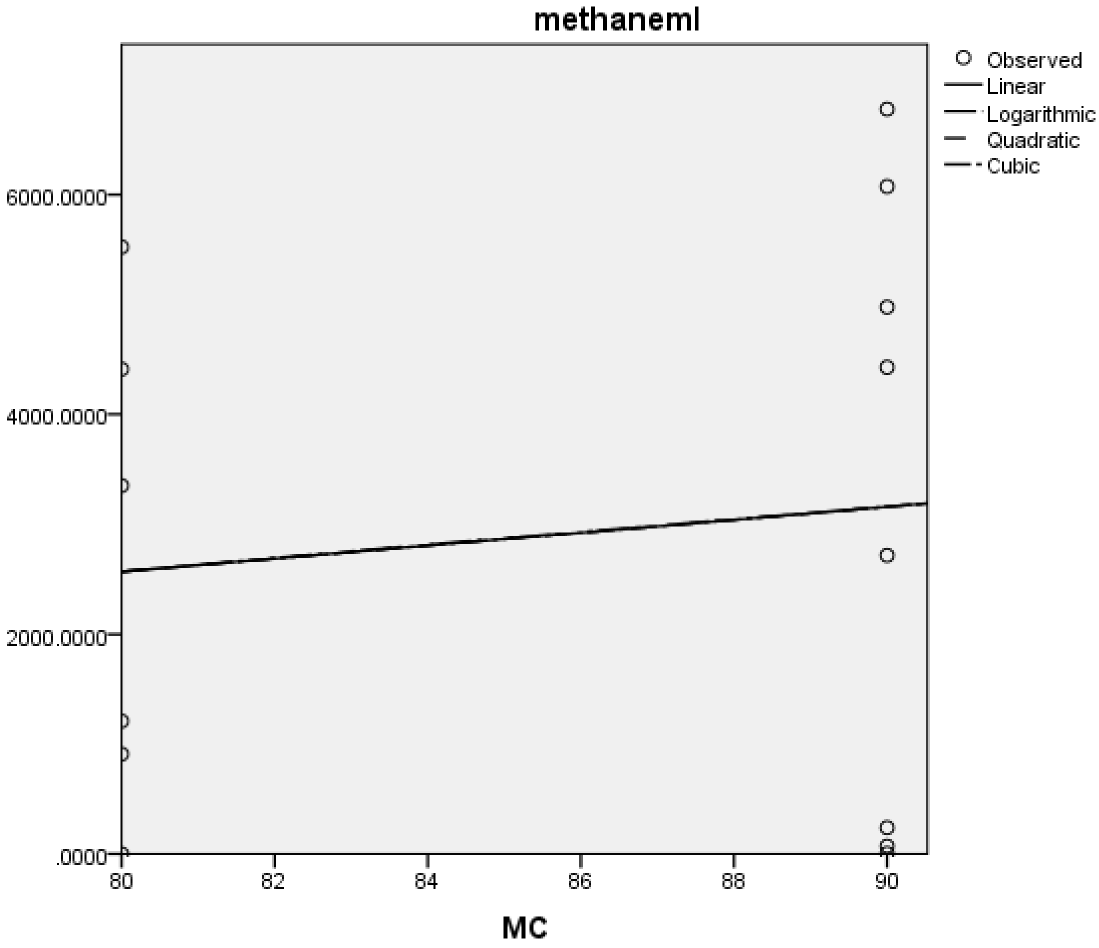
ANOVA

	Sum of Squares	df	Mean Square	F	Sig.
Regression	1205064.257	1	1205064.257	.184	.676
Residual	78703090.930	12	6558590.911		
Total	79908155.190	13			

The independent variable is MC.

Coefficients

	Unstandardized Coefficients		Standardized Coefficients		
	B	Std. Error	Beta	t	Sig.
MC	59.286	138.308	.123	.429	.676
(Constant)	-2174.537	11874.751		-.183	.858


methaneml
Observed
Linear
Logarithmic
Quadratic
Cubic
6000.0000
4000.0000
2000.0000
.0000
80
82
84
86
88
90
MC

50/50 MIX REGRESSION

Curve Fit

Warnings
The Quadratic model could not be fitted due to near-collinearity among model terms.
The Cubic model could not be fitted due to near-collinearity among model terms.

Model Description

Model Name		MOD_3
Dependent Variable	1	methaneml
Equation	1	Linear
	2	Logarithmic
	3	Quadratic
	4	Cubic
Independent Variable		MC
Constant		Included
Variable Whose Values Label Observations in Plots		Unspecified
Tolerance for Entering Terms in Equations		.0001

Linear

Model Summary

R	R Square	Adjusted R Square	Std. Error of the Estimate
.479	.230	.166	901.381

The independent variable is MC.

ANOVA

	Sum of Squares	df	Mean Square	F	Sig.
Regression	2907431.748	1	2907431.748	3.578	.083
Residual	9749842.916	12	812486.910		
Total	12657274.660	13			

The independent variable is MC.

Coefficients

	Unstandardized Coefficients		Standardized Coefficients		
	B	Std. Error	Beta	t	Sig.
MC	-92.087	48.680	-.479	-1.892	.083
(Constant)	8492.700	4179.530		2.032	.065

Exponential

Model Summary

R	R Square	Adjusted R Square	Std. Error of the Estimate
.487	.237	.173	1.913

The independent variable is MC.

ANOVA

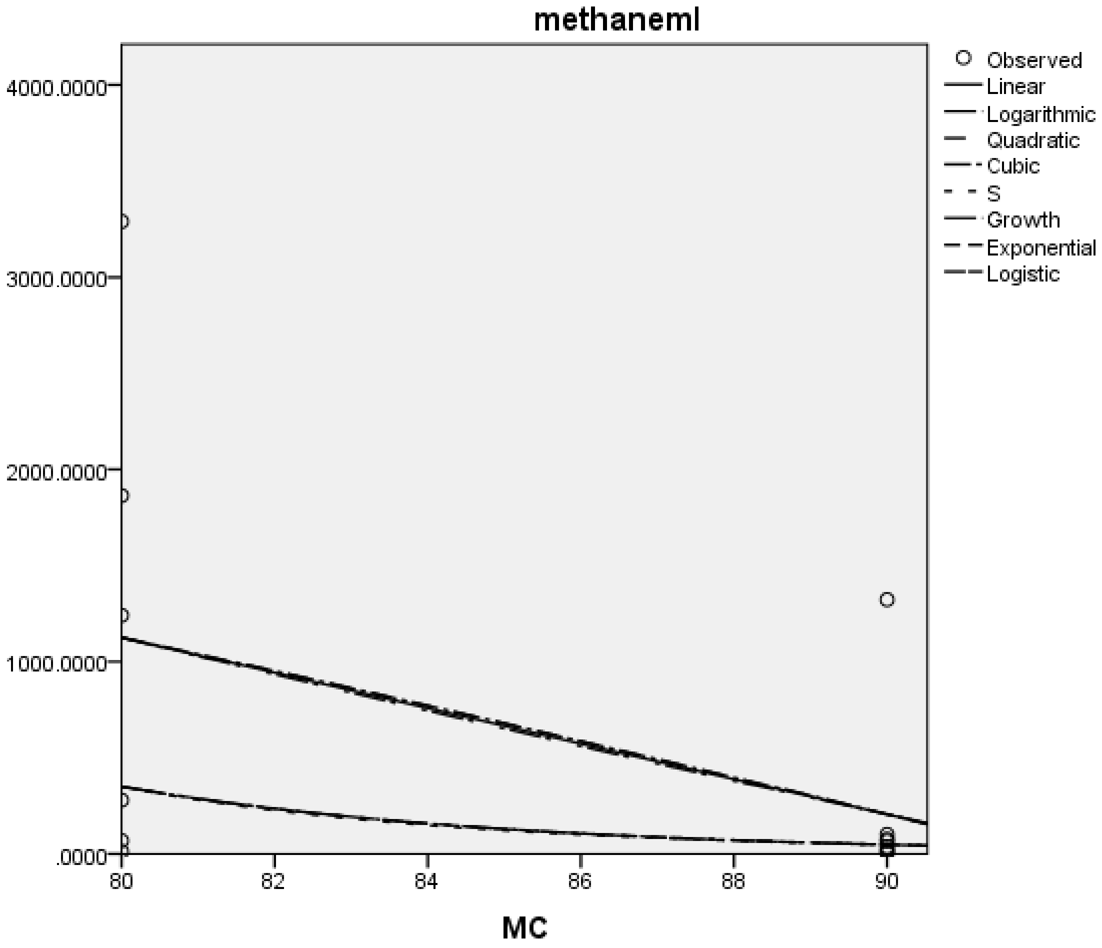
	Sum of Squares	df	Mean Square	F	Sig.
Regression	13.620	1	13.620	3.722	.078
Residual	43.911	12	3.659		
Total	57.531	13			

The independent variable is MC.

Coefficients

	Unstandardized Coefficients		Standardized Coefficients		
	B	Std. Error	Beta	t	Sig.
MC	-.199	.103	-.487	-1.929	.078
(Constant)	2936792358.000	26048709320.000		.113	.912

The dependent variable is ln(methaneml).


methaneml
Observed
Linear
Logarithmic
Quadratic
Cubic
S
Growth
Exponential
Logistic
4000.0000
3000.0000
2000.0000
1000.0000
.0000
80
82
84
86
88
90
MC

Curve Fit

Linear

Model Summary

R	R Square	Adjusted R Square	Std. Error of the Estimate
.216	.047	.011	1520.696

The independent variable is MC.

ANOVA

	Sum of Squares	df	Mean Square	F	Sig.
Regression	3057385.881	1	3057385.881	1.322	.260
Residual	62437946.040	27	2312516.520		
Total	65495331.920	28			

The independent variable is MC.

Coefficients

	Unstandardized Coefficients		Standardized Coefficients		
	B	Std. Error	Beta	t	Sig.
MC	-32.566	28.323	-.216	-1.150	.260
(Constant)	3180.838	2176.797		1.461	.155

Cubic Model

Model Summary

R	R Square	Adjusted R Square	Std. Error of the Estimate
.255	.065	-.007	1534.661

The independent variable is MC.

ANOVA

	Sum of Squares	df	Mean Square	F	Sig.
Regression	4260541.261	2	2130270.631	.905	.417
Residual	61234790.660	26	2355184.256		
Total	65495331.920	28			

The independent variable is MC.

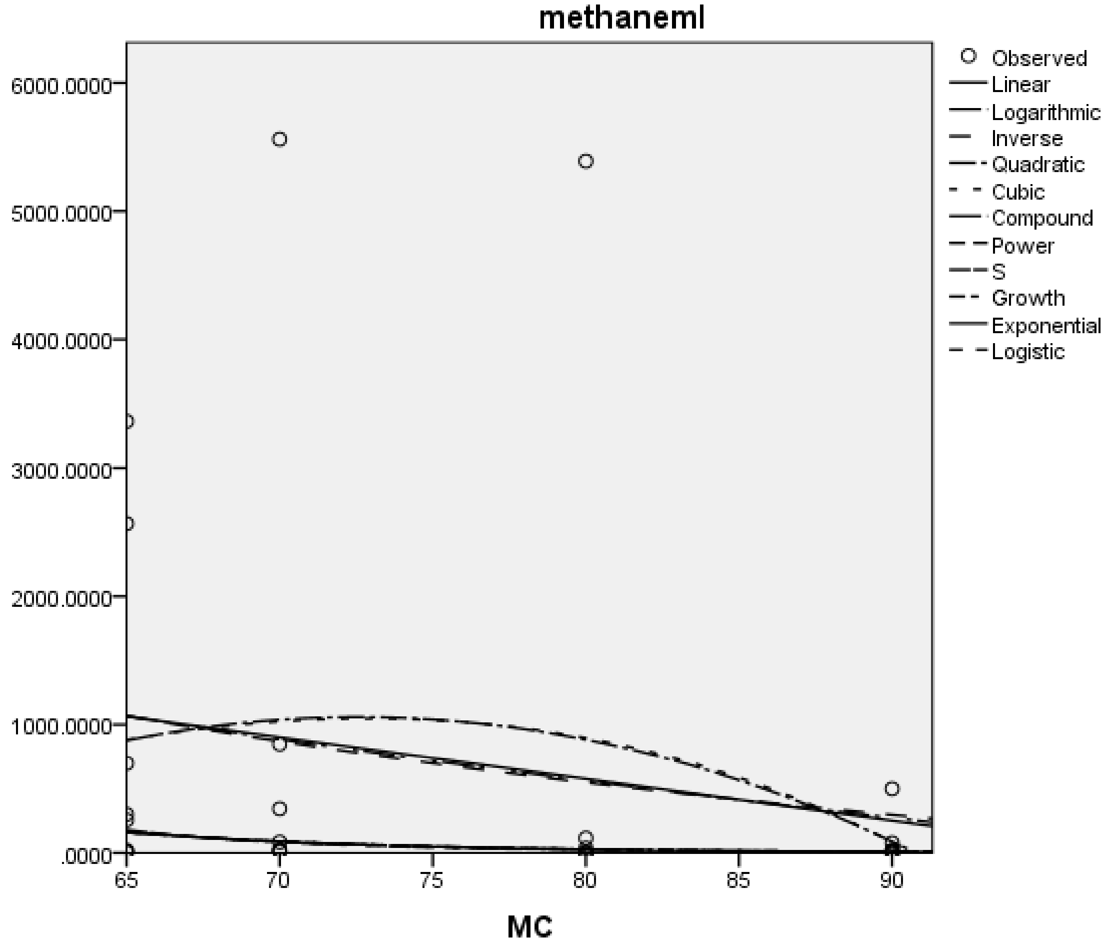
Coefficients

	Unstandardized Coefficients		Standardized Coefficients		
	B	Std. Error	Beta	t	Sig.
MC ** 2	2.856	4.600	2.945	.621	.540
MC ** 3	-.026	.039	-3.169	-.668	.510
(Constant)	-4013.034	9023.237		-.445	.660

Excluded Terms

	Beta In	t	Sig.	Partial Correlation	Minimum Tolerance
MC[a]	-8.429	-.089	.929	-.018	.000

a. The tolerance limit for entering variables is reached.



APPENDIX B: ENERGY MODEL CODE

```
Energy_Production.B0[Water_Type]
Energy_Production.Converter_1[Water_Type]
Energy_Production.H2O_Type[Water_Type]
Feedlot.Annual_Manure[Storage]
Feedlot.Energy_Losses[Storage]
Feedlot.Manure_for_Utilization[Storage]
Feedlot.Manure_Storage[Storage]

Corn =
With_Supplemental_P,Without_Supplemental_P,With_25%_Wet_Distillers_Grains,With_30%_Wet_Gluten_Feed
Energy_Type = Electricity,Diesel
Gas_Treatment = Clean,Upgrade
MC = Sixty_five,seventy,eighty,ninety
MC_Water_Type = 1 elements
Power = Fuel,Electricity
Silage1 = Yes,No
Storage = Zero_Days,Thirty_Days,Sixty_Days,Ninety_Days,No
SUPP_S = YES,NO
Treat = Gas_Energy,Elec_Energy
Water_Type = PFW Mix,DI,Well

{ INITIALIZATION EQUATIONS }
: S Energy_Production.Anaerobic_Digester = 0
UNITS: Cubic Meters
: S Energy_Production.Electricity = 0
UNITS: kWh
: S Energy_Production.Fuel = 0
UNITS: L
: S Energy_Production.Methane_Volume = 0
UNITS: Cubic Meters
: S Feedlot.Manure_Storage[Zero_Days] = .005
UNITS: Kilograms
: S Feedlot.Manure_Storage[Thirty_Days] = 0.1
UNITS: Kilograms
: S Feedlot.Manure_Storage[Sixty_Days] = .25
UNITS: Kilograms
```

```
: S Feedlot.Manure_Storage[Ninety_Days] = .5
UNITS: Kilograms
: S Feedlot.Manure_Storage[No] = 1
UNITS: Kilograms
UNITS: Kilograms
: S Feedlot."Soil,_Water,_Atmosphere" = 0
UNITS: Kilograms
: c Energy_Production.MC_Standard_Deviation = 1
: c Energy_Production.MC_Manure = NORMAL(.318, MC_Standard_Deviation)
UNITS: percentage
: c Feedlot.Variance_VS = 1
: f Feedlot.Manure_for_Utilization[Storage] = Manure_Storage*1
UNITS: kg/Months
: c Feedlot.VS = NORMAL(24.6/100,
Variance_VS)*Manure_for_Utilization[Zero_Days]
: c Energy_Production."%_Gas" = .5
: c Feedlot.DM = Manure_for_Utilization[Zero_Days]*5.2
UNITS: Kilograms
: c Energy_Production.H2O_Type[PFW] = 1
UNITS: Dimensionless
: c Energy_Production.H2O_Type[Mix] = 1
UNITS: Dimensionless
: c Energy_Production.H2O_Type[DI] = 1
UNITS: Dimensionless
: c Energy_Production.H2O_Type[Well] = 1
UNITS: Dimensionless
UNITS: Dimensionless
: c Energy_Production.Moisture_Content = 60
: c Energy_Production.Converter_1[PFW] = IF(H2O_Type[PFW])THEN ((343,662e^(-
0.118x*Moisture_Content)) ELSE 0
: c Energy_Production.Converter_1[Mix] = IF H2O_Type[Mix]THEN (2.94E+09e^(-
0.199*Moisture_Content)) ELSE 0
: c Energy_Production.Converter_1[Well] = IF H2O_Type[Well]THEN
(Moisture_Content*59.286-2,174) ELSE 0
: c Energy_Production.m3 = .001
UNITS: Cubic Meters
: f Energy_Production.Methane = (Converter_1[PFW]*m3)
UNITS: Cubic Meters/Months
: c Energy_Production.B0[Water_Type] = ((Methane)/(Feedlot.VS/Feedlot.DM))
UNITS: Cubic Meters per kg VS
: c Energy_Production.Converter_2 = Feedlot.DM*0.5721*B0[PFW]
: f Energy_Production."Gas_(L)" = Methane_Volume*"%_Gas"*Converter_2
UNITS: Cubic Meters/Months
: c Energy_Production."%_Electric" = .5
: f Energy_Production.kWh = (Methane_Volume*2)*"%_Electric"*Converter_2
UNITS: Cubic Meters/Months
```

```
: c Energy_Production.MC_Converter = Moisture_Content/100
: f Energy_Production.Substrate = (Feedlot.DM/MC_Manure)+((MC_Manure-
MC_Converter)/(MC_Converter-1))
UNITS: Cubic Meters/Months
: c Energy_Production.Weight_Water = Substrate
UNITS: Kilograms
: c Feedlot.lbs_per_day_as_excreted = 65
UNITS: pounds
: c Feedlot.Weight = 900
UNITS: Pounds
: c Feedlot.Animal_Unit = 1000
UNITS: Pounds
: c Feedlot.Weight_Adjustment = (Weight/Animal_Unit)
UNITS: pounds
: c Feedlot."%_Capacity" = 1
UNITS: percentage
: c Feedlot.Feedlot_Capactiy = 1000
UNITS: Dimensionless
: c Feedlot.Total_Cattle = "%_Capacity"*Feedlot_Capactiy
UNITS: Dimensionless
: c Feedlot.Days = 365
UNITS: Per Year
: c Feedlot.kg = 0.453592
: f Feedlot.Annual_Manure[Storage] =
(((lbs_per_day_as_excreted*Weight_Adjustment)*Total_Cattle)*Days)*kg
UNITS: kg/Months
: f Feedlot.Energy_Losses[Storage] = 0
UNITS: kg/Months
: c Feedlot.Moisture = Manure_for_Utilization[Zero_Days]*.92
UNITS: Kilograms


{ RUNTIME EQUATIONS }
: S Energy_Production.Anaerobic_Digester(t) = Anaerobic_Digester(t - dt) + (Substrate -
Methane) * dt
UNITS: Cubic Meters
: S Energy_Production.Electricity(t) = Electricity(t - dt) + (kWh) * dt
UNITS: kWh
: S Energy_Production.Fuel(t) = Fuel(t - dt) + ("Gas_(L)") * dt
UNITS: L
: S Energy_Production.Methane_Volume(t) = Methane_Volume(t - dt) + (Methane -
"Gas_(L)" - kWh) * dt
UNITS: Cubic Meters
: S Feedlot.Manure_Storage[Zero_Days](t) = Manure_Storage[Zero_Days](t - dt) +
(Annual_Manure[Zero_Days] - Manure_for_Utilization[Zero_Days] -
Energy_Losses[Zero_Days]) * dt
```

```
UNITS: Kilograms
: S Feedlot.Manure_Storage[Thirty_Days](t) = Manure_Storage[Thirty_Days](t - dt) +
(Annual_Manure[Thirty_Days] - Manure_for_Utilization[Thirty_Days] -
Energy_Losses[Thirty_Days]) * dt
UNITS: Kilograms
: S Feedlot.Manure_Storage[Sixty_Days](t) = Manure_Storage[Sixty_Days](t - dt) +
(Annual_Manure[Sixty_Days] - Manure_for_Utilization[Sixty_Days] -
Energy_Losses[Sixty_Days]) * dt
UNITS: Kilograms
: S Feedlot.Manure_Storage[Ninety_Days](t) = Manure_Storage[Ninety_Days](t - dt) +
(Annual_Manure[Ninety_Days] - Manure_for_Utilization[Ninety_Days] -
Energy_Losses[Ninety_Days]) * dt
UNITS: Kilograms
: S Feedlot.Manure_Storage[No](t) = Manure_Storage[No](t - dt) +
(Annual_Manure[No] - Manure_for_Utilization[No] - Energy_Losses[No]) * dt
UNITS: Kilograms
UNITS: Kilograms
: S Feedlot."Soil,_Water,_Atmosphere"(t) = "Soil,_Water,_Atmosphere"(t - dt) +
(Energy_Losses[Zero_Days] + Energy_Losses[Thirty_Days] +
Energy_Losses[Sixty_Days] + Energy_Losses[Ninety_Days] + Energy_Losses[No]) * dt
UNITS: Kilograms
: c Energy_Production.MC_Manure = NORMAL(.318, MC_Standard_Deviation)
UNITS: percentage
: f Feedlot.Manure_for_Utilization[Storage] = Manure_Storage*1 {UNIFLOW}
UNITS: kg/Months
: c Feedlot.VS = NORMAL(24.6/100,
Variance_VS)*Manure_for_Utilization[Zero_Days]
: c Feedlot.DM = Manure_for_Utilization[Zero_Days]*5.2
UNITS: Kilograms
INFLOWS:
Methane[PFB] = (Anaerobic_Digester*.001)+IF(H2O_Type[PFB])THEN
(343662*(2.7183^(-0.118*Moisture_Content))) ELSE 0 {UNIFLOW}
UNITS: Cubic Meters/Months
Methane[Mix] = (Anaerobic_Digester*.001)+(IF(H2O_Type[Mix]) THEN
(2.49E+09)*(2.7183^(-0.1999*Moisture_Content)) ELSE 0) {UNIFLOW}
UNITS: Cubic Meters/Months
Methane[DI] = (Anaerobic_Digester/10000)+(IF H2O_Type[DI]THEN(-
1149+(Moisture_Content*21.47)) ELSE 0) {UNIFLOW}
UNITS: Cubic Meters/Months
Methane[Well] = (Anaerobic_Digester*.001)+(IF
H2O_Type[Well]THEN((Moisture_Content*59.286)-2174) ELSE 0) {UNIFLOW}
UNITS: Cubic Meters/Months
: c Energy_Production.B0[Water_Type] = ((Methane)/(Feedlot.VS/Feedlot.DM))
UNITS: Cubic Meters per kg VS
: c Energy_Production.Converter_2 = Feedlot.DM*.5721*B0[PFW]
```

```
: f Energy_Production."Gas_(L)" = Methane_Volume*"%_Gas"*Converter_2
{UNIFLOW}
UNITS: Cubic Meters/Months
: f Energy_Production.kWh = (Methane_Volume*2)*"%_Electric"*Converter_2
{UNIFLOW}
UNITS: Cubic Meters/Months
: c Energy_Production.MC_Converter = Moisture_Content/100
: f Energy_Production.Substrate = (Feedlot.DM/MC_Manure)+((MC_Manure-
MC_Converter)/(MC_Converter-1)) {UNIFLOW}
UNITS: Cubic Meters/Months
: c Energy_Production.Weight_Water = Substrate
UNITS: Kilograms
: c Feedlot.Weight_Adjustment = (Weight/Animal_Unit)
UNITS: pounds
: c Feedlot.Total_Cattle = "%_Capacity"*Feedlot_Capactiy
UNITS: Dimensionless
: f Feedlot.Annual_Manure[Storage] =
(((lbs_per_day_as_excreted*Weight_Adjustment)*Total_Cattle)*Days)*kg
{UNIFLOW}
UNITS: kg/Months
: c Feedlot.Moisture = Manure_for_Utilization[Zero_Days]*.92
UNITS: Kilograms

{ TIME SPECS }
STARTTIME=0
STOPTIME=12
DT=0.25
INTEGRATION=EULER
RUNMODE=NORMAL
PAUSEINTERVAL=0
{ The model has 41 (66) variables (array expansion in parens).
In root model and 2 additional modules with 0 sectors.
Stocks: 6 (10) Flows: 7 (19) Converters: 28 (37)
Constants: 15 (22) Equations: 20 (34) Graphicals: 0 (0)
```

APPENDIX C: EMERGY MODEL DATA

Table 24: Emergy Transformity Table

Material	Transformity	Source
Cattle	2.00E+05	Odum, 1996
Corn	6.80E+04	Odum, 1996
Digester Materials	9.26E+07	Ciotola, 2011
Electricity	2.92E+05	Odum, 1996
ET_0	6.36E+03	Campbell, 2012
Feed	6.80E+04	Odum, 1987
Geothermal	2.03E+04	Campbell, 2012
Goods & Services	2.49E+10	Campbell, 2012
Groundwater	1.59E+05	Odum, 1996
Machinery	6.79E+09	Odum, 1996
Machinery	1.13E+10	Campbell, 2012
Manure	1.13E+06	Bastianoni, 2000
CH_4	2.48E+05	Bastianoni, 2000
Misc. Goods	7.22E+07	Campbell, 2012
N fertilizer	1.69E+06	Odum, 1996
Natural gas	4.80E+04	Odum, 1996
Petroleum	8.70E+04	Campbell, 2012
Rain Chemical Potential	1.54E+04	Bastianoni, 2000
Rain Geopotential	1.10E+04	Campbell, 2012
Soil	1.68E+09	Campbell, 2012
Solar Energy	1.00E+00	Odum, 1996
SOM	1.18E+04	Campbell, 2012
Steel	1.78E+09	Odum, 1996
Transpiration	6.36E+03	Campbell, 2012
Wind	1.58E+03	Campbell, 2012

Table 25: Emergy Calculations

		Calculation	Value	Unit	Source
EMR		Total US Emergy (2014)	2.96E+25	seJ	(NEAD, 2019)
		GDP 2019	2.13E+13	$	(BEA, 2019)
		(Emergy) /(GDP)	1.39E+12	seJ/$	
Sunlight	1	Land Area	9.68E+06	m^2	
		Insolation	1.91E+07	$J/m^2/d$	(NASA, 2017)
		Albedo	0.18		(NASA, 2017)
		(area) x (Insolation) x (1-albedo)	1.52E+14	J/year	
Rain Chemical	2	Land Area	9.68E+06	m^2	
		Annual Rainfall (1981-2010 Avg.)	5.12E-01	m/yr	(NOAA, 2019)
		Total Volume Rain (rain x area)	4.96E+06	m^3	
		Chemical Pot. Energy Rain Water	4.94E+00	J/g	(Odum, 1996)
		(volume) x (Chem. Pot energy) x (4,940 J/kg) x 1000kg/m^3	1.21E+14	J/yr	
Rain geochemical	3	Land Area	9.68E+06	m^2	
		Elevation Change	3.06E+05	m	
		Annual Rainfall (1981 - 2010 Avg.)	5.12E-01	m/yr	(NOAA, 2019)
		(volume rain) x (change in elevation) x (density) x (gravity)	1.48E+19	J/yr	
Wind	4	Land Area	9.68E+06	m^2	
		Air density	1.30E+00	kg/m^3	
		Average Annual Wind Velocity	6.16E+00	m/s	Weather Underground
		Geostrophic Winds (obs. wind /0.60)	1.03E+01		
		Drag Coefficient	1.63E-03		
		(area) x (density) x (d. coeff.) x (g. wind) x (s/yr)	6.64E+12	J	
ET_0	5	Land Area	9.68E+06	m^2	
		ET_0 Rate	1.41E+00	m/yr	(TAMU, 2019)
		Total ET_0	1.37E+07	m^3	
		Potential Energy of Water	4.94E+00	J/g	
		(volume) x (1000 kg/m^3) x (4,940 J/kg)	6.75E+10	J/yr	
Manure	6	Daily Weight	5.85E+01	g	(AWMH, 1999)
		Year	3.65E+02	days	
		(daily weight) x (year) x #livestock	1.28E+07	g/yr	
		Energy in Joules = mass(kg)*c^2	1.15E+21		
Cattle	19	Cattle	6.00E+02		Odum, 1987
		Turnover Rate (TR)	2.25E+00		
		Weight	4.54E+05	g/h	
		Energy of cattle	2.82E+00	kcal/g	
		(Cattle) x (TR) X (weight) x (Energy) x (Joule/kcal)	7.23E+12	J/y	
Soil	8	Area Top soil	2.39E+03	acres	(NRCS, 2009)
		Bulk Density of clay loam soil	1.50E+00	g/cm3	
		Avg SOM	2.13E-02	%	
		% area covered by soil	9.50E-01	%	
		top soil	5.46E+09	lbs	
		top soil	2.73E+06	tons	
	Energy	wt (tons) x soil area x %SOM x 5.4 cal/J x 4186J/kcal	1.25E+09	J/yr	
Groundwater	10	Annual Available Groundwater	2.34E+07	m^3	
		(available water) x Density H_2O(g/cm^3) x (J/g)	1.15E+14	J/yr	
Carbon Sink		(volume) x (Chem. Pot energy) x (4,940 J/kg) x 1000kg/m3	1.21E+14	J/yr	
		40% x rain chemical	4.84E+13	J/yr	

Cattle	15	Cattle	6.00E+02		
		Turnover Rate (TR)	2.25E+00		
		Weight	5.76E+03	g/h	
		Energy of cattle	2.82E+00	kcal/g	
		(Cattle) x (TR) X (weight) x (Energy) x (Joule/kcal)	2.19E+07	J/y	
Well water Pumped		44,300,000kg Digester + 76,595,900 kg (cattle and operations)	1.21E+08	kg	
		Potential Energy	4.94E+03	J/kg	
		Total Water	5.97E+11	J	
Machinery		TW all machinery	8.35E+04	kg	Estimate
		TW/acres/15 y life	2.33E+00	kg	
		c	3.00E+08	m/s	
		kg * c	6.98E+08	J	
Electricity		energy in kWh	3.60E+06	J/kWh	Collected in study
		Estimated Electricity with biogas	2.72E+09	kWh/yr	
		Estimated Electricity without	1.37E+08	kWh/yr	
		total biogas	9.80E+15	J/yr	
		total without	3.73E+17	j/yr	
Petro Products	9	Total Fuel Use	3961.905	bbl	Estimate
		Barrel	2.38E-02	bbl	
		Energy in Barrel	6.28E+09	J/bbl	
		PFW x Barrel x Energy Barrel	5.92E+11	J/yr	
Methane	21	Well	6.31E+03	bbl	collected in study
		Barrel	2.38E-02	bbl	
		Energy in Barrel	6.28E+09	J/bbl	
		PFW x Barrel x Energy Barrel	9.44E+11	J/yr	
Methane	20	PFW	4.24E+03	bbl	collected in study
		Barrel	2.38E-02	bbl	
		Energy in Barrel	6.28E+09	J/bbl	
		PFW x Barrel x Energy Barrel	6.34E+11	J/yr	
	22	Electricity PFW	1.39E+05	kWh/yr	Collected in Study
		energy in kWh	3.60E+06	J/kWh	
		Electricity PFW x energy kWh	5.00E+11	J/yr	
	23	Electricity Well Water	9.30E+04	kWh	Collected in Study
		energy in kWh	3.60E+06	J/kWh	
		Electricity Well Water x energy kWh	3.35E+11	J/yr	
Nutrients	24	5810000 kg manure x 1000	5810000	kg/yr	
		5.79% N in sludge collected in study (avg)	342.79	kg N/yr	collected in study
		c	3.00E+08	m/s	
		kg * c	1.03E+11	J/yr	
Digester Const. Materials	17	Includes PVC, Plastic, Wood, Steel and Concrete	19068180	g/yr	Ciotola, 2011
			19068.18	kg/yr	
		c	3.00E+08	m/s	
		c* kg	5.72E+12	J/yr	

STELLA EMERGY MODEL CODE

```
Purchased_Inputs.Biogas[Biogas_Option]
Purchased_Inputs.Biogas_Selection[Biogas_Option]
Purchased_Inputs.PFW_Selector[Producedyesorno]
Purchased_Inputs.Well_Selector[Wellyesorno]

Biogas_Option = No,Yes
Producedyesorno = Yes,No
Wellyesorno = Yes,No

: S Nance_Ranch.EM_$ = 0
: S Nance_Ranch.Total_Inputs = 0
: S "Non-renewable_Inputs"."Total_Non-Renewable" = 0
: S Products.Total_Emergy_Outputs = 0
: S Purchased_Inputs."Total_External_Inputs_(seJ)" = 0
UNITS: seJ
: S Renewable_Inputs.Total_Renewable_Emergy = 0
UNITS: seJ
: f Nance_Ranch.Non_Renewable = "Non-renewable_Inputs"."Total_Non-Renewable"
: f Nance_Ranch.Products = Total_Inputs/1.39*10^12
: f Nance_Ranch.Purchased = Purchased_Inputs."Total_External_Inputs_(seJ)"
: f Nance_Ranch.Renewable = Renewable_Inputs.Total_Renewable_Emergy
: c "Non-renewable_Inputs"."Available_Groundwater_(acre-ft)" = 18952.0814
UNITS: acre foot
: c "Non-renewable_Inputs".GW_Converter = "Available_Groundwater_(acre-
ft)"*1233.48
UNITS: Cubic Meters: c "Non-renewable_Inputs".Density_Water = 997000
UNITS: grams per cubic meter
: c "Non-renewable_Inputs"."J/g" = 4.94
UNITS: Joule per gram
: c "Non-renewable_Inputs".Groundwater_Transformity = 159000
: f "Non-renewable_Inputs".Groundwater =
(GW_Converter*Density_Water*"J/g")/Groundwater_Transformity
: c "Non-renewable_Inputs".Bulk_Density = 1.5
UNITS: gram per cubic centimeter
: c "Non-renewable_Inputs".Acres = 2393
: c "Non-renewable_Inputs".Converter = .0005
: c "Non-renewable_Inputs".Soil_Organic_Matter = 2.13
UNITS: Percentage
: c "Non-renewable_Inputs".SOM_Converter = Soil_Organic_Matter/100
: c "Non-renewable_Inputs".Soil_Coverage = 95
UNITS: percentage
: c "Non-renewable_Inputs".SC_Converter = Soil_Coverage/100
UNITS: Dimensionless
: c "Non-renewable_Inputs"."cal/J" = 5.4
```

```
UNITS: cal/J
: c "Non-renewable_Inputs"."J/Kcal" = 4186
UNITS: J/kcal
: c "Non-renewable_Inputs".Soil_Transformity = 1680000000
UNITS: seJ/J
: f "Non-renewable_Inputs".Soil_Loss =
((((Bulk_Density*62.4*24393.6)*Acres)*Converter)*SOM_Converter*SC_Converter*"c
al/J"*"J/Kcal")/Soil_Transformity
: c Products."#of_Cattle" = 600
: c Products.Death_Loss = 5
UNITS: Percentage
: c Products.Turnover_Rate = 2.25
: c Products.Energy = 2.82
UNITS: kcal/g
: c Products.Average_Weight = 900
UNITS: lbs
: f Products.Cattle =
"#of_Cattle"*Death_Loss*Turnover_Rate*Energy*(Average_Weight*0.453592)
: c Products.PFW_kwh = 93000
: c Products.Well_kWh = 0
: c Products.Electricity_Produced = PFW_kwh+Well_kWh
: c Products.Percentage_Electricity = .5
UNITS: percentage
: c Products.Electricity_Tranformity = 1.19*10^6
UNITS: seJ/J
: f Products.Electricity =
(Electricity_Produced*Percentage_Electricity)/Electricity_Tranformity
: c Products.Percentage_Fuel = .5
UNITS: percentage
: c Products."Well_(L)" = 0
: c Products."PFW_(L)" = 47000
: c Products.Fuel_Produced = "Well_(L)"+"PFW_(L)"
: c Products.Fuel_Transformity = 2.48*10^5
UNITS: seJ/J
: f Products.Fuel = (Percentage_Fuel*Fuel_Produced)/Fuel_Transformity
: f Products.Output = Total_Emergy_Outputs
: c Products.N = 0.0579
UNITS: Percentage
: c Products.Total_Weight = 5810000
UNITS: kg
: c Products.N_transformity = 8.49*10^10
UNITS: seJ/J
: f Products.Sludge_Nutrients_for_Application = (N*Total_Weight)/N_transformity
: c Purchased_Inputs.Biogas_Selection[No] = 0
UNITS: Dimensionless
: c Purchased_Inputs.Biogas_Selection[Yes] = 1
```

```
UNITS: Dimensionless
UNITS: Dimensionless
: c Purchased_Inputs."Materials_(J)" = Biogas_Selection[No]*5.72*10^12
: c Purchased_Inputs.Concrete_Transformity = 9.26*10^7
UNITS: seJ/J
: f Purchased_Inputs.Digester_Construction_Materials =
"Materials_(J)"/Concrete_Transformity
UNITS: seJ/Months
: c Purchased_Inputs."kWh/yr" = 3.7
: c Purchased_Inputs.Biogas[No] = 1
: c Purchased_Inputs.Biogas[Yes] = 1
: c Purchased_Inputs.Electric_Transformity = 1.19*10^6*Biogas[No]
UNITS: seJ/J
: f Purchased_Inputs.Electricity = "kWh/yr"/Electric_Transformity
UNITS: seJ/Months
: c Purchased_Inputs.Average_Cattle_Weight = 575
UNITS: pounds
: c Purchased_Inputs.Weight_Converter = 453.592*Average_Cattle_Weight
UNITS: Grams
: c Purchased_Inputs.Days = 365
UNITS: Year
: c Purchased_Inputs."J/kcal" = 4186
UNITS: J/kcal
: c Purchased_Inputs."%_BW" = 1.7
UNITS: percentage
: c Purchased_Inputs.Converter_1 = "%_BW"/100
UNITS: Dimensionless
: c Purchased_Inputs."mcal/lb" = 1.66
UNITS: mcal/lb
: c Purchased_Inputs.energy_converter = ("mcal/lb"*2.2046)/1000
UNITS: kcal/g
: c Purchased_Inputs.Feed_Transformity = 6.8*10^4
: f Purchased_Inputs.Feed_Emergy =
(Weight_Converter*Days*"J/kcal"*Converter_1*energy_converter)/Feed_Transformity
UNITS: seJ/Months
: c Purchased_Inputs."#_of_Cattle" = 600
UNITS: Dimensionless
: c Purchased_Inputs.Turnover_Rate = 2.25
UNITS: Dimensionless
: c Purchased_Inputs."kcal/g" = 2.82
: c Purchased_Inputs.Cattle_Transformity = 200000
UNITS: seJ/J
: f Purchased_Inputs.Input_Cattle_Emergy =
("#_of_Cattle"*Weight_Converter*Turnover_Rate*"kcal/g")/Cattle_Transformity
UNITS: seJ/Months
: c Purchased_Inputs.Machinery_Weight = 83536 UNITS: kg
```

```
: c Purchased_Inputs.Machinery_Transformity = 6.79*10^9
UNITS: seJ/J
: f Purchased_Inputs.Machinery =
Machinery_Weight*300000000/Machinery_Transformity
UNITS: seJ/Months
: c Purchased_Inputs."gal/yr" = Biogas[No]*3961.905
UNITS: b
: c Purchased_Inputs.Petroleum_Transformity = 8.70*10^4
UNITS: seJ/J
: f Purchased_Inputs.Petroleum = "gal/yr"/Petroleum_Transformity
UNITS: seJ/Months
: c Purchased_Inputs.PFW_Selector[Yes] = 1
: c Purchased_Inputs.PFW_Selector[No] = 0
: c Purchased_Inputs.PFW = 1.13*10^12*PFW_Selector[No]
: c Purchased_Inputs.PFW_Transformity = 1.64*10^5
UNITS: seJ/J
: f Purchased_Inputs.Produced_Water = PFW/PFW_Transformity
UNITS: seJ/Months
: c Purchased_Inputs.Well_Selector[Yes] = 1
: c Purchased_Inputs.Well_Selector[No] = 0
: c Purchased_Inputs.Well_Water_Pumped = 5.97*10^11*Well_Selector[Yes]
UNITS: J
: c Purchased_Inputs.Well_Water_Pumped_Transformity = 2.55*10^5
UNITS: seJ/J
: f Purchased_Inputs.Well_Water =
Well_Water_Pumped/Well_Water_Pumped_Transformity
UNITS: seJ/Months
: c Purchased_Inputs."STD,_DEV_Feed" = .1
UNITS: pounds
: c Renewable_Inputs.Solar_Insolation = 19083168.00
UNITS: Joules/squared meters/day
: c Renewable_Inputs.Albedo = 0.18
: c Renewable_Inputs.Albedo_Correction = 1-Albedo
UNITS: Dimensionless
: c Renewable_Inputs."Days/Year" = 365
UNITS: year
: c Renewable_Inputs.Area_Acres = 2393
UNITS: Acres
: c Renewable_Inputs.Acre_Metric_Converter = Area_Acres*4046.86
UNITS: squared meters
: c Renewable_Inputs.Area = Acre_Metric_Converter
UNITS: Square Meters
: c Renewable_Inputs.Raw_Solar_Energy =
Solar_Insolation*Albedo_Correction*"Days/Year"*Area
UNITS: Joules
: c Renewable_Inputs.Solar_Transformity = 1
```

```
UNITS: seJ/J
: f Renewable_Inputs.Solar_Emergy = Raw_Solar_Energy/Solar_Transformity
UNITS: seJ/Months
: c Renewable_Inputs.Average_Weight = 900
UNITS: pounds
: c Renewable_Inputs.Animal_Unit = 1000
UNITS: Pounds
: c Renewable_Inputs."Weight/Animal_Unit" = ((Average_Weight*Animal_Unit)*65)
UNITS: Grams
: c Renewable_Inputs.Feedlot_Capacity = 600
UNITS: Dimensionless
: c Renewable_Inputs.Turnover_Rate = 2.25
UNITS: Dimensionless
: c Renewable_Inputs.Metric_Weight_Converter = 453.592
UNITS: gram
: c Renewable_Inputs.Mass_Manure =
"Weight/Animal_Unit"*Feedlot_Capacity*Turnover_Rate*Metric_Weight_Converter
: c Renewable_Inputs.Speed_of_Light = 300000000
UNITS: m/s
: c Renewable_Inputs.Energy = Mass_Manure*(Speed_of_Light^2)
UNITS: Joules
: c Renewable_Inputs.Manure_Transformity = 1.13*10^8
UNITS: seJ/J
: f Renewable_Inputs.Manure_Emergy = Energy/Manure_Transformity
UNITS: seJ/Months
: c Renewable_Inputs."Average_Annual_Rainfall_(in)" = 20.15
UNITS: Inches
: c Renewable_Inputs.Metric_Converter = "Average_Annual_Rainfall_(in)"*0.0254
UNITS: Meters
: c Renewable_Inputs.Volume_Rainfall = Metric_Converter*Area
UNITS: cubic meters per year
: c Renewable_Inputs.Potential_Energy_Water = 4940
UNITS: Joule per kilogram
: c Renewable_Inputs.Density_Water = 997000
UNITS: grams per cubic meter
: c Renewable_Inputs.Change_in_Elevation = 978777.6
UNITS: meters
: c Renewable_Inputs.Geopotential_Energy =
Volume_Rainfall*Potential_Energy_Water*Density_Water*Change_in_Elevation
UNITS: Joules
: c Renewable_Inputs.Geopotential_Transformity = 11000
UNITS: seJ/J
: c Renewable_Inputs.Chemical_Energy = Volume_Rainfall*4940*1000
UNITS: Joules
: c Renewable_Inputs.Chemical_Transformity = 15444
UNITS: seJ/J
```

```
: f Renewable_Inputs.Rain_Emergy = (Geopotential_Energy/Geopotential_Transformity)+(Chemical_Energy/Chemical_Transformity)
UNITS: seJ/Months
: c Renewable_Inputs.Air_Density = 1.3
UNITS: kilogram/cubic meter
: c Renewable_Inputs.Average_Annual_Wind = 13.7773
UNITS: Miles Per Hour
: c Renewable_Inputs.Geostrophic_Wind = Average_Annual_Wind*0.6
UNITS: Miles Per Hour
: c Renewable_Inputs."m/s" = 0.4474
UNITS: meters/second
: c Renewable_Inputs.Drag_Coeffiecient = 0.00163
UNITS: Dimensionless
: c Renewable_Inputs."seconds/year" = 86400*"Days/Year"
UNITS: Seconds/year
: c Renewable_Inputs.Wind_Transformity = (1.58*10^3)
UNITS: seJ/J
: f Renewable_Inputs.Wind_Emergy = (Area*Air_Density*(Geostrophic_Wind*"m/s")*Drag_Coeffiecient*"seconds/year")/Wind_Transformity
UNITS: seJ/Months

{ RUNTIME EQUATIONS }
: S Nance_Ranch.EM_$(t) = EM_$(t - dt) + (Products) * dt
: S Nance_Ranch.Total_Inputs(t) = Total_Inputs(t - dt) + (Non_Renewable + Renewable + Purchased - Products) * dt
: S "Non-renewable_Inputs"."Total_Non-Renewable"(t) = "Total_Non-Renewable"(t - dt) + (Soil_Loss + Groundwater) * dt
: S Products.Total_Emergy_Outputs(t) = Total_Emergy_Outputs(t - dt) + (Cattle + Fuel + Electricity + Sludge_Nutrients_for_Application - Output) * dt
: S Purchased_Inputs."Total_External_Inputs_(seJ)"(t) = "Total_External_Inputs_(seJ)"(t - dt) + (Input_Cattle_Emergy + Feed_Emergy + Digester_Construction_Materials + Machinery + Petroleum + Electricity + Produced_Water + Well_Water) * dt
UNITS: seJ
: S Renewable_Inputs.Total_Renewable_Emergy(t) = Total_Renewable_Emergy(t - dt) + (Solar_Emergy + Wind_Emergy + Rain_Emergy + Manure_Emergy) * dt
UNITS: seJ
: f Nance_Ranch.Non_Renewable = "Non-renewable_Inputs"."Total_Non-Renewable" {UNIFLOW}
: f Nance_Ranch.Products = Total_Inputs/1.39*10^12 {UNIFLOW}
: f Nance_Ranch.Purchased = Purchased_Inputs."Total_External_Inputs_(seJ)" {UNIFLOW}
: f Nance_Ranch.Renewable = Renewable_Inputs.Total_Renewable_Emergy {UNIFLOW}
```

```
: c "Non-renewable_Inputs".GW_Converter = "Available_Groundwater_(acre-
ft)"*1233.48
UNITS: Cubic Meters
: f "Non-renewable_Inputs".Groundwater =
(GW_Converter*Density_Water*"J/g")/Groundwater_Transformity {UNIFLOW}
: c "Non-renewable_Inputs".SOM_Converter = Soil_Organic_Matter/100
: c "Non-renewable_Inputs".SC_Converter = Soil_Coverage/100
UNITS: Dimensionless
: f "Non-renewable_Inputs".Soil_Loss =
((((Bulk_Density*62.4*24393.6)*Acres)*Converter)*SOM_Converter*SC_Converter*"c
al/J"*"J/Kcal")/Soil_Transformity {UNIFLOW}
: f Products.Cattle =
"#of_Cattle"*Death_Loss*Turnover_Rate*Energy*(Average_Weight*0.453592)
{UNIFLOW}
: c Products.Electricity_Produced = PFW_kwh+Well_kWh
: c Products.Electricity_Tranformity = 1.19*10^6
UNITS: seJ/J
: f Products.Electricity =
(Electricity_Produced*Percentage_Electricity)/Electricity_Tranformity {UNIFLOW}
: c Products.Fuel_Produced = "Well_(L)"+"PFW_(L)"
: c Products.Fuel_Transformity = 2.48*10^5
UNITS: seJ/J
: f Products.Fuel = (Percentage_Fuel*Fuel_Produced)/Fuel_Transformity {UNIFLOW}
: f Products.Output = Total_Emergy_Outputs {UNIFLOW}
: c Products.N_transformity = 8.49*10^10
UNITS: seJ/J
: f Products.Sludge_Nutrients_for_Application = (N*Total_Weight)/N_transformity
{UNIFLOW}
: c Purchased_Inputs."Materials_(J)" = Biogas_Selection[No]*5.72*10^12
: c Purchased_Inputs.Concrete_Transformity = 9.26*10^7
UNITS: seJ/J
: f Purchased_Inputs.Digester_Construction_Materials =
"Materials_(J)"/Concrete_Transformity {UNIFLOW}
UNITS: seJ/Months
: c Purchased_Inputs.Electric_Transformity = 1.19*10^6*Biogas[No]
UNITS: seJ/J
: f Purchased_Inputs.Electricity = "kWh/yr"/Electric_Transformity {UNIFLOW}
UNITS: seJ/Months
: c Purchased_Inputs.Weight_Converter = 453.592*Average_Cattle_Weight
UNITS: Grams
: c Purchased_Inputs.Converter_1 = "%_BW"/100
UNITS: Dimensionless
: c Purchased_Inputs.energy_converter = ("mcal/lb"*2.2046)/1000
UNITS: kcal/g
: c Purchased_Inputs.Feed_Transformity = 6.8*10^4
```

```
: f Purchased_Inputs.Feed_Emergy =
(Weight_Converter*Days*"J/kcal"*Converter_1*energy_converter)/Feed_Transformity
{UNIFLOW}
UNITS: seJ/Months
: f Purchased_Inputs.Input_Cattle_Emergy =
("#_of_Cattle"*Weight_Converter*Turnover_Rate*"kcal/g")/Cattle_Transformity
{UNIFLOW}
UNITS: seJ/Months
: c Purchased_Inputs.Machinery_Transformity = 6.79*10^9
UNITS: seJ/J
: f Purchased_Inputs.Machinery =
Machinery_Weight*300000000/Machinery_Transformity {UNIFLOW}
UNITS: seJ/Months
: c Purchased_Inputs."gal/yr" = Biogas [No]*3961.905
UNITS: b
: c Purchased_Inputs.Petroleum_Transformity = 8.70*10^4
UNITS: seJ/J
: f Purchased_Inputs.Petroleum = "gal/yr"/Petroleum_Transformity {UNIFLOW}
UNITS: seJ/Months
: c Purchased_Inputs.PFW = 1.13*10^12*PFW_Selector[No]
: c Purchased_Inputs.PFW_Transformity = 1.64*10^5
UNITS: seJ/J
: f Purchased_Inputs.Produced_Water = PFW/PFW_Transformity {UNIFLOW}
UNITS: seJ/Months
: c Purchased_Inputs.Well_Water_Pumped = 5.97*10^11*Well_Selector[Yes]
UNITS: J
: c Purchased_Inputs.Well_Water_Pumped_Transformity = 2.55*10^5
UNITS: seJ/J
: f Purchased_Inputs.Well_Water =
Well_Water_Pumped/Well_Water_Pumped_Transformity {UNIFLOW}
UNITS: seJ/Months
: c Renewable_Inputs.Albedo_Correction = 1-Albedo
UNITS: Dimensionless
: c Renewable_Inputs.Acre_Metric_Converter = Area_Acres*4046.86
UNITS: squared meters
: c Renewable_Inputs.Area = Acre_Metric_Converter
UNITS: Square Meters
: c Renewable_Inputs.Raw_Solar_Energy =
Solar_Insolation*Albedo_Correction*"Days/Year"*Area
UNITS: Joules
: f Renewable_Inputs.Solar_Emergy = Raw_Solar_Energy/Solar_Transformity
UNITS: seJ/Months
: c Renewable_Inputs."Weight/Animal_Unit" = ((Average_Weight*Animal_Unit)*65)
UNITS: Grams
: c Renewable_Inputs.Mass_Manure =
"Weight/Animal_Unit"*Feedlot_Capacity*Turnover_Rate*Metric_Weight_Converter
```

```
: c Renewable_Inputs.Energy = Mass_Manure*(Speed_of_Light^2)
UNITS: Joules
: c Renewable_Inputs.Manure_Transformity = 1.13*10^8
UNITS: seJ/J
: f Renewable_Inputs.Manure_Emergy = Energy/Manure_Transformity {UNIFLOW}
UNITS: seJ/Months
: c Renewable_Inputs.Metric_Converter = "Average_Annual_Rainfall_(in)"*0.0254
UNITS: Meters
: c Renewable_Inputs.Volume_Rainfall = Metric_Converter*Area
UNITS: cubic meters per year
: c Renewable_Inputs.Geopotential_Energy =
Volume_Rainfall*Potential_Energy_Water*Density_Water*Change_in_Elevation
UNITS: Joules
: c Renewable_Inputs.Chemical_Energy = Volume_Rainfall*4940*1000
UNITS: Joules
: f Renewable_Inputs.Rain_Emergy =
(Geopotential_Energy/Geopotential_Transformity)+(Chemical_Energy/Chemical_Transformity) {UNIFLOW}
UNITS: seJ/Months
: c Renewable_Inputs.Geostrophic_Wind = Average_Annual_Wind*0.6
UNITS: Miles Per Hour
: c Renewable_Inputs."seconds/year" = 86400*"Days/Year"
UNITS: Seconds/year
: c Renewable_Inputs.Wind_Transformity = (1.58*10^3)
UNITS: seJ/J
: f Renewable_Inputs.Wind_Emergy =
(Area*Air_Density*(Geostrophic_Wind*"m/s")*Drag_Coeffiecient*"seconds/year")/Wind_Transformity {UNIFLOW}
UNITS: seJ/Months
```