THESIS

SOLID WASTE MANAGEMENT: A COMPARATIVE CARBON FOOTPRINT AND COST ANALYSIS

Submitted by

Andy Carroll

Department of Civil and Environmental Engineering

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Master's Committee:

Advisor: Sybil Sharvelle
Co Advisor: Christopher A. Bareither

Jason Quinn

ABSTRACT

SOLID WASTE MANAGEMENT: A COMPARATIVE CARBON FOOTPRINT AND COST ANALYSIS

As the world's urban population continues to grow, the need to efficiently manage the resulting solid waste generation will become increasingly important. Currently, most of the world's solid waste is landfilled or disposed of in open dumps. Landfilling organic solid waste leads to the production of methane, which is a strong greenhouse gas (GHG). In addition, urban areas with high densities and limited open land may find it hard to accommodate large landfill footprints. Thus, increased awareness of climate change and landfill diversion has prompted many municipalities and solid waste planners to find synergistic waste management alternatives to landfilling. However, waste management strategies vary from region to region, so site-specific data and analysis are often required to determine appropriate waste management options. A carbon footprint study using life cycle analysis (LCA) was conducted to compare multiple scenarios of organic waste management strategies for two cities: Fort Collins, Colorado, USA and Todos Santos, Baja California Sur, Mexico. Fort Collins is a progressive city within the developed world, and has a strong green ethic, whereas Todos Santos is considered to be in the developing world, where resources are not as abundant and financial limitations exist. LCA is a cradle-to-grave analysis tool designed to assess the environmental impacts of a process. A side-by-side comparison of GHG emissions associated with site-specific organic waste management options was conducted for each city. Along with the environmental impacts, the economic aspects of waste management are important in any city, especially Todos Santos. Thus, a cost analysis of compost facilities and recycling was conducted for Todos Santos.

In Fort Collins, four scenarios were compared to the status quo of landfilling organic waste, deemed the No-Action Scenario. The four scenario were: Scenario AD 1 - anaerobic digestion of

commercial food waste, and the remainder of organic waste being composted regionally using a transfer station; Scenario AD 2 - anaerobic digestion of commercial food waste with co-generation, with the remainder of organic waste being composted regionally without using a transfer station; Scenario Regional Compost with TS - Regional compost of all organic waste using a transfer station; and Scenario Regional Compost without TS - Regional compost of all organic waste without using a transfer station. The functional unit was one metric ton (Mg) of organic waste diverted from the landfill. The only environmental impact category analyzed was GHG emissions expressed as kg CO_2 equivalents; thus, this study is referred to as carbon footprint, instead of a full ISO standard LCA. Scenario AD 1 was found to produce the least GHG emissions (130.7 kg CO_2 equivalents/functional unit), followed by Scenario AD 2 (168.8 kg CO_2 equivalents/functional unit), Scenario Regional Compost with TS (197.1 kg CO_2 equivalents/functional unit), Scenario Regional Compost without TS (249.8 kg CO_2 equivalents/functional unit), and finally the No-Action Scenario produced the most GHG emissions (780.4 197.1 kg CO_2 equivalents/functional unit).

The primary reason the No-Action Scenario produces the highest GHG emissions is because Fort Collins sends municipal solid waste (MSW) to two different landfills: one with landfill gas (LFG) collection and one without. This analysis found that GHG emissions due to landfilling could be greatly reduced (69%) if all organic waste is sent to the landfill with a LFG collection system. In addition, if Fort Collins reduces the number of current waste haulers from three to one, there would be a drop in emissions of 7% for the No-Action Scenario, 29% for Scenario AD 1, 44% for Scenario AD 2, 20% for Scenario Regional Compost with TS, and 36% for Scenario Regional Compost without TS.

Todos Santos does not have an engineered landfill. Solid waste is collected and transported to an open dump on the outskirts of the city. Two different scenarios were compared to the status quo, or No-Action Scenario, of landfilling organic waste. The scenarios were: Scenario Local WC - Organic waste is composted locally at the current landfill using windrow composting); and Scenario Local SAC - Organic waste is composted locally using static aeration composting. The functional unit and environmental impact categories were the same as the Fort Collins analysis. Scenario Local WC produced the lowest GHG emissions (101.5 kg CO_2 equivalents/functional unit), followed by Scenario Local SAC (153.9 kg CO_2 equivalents/functional unit), and finally the No-Action Scenario produced the most GHG emissions (1,487.9 kg CO_2 equivalents/functional unit). The lack of LFG capture at the current landfill explains the high GHG emissions. The primary difference between static aerated and windrow compost regarding GHG emissions is static aerated compost produces higher nitrous oxide and methane emissions than windrow compost. While windrow and static aerated compost produce lower GHG emissions than landfilling, the financial conditions for compost in Todos Santos are unknown. A capital cost analysis found that a windrow compost facility would cost about 1.5 times more than a static aerated compost facility; however, the demand and revenue from selling compost would still need to be analyzed prior to implementation of a compost facility.

Recycling in Todos Santos is not as established as recycling in Fort Collins. Currently, there is a small drop-off recycling facility in Todos Santos called Punto Verde. Utilizing best available data, it is estimated that Punto Verde only collects about 1% of the total available recyclables. If 100% of the recyclables are collected the value is estimated to be about $87,000 per year. However, increasing recycling rates in Todos Santos is difficult due to long transportation routes, lack of government support, and cultural attitudes that have not embraced recycling as the norm. This analysis has shown that there is a potential revenue stream for recyclables in Todos Santos; however, education campaigns, financial incentives, and key stakeholder support are needed to improve recycling rates.

This study found that landfilling without LFG capture produced the most GHG emissions in both a developed, environmentally progressive city, and a city in a developing country with economic and cultural restraints surrounding sustainable waste management. Furthermore, this study highlighted the need for site-specific analysis when assessing waste management improvements for a city or municipality. Transfer stations and efficient waste collection will vary by location, but are important to quantify as transportation plays a key role in waste management. In addition, selecting feasible alternatives to the status quo will require conversations with stakeholders and assessment of site-specific data, ideally before any assessment is conducted.

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Chapter 1: Introduction

Over the next 20 to 30 years the world will experience large increases in urban populations, especially in developing countries (United Nations, 2014). With this increase comes the need to effectively manage the resulting solid waste in a way that is beneficial for both human and environmental health. Solid waste management is also a contributor to climate change. Municipal solid waste accounts for nearly 5% of total global greenhouse gas emissions, and 12% of global methane (CH_4) emissions are generated from landfills (World Bank, 2012). Thus, implementing integrated solid waste management (ISWM) programs in developed and developing countries will become increasingly important to maintain human health and environment sustainability.

ISWM is defined as a comprehensive waste prevention, recycling, composting, and disposal program (EPA, 2002). A schematic of ISWM strategies from the U.S. Environmental Protection Agency (EPA) is shown in Figure 1. Waste management strategies rank from source reduction being the most preferred, followed by recycling, energy recovery, treatment, and finally disposal. Furthermore, a major goal of ISWM in low-, middle-, and high-income countries is a paradigm shift toward viewing waste as a resource as opposed to a burden. This can be achieved through various recycling programs, waste-to-energy technologies, and treatments such as composting. Generally, these waste management techniques are more commonly applied in high-income countries than low- to middle-income countries, due to available funding, professional expertise, and project feasibility. In many low- to middle-income countries, open dumping/burning is the usual method for waste management; however, there is a growing push away from this due to the negative consequences on public and environmental well-being. Regardless of a country's developmental status, designing or analyzing waste management strategies requires consideration of social, environmental, and financial factors. This study presents two site-specific analyses on waste management. The first is in a community in the developed world. i.e. Fort

Collins, CO, and the second is in a developing country with economic and resource limitations, i.e. Todos Santos, Mexico.

Figure 1: Waste management hierarchy developed by the U.S. EPA. Figure taken from (United States Environmental Protection Agency, 2017).

1.1 Fort Collins, Colorado

Fort Collins, Colorado is a Northern Colorado city with a population of 164,207 as of 2016. The city is growing rapidly at about 2% per year ("Fort Collins Population," 2016), which puts increased pressure on solid waste management. As the population increases, Fort Collins strives to reduce the amount of landfilled waste. A portion of waste from Fort Collins is sent to the Larimer County Landfill (LCL), which is estimated to reach capacity between 2025 and 2028. The remaining portion is sent to North Weld Landfill. This privately-owned facility is expected to reach capacity by 2021-2022 (Waste Management, 2016). In 1999, the City of Fort Collins municipality adopted a community waste diversion goal of 50% by 2010 deemed the Road to Zero Waste (Zero Waste, 2013). Diversion refers to materials generated within Fort Collins that are recycled or composted. In 2014, Fort Collins achieved a 68.4% diversion rate, and has since set new goals of 75% by 2020, 90% by 2025, and zero waste by 2030.

In addition to reducing waste sent to the landfill, Fort Collins has also adopted ambitious goals regarding greenhouse gas (GHG) emissions. Among these are reducing GHG emissions 20% below the 2005 levels by 2020, 80% below the 2005 levels by 2030, and carbon neutral by 2050 (City of Fort Collins, 2015). Waste management can play an integral role in reducing GHG emissions by eliminating organic materials from the landfill. Organic waste can decompose anaerobically in a landfill and produce a mixture of gas that is approximately 50% carbon dioxide (CO_2) and 50% CH_4. The CO_2 is considered biogenic, i.e., produced by natural decomposition process. However, the CH_4 produced occurred due to anthropogenic activities and is considered non-biogenic. In addition, CH_4 is a GHG that is 25 times more efficient at trapping atmospheric heat than CO_2. Thus, diverting organic waste from the landfill not only helps achieve goals set forth in the Road to Zero Waste, but can also help reduce GHG emissions.

1.2 Todos Santos, Baja California Sur, Mexico

Todos Santos is a small town on the west coast of Baja California Sur with a population of 5,148 as of 2010. Similar to Fort Collins, Todos Santos is experiencing increased growth rates with the population increasing by 25% from 2005 to 2010 (Pickering et al., 2015). Although the downtown is kept fairly litter free, there is not an effective waste management strategy for final disposal. Garbage can be found scattered throughout the natural landscape, even encroaching onto natural preserves. In a community-needs assessment conducted in 2015, waste management was highlighted as a community priority, and more specifically, public health, environmental health, “visual contamination”, and lack of cultural awareness surrounding waste and proper disposal were community concerns (Pickering et al., 2015).

Although the need for better waste management has been highlighted by the community, there are several hurdles. An obvious constraint is the financial requirements of waste management programs. Collection costs alone can take up to 80-90% of the total solid waste management budget, leaving limited financial resources for proper-end-of-life disposal (United Nations, 2011). However, increasing efficiencies throughout a waste management system as well as creative financing methods such as public-private partnerships can reduce costs. The support of the citizens and government is critical when implementing any civil infrastructure project. In addition, cultural attitudes about waste management take time to change. Transitioning from the status quo of waste management in Todos Santos will require educational campaigns, financial incentives, and key stakeholder support. In Todos Santos, there is evidence of this culture change beginning to take place in the form of a small recycling facility, supportive local government personnel, and educational opportunities for children.

1.3 Objectives

The objective of this study was to use a common methodology to compare and highlight beneficial solid waste management options for two very different municipalities. In both Fort Collins and Todos Santos, a carbon footprint, using life cycle analysis (LCA) methodology, was used to compare GHG emissions for various organic waste management scenarios. In addition, a financial analysis was conducted for recycling and composting in Todos Santos. This analysis is designed to span the triple bottom line, i.e., social, environmental, and economic conditions and factors.

Chapter 2: BACKGROUND

2.1 Site Information

Fort Collins, Colorado, USA

Fort Collins, Colorado has an established and effective waste management program. Unlike most cities, the waste collection system in Fort Collins is conducted via three commercial waste haulers, instead of the more common approach whereby the municipality handles all waste collection. Consumers are allowed to choose which hauler to employ, and payment is based on the amount of volume residents generate. This system is referred to as "pay-as-you-throw" (PAYT), where residents pay different rates based on the size of their trash cans. This type of policy is designed to decrease household waste generation, based on the incentive that the less waste a resident generates the less they will have to pay for collection. Fort Collins has several different end stages for MSW disposal including landfill, compost facilities, and recycling.

Landfill

Fort Collins sends MSW to two different landfills; approximately 56% is sent to the Larimer County Landfill and 44% is sent to North Weld Landfill Management Facility (City of Fort Collins Staff, personal communication, 2016). The Larimer County Landfill employs a landfill gas capture system where the collected gas is flared. According the Larimer County website, tipping fees for 2017 are $6.05 per cubic yard for household trash, commercial waste, and green waste. Compacted waste has a tipping fee of $6.97/cubic yard. The Larimer County Landfill is expected to reach capacity around 2025 (Carcasson, 2016).

The North Weld Landfill is owned and operated by Waste Management. The landfill has a voluntary landfill gas collection system, in which collected gas is passed through an activated carbon filtration system to control odor (Waste Management, 2016). Since activated carbon filtration does not remove methane, the North Weld Landfill is modeled as having no landfill gas collection system for the purposes of quantifying GHG emissions. The landfill is expected to close by between 2021-2022 (Waste Management, 2016)

Compost

Composting is a well understood and utilized technique for organic waste management. For the purposes of this analysis, a privately owned and operated windrow composting facility within Larimer County was analyzed. Windrow compost requires heavy duty machinery and is a technique usually employed in large-scale composting facilities. The compost piles are physically turned to introduce oxygen and promote effective composting. The facility modeled in this analysis is located in Eaton, Colorado and accepts organic waste from residential and commercial sources.

Recycling

Fort Collins has single-stream recycling that is built into the cost of waste collection. In other words, residents and businesses who pay for garbage collection automatically receive a collection bin for single-stream recycling. Single-stream recycling is the process of collecting paper, cardboard, plastic containers, metal containers, and glass all in one bin. Fort Collins also has a facility called the Timberline Recycling Center that allows residents and businesses to drop off common recyclables such as cardboard, paper, mixed bottles and cans, and glass for no extra fee. Hard to recycle materials such as paint, motor oil, antifreeze, etc. require a $5 fee. The recycling program in Fort Collins was not analyzed in this study as the focus in Fort Collins was on organic waste management. However, the recycling program in Fort Collins is useful to provide background for potential recycling for Todos Santos.

Todos Santos, Baja California Sur, Mexico

The collection of waste in Todos Santos is not as organized as Fort Collins. In Todos Santos, municipal staff will collect waste from curbsides or in some scenarios from a common drop off location, such as the one displayed in Figure 2. There are no individual bins, and residents usually use trash bags or makeshift bins. The legislation surrounding waste management in Mexico is termed the General Law for the Prevention and Integral Management of Wastes. This law categorizes municipal solid waste into three main categories: household, special handling, and hazardous waste, which are further defined in Table 1. Furthermore, the law classifies three different levels of waste generators. If an individual or entity generates more than 10 Mg of waste per year, they are considered to be a large generator. Small generators are those who generate between 400 kg to 10 Mg per year, and micro generators are those who generate up to 400 kg per year (Basurto et al., 2007). The municipality is responsible for the collection, sweeping, transportation, and final disposal of MSW (US Environmental Protection Agency, 2012).

Figure 2: Garbage that is ready to be picked up by the municipality in Todos Santos.

Small, non-household waste generators are classified as special handling, and the producer of the waste is required to pay for their own waste management. Depending on the state and the signed agreements, household waste is usually handled by the state government. However, through personal conversations with Todos Santos officials, Todos Santos often handles special handling waste in addition to household waste due to lack of state involvement. This puts additional strain on the waste management system in Todos Santos. Large waste generators are also required to pay for the management of waste, but according to Todos Santos officials, larger producers will frequently not pay for the services required, so similar to special handling waste, the municipality ends up collecting the waste for free.

Table 1: Waste Classification in Baja California Sur

Type of Waste	Definition[1]
Household solid waste	Waste generated in the houses; waste that comes from any other activity within establishments or on the road that generates waste with household characteristics, along with waste resulting from the cleaning of roads and public places
Special handling waste	Waste generated in the production processes, which does not meet the characteristics to be considered hazardous or household waste, and is not produced by large household generators
Hazardous waste	Waste that possess some of the characteristics of corrosiveness, reactivity, explosiveness, toxicity, flammability, or containing infectious agents, as well as packaging, containers, soils that have been contaminated

1. Translated from (Verdugo et al., 2016)

In Mexico, many towns like Todos Santos lack the required solid waste collection and disposal technology. Often these services are limited to the head municipality, which for Todos Santos is La Paz, the largest city in Baja California Sur (Buenrostro et al., 2003). Furthermore, the lack of administrative organization between departments in Mexican municipalities can result in poor solid waste management. In most situations, sanitation services is the responsibility of the Deputy Mayor at City

Hall, who is also in charge of public parks, green areas, public cemeteries, etc. (Buenrostro et al., 2003). This can lead to conflicts regarding allocation of funds as well as inadequate staff and time to handle the complexities of solid waste.

Landfill

The current landfill near Todos Santos is more accurately described as an open dump. There are no fees, regulations, or staff to oversee the dump. Additionally, the landfill does not have any type of engineered liner system, landfill gas collection system, or leachate collection system. Currently, waste is collected from Todos Santos five days a week. Waste is also collected from the small neighboring community of El Pescadero once a week and brought to the same landfill. The landfill is expected to reach capacity in the next 10 years (Municipal staff, personal communication, 2017) and the municipal staff of Todos Santos desire a new engineered landfill designed with a weigh station to record waste collection and disposal. However, there does not appear to be an organized or official approach to the new landfill, such that the feasibility of a new, engineered landfill is uncertain.

Compost

Currently there is no city-wide compost operation in Todos Santos. There is at least one small-scale composting operation located at Jazzamango, a local farm-to-table restaurant. Jazzamango has a large garden where they grow a variety of vegetables for their menu, and use their green waste for compost. At present, their operation is small, but there is interest in expanding and collaborating with other parts of Todos Santos. A motivating factor for additional compost is that the local soil is very sandy and makes agriculture difficult, which supports the need for available organic amendments.

Recycling

The only facility that accepts recycling in Todos Santos is a small, grass roots facility called Punto Verde. Punto Verde serves primarily as a free drop-off facility, although staff members will also pick up recyclables. Workers at the facility hand-sort all materials, and then transport the recyclables to either La Paz or Cabo San Lucas, depending on the material. According to Alex Miro, the founder of Punto Verde, the majority of recyclables come from foreigners living in the Todos Santos area, as opposed to native Mexican residents.

2.2 Literature Review

2.2.1 Life Cycle Analysis

Life Cycle Analysis (LCA) is a cradle-to-grave system analysis tool designed to assess the environmental impacts of a product or process. Numerous environmental impacts can be analyzed assuming the necessary data and software are available. Common environmental impacts include global warming, freshwater eutrophication, terrestrial eco-toxicity and acidification, and human toxicity. Although LCA is a relatively new type of analysis, having been developed primarily in the 1990's, the International Organization for Standardization (ISO) has set standards and guidelines for proper LCA practices.

There are two general types of LCA, consequential and attributional. Consequential LCA is designed to provide information on the impacts of a system and consequences that could occur outside of the system or product. Attributional LCA offers information regarding the impacts of the product or system, but does not consider the indirect consequences brought about by the change in the product or system. Consequential LCAs are much more complicated as they rely on economic models, policy changes, and other highly-dependent variables that generate results that should be interpreted with caution (Brander et al., 2008). Distinguishing between the two types of LCA is important before beginning any LCA. All methods used in this paper are based on attributional LCA.

The overall process for conducting an LCA follows four main steps: 1) goal and scope definition, 2) inventory analysis, 3) impact assessment, and 4) interpretation of results (Curran, 2016). The goal and scope must be clearly formulated and expressed before attempting to undertake any type of analysis. According to ISO, the goal of an LCA needs to state the intended application, reasons for the study, and intended audience. The scope is similarly critical and defines the system boundary, the system being analyzed, impact categories, assumptions, limitations, and data necessities. The scope section also contains the functional unit, which is defined as "the function the system delivers at the product or unit level" (Curran, 2016). Assigning functional units to different products or processes is important to develop comparisons. For example, if liquid dishwasher detergent is being compared to powdered dishwasher detergent, the functional unit might be the amount of detergent needed to clean a certain number of dishes.

Inventory analysis is the act of compiling all data requirements for energy and material inputs and is often the most time consuming aspect of LCA (Rebitzer et al., 2004). Various software products with large databases are available to assist in this inventory phase, but users must understand the assumptions made when using these databases. The impact assessment will often vary depending on the LCA. Different impact categories include global warming, freshwater eco-toxicity, mineral resources, ionizing radiation, acidification, eutrophication, among others. Uncertainty associated with various impact assessments should be considered when choosing impact categories (Curran, 2016). Due to the fact that the only impact category chosen for this thesis is GHG emissions, this study is classified as a carbon footprint utilizing LCA methodology instead of a full LCA.

Interpretation of the results of an LCA should consist of at least three phases: identify significant issues from the inventory and impact assessment steps, check and evaluate the completeness and sensitivity results, and state the conclusions, limitations, and recommendations (Curran, 2016). The main objective of the interpretation phase is to determine the degree of confidence in the final results, and to express those results as fairly and accurately as possible. LCA rarely yields a black and white answer, and the complexity contained in the outcome of an LCA needs to be communicated. Often, a sensitivity analysis can be conducted in order to test the effect of system boundaries, parameter values, and impact categories on the overall result of the LCA (Guo et al., 2012). Sensitivity analysis can reduce uncertainty and lead to higher transparency.

2.2.2 Carbon Footprint/LCA as a Tool for Waste Management Decision Making

Life cycle analysis can provide solid waste decision makers with an excellent framework to compare different waste management scenarios (Banar et al., 2009). In addition, as the importance of sustainable waste management increases throughout the world, LCA is being utilized more and more as a tool to improve and analyze current waste management techniques (Laurent et al., 2014). The holistic nature of LCA is ideal for comparing environmental and economic impacts of waste management strategies. However, LCA is often time and data intensive, which is enhanced even more when analyzing complex systems such as solid waste where practices are site-specific. In fact, due to differences in environments and city cultures, local research is often required (Chen et al., 2008).

A literature review of 222 LCA studies by Laurent et al. (2014) led to several important conclusions regarding waste management. Of particular interest was their major finding that the studies were mainly focused in Europe, with only a few in developing countries (Laurent et al., 2014). In addition, Laurent et al. (2014) reported that many of the studies overlooked waste types outside of household waste and found that a generalization of LCA results of waste management techniques is difficult due to local conditions. However, this lack of generalization is exactly what allows for LCA to be a more useful tool than widespread waste management hierarchies such as the “4 R’s”, i.e. reduce, reuse, recycle, and recover. Site-specific characteristics can be built into LCA models, which will lead to more useful conclusions and recommendations for policy makers.

An example of the site-specific nature of LCA can be seen in studies that compare landfilling waste to other waste management options. The majority of LCA papers agree that landfilling solid waste is the least environmentally favorable option when compared to recycling and incineration (Moberg et al., 2005). However, different waste types and local conditions such as transportation, technology, temporal scale, and impact assessments can change or even make landfilling more preferable (Moberg et al., 2005). Another variable that can influence the results of an LCA are the system boundaries. This will ensure that all credits and burdens within the system are assigned correctly (Clift et al., 2000). Transparency in the goal and scope section is critical when examining the results of any LCA.

2.2.3 Carbon Footprint/LCA for Organic Waste in Developing Countries

As mentioned previously, there are limited published studies regarding LCAs conducted in developing countries. This is logical, as LCA can be data intensive and data on waste management in developing countries is often limited. Nevertheless, developing countries can strongly benefit from LCA or carbon footprint analysis on waste management. Depending on the country, waste management technologies that are low-tech and can be scaled to community variants to offer a good initial option for waste management. Cities in developing countries generally spend 30-50% of their operating budgets on waste management, yet only collect between 50 to 80% of the waste generated (Medina, 2000). Often the only option for collected waste is uncontrolled, unmanned, open dumps.

A case study comparing composting, anaerobic digestion, and open landfilling in Ghana found that both composting and anaerobic digestion reduced GHG emissions by 41% and 58%, respectively, compared to open landfilling (Galgani et al., 2014). The study also analyzed the economic sustainability of compost, biogas from anaerobic digestion, and biochar (carbon dense substance used as a soil amendment). Without subsidies or income from carbon markets, Galgani et al. (2014) found that none of the three technologies would have a positive return on investment. However, carbon markets could make the organic waste technologies economically sustainable with carbon prices within 30-84 Euros per Mg. Even with the volatile nature of carbon markets, analyzing the carbon footprint is critical in determining the overall success of potential organic waste management options.

A separate case study of waste disposal options for traditional markets in Indonesia utilized LCA to compare the technologies. The study found that composting in labor intensive plants, centralized composting using a wheel loader, centralized biogas production from anaerobic digestion, and electricity production from landfill gas all had lower environmental impacts compared to open landfilling (Aye et al., 2006). Biogas production from anaerobic digestion was reported to have the lowest environmental impacts followed by the two composting options, and finally landfilling with electricity production. The study also included an economic analysis that found composting in centralized plants to have the highest benefit-to-cost ratio. Composting in centralized plants was deemed by the authors to have the highest potential for success, due to the strong economic incentives and moderate to low environmental impacts. This study illuminates the point that economic incentives are extremely advantageous to include in conjunction with LCA, especially in developing countries.

Chapter 3: Material Flow Analysis and Approaches for Carbon Footprint Reduction in Fort Collins, CO

3.1 Introduction

Fort Collins, Colorado has adopted ambitious goals regarding GHG emissions. Due to these objectives, there is strong interest in diverting waste and managing the waste in a sustainable way. There are several opportunities that exist for organic waste that aid in resource recovery and landfill diversion. Also, due to the North Weld Landfill's lack of LFG capture, anaerobic digestion (AD) and composting are ways to reduce GHG emissions, and increase organic waste diversion. Compost is a natural process whereby organic matter is broken down by various fungi, worms, and bacteria. Compost is primarily used for soil amendment, but can also be used as a natural pesticide, erosion control, and bioremediation. Anaerobic digestion is a technology used around the world in which microorganisms break down organic material in an anaerobic environment and produce biogas. Biogas is primarily composed of approximately 60-65% methane, which can used in a cogeneration process to produce electricity and capture heat (Sosnowski et al., 2003).

To highlight best organic waste management strategies to achieve carbon footprint benefits, a study on food waste was first undertaken. A material flow analysis (MFA) was conducted in order to understand the mass of food waste generated in Fort Collins. The results of this MFA spurred the undertaking of a separate study conducted by City of Fort Collins staff that analyzed food waste diversion to the anaerobic digesters at the Drake Wastewater Reclamation Facility (DWRF). This study is summarized in Section 3.3. Utilizing the MFA along with the results of the City study on anaerobic digestion of food waste, a carbon footprint analysis of organic waste management as a whole was conducted (Section 3.4).

3.2 Material Flow Analysis of Food Waste

Food waste is a strong candidate for diversion, i.e., being utilized in compost or anaerobic digestion instead of landfilled. A useful first step toward developing any type of waste management plan is to first understand the flows and amounts of the waste materials. To identify opportunities for food waste diversion and reduction, a Material Flow Analysis (MFA) was conducted. MFA is an analytical way to quantify flows and stocks of materials through a defined geographical area and over a set period of time. In this case, the geographical area was Fort Collins and the time frame was one year. MFA helps to reduce the complexity of the system, while still providing a basis for sound decision-making. In addition, MFA assists in establishing priorities regarding environmental protection, resource conservation, and waste management. When used in conjunction with tools such as LCA, the results can yield a waste stream mass balance along with the associated environmental impacts for waste management techniques.

In Fort Collins food waste is a ubiquitous waste stream that makes up a relatively large percentage of both residential (34%) and commercial (43%) organic waste (SloanVasquezMcAfee, 2016). When food waste is sent to the landfill, it is subject to scavenging from animals, aerobic decomposition, and anaerobic decomposition. Anaerobic decomposition results in the production of methane, a GHG 25 times more potent than CO_2 (IPCC, 2007). Furthermore, the embodied energy within food can be beneficially used for compost or anaerobic digestion.

The food waste MFA was calculated using a 2014 City of Fort Collins business database that included business name, North American Industry Classification System (NAICS) code, and number of employees (see Appendix A for full report). The various businesses in Fort Collins were sorted into 8 categories that include Education, Food Wholesaler and Distributors, Food Manufacturers and Processors, Hospitality/Healthcare, Food Retailers, Residential, Food Bank for Larimer County, and Other. The total mass balance of food waste generation by category shows that a total of 32,616 short tons or 29,589 Mg of food waste is generated per year in Fort Collins (Figure 3). Residential food waste makes up slightly more than half of the total food waste produced in Fort Collins (Figure 4). When commercial food waste is broken down into the various sectors, over half of the commercial food waste comes from food retailers (Figure 5).

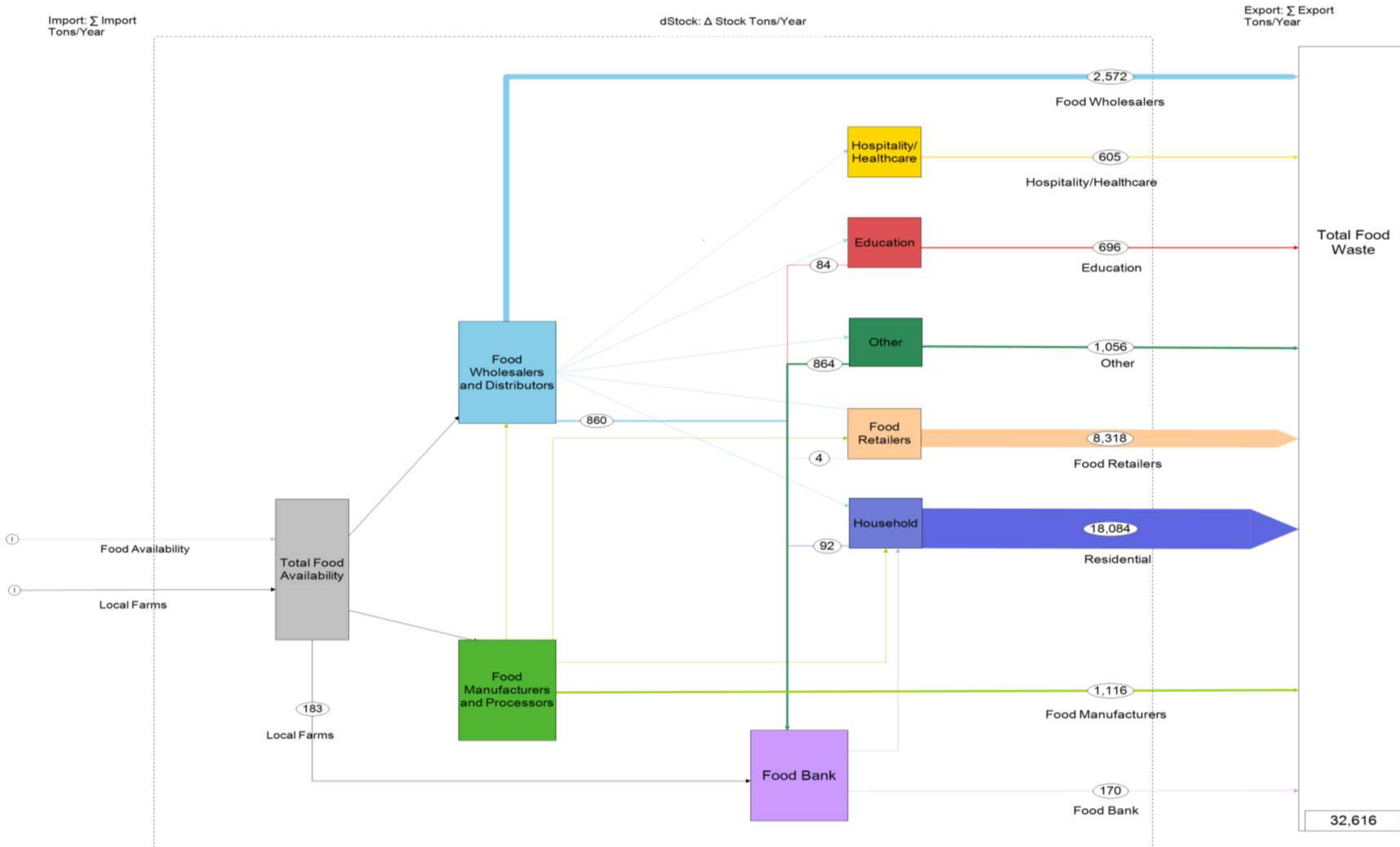

Figure 3: MFA of food waste generation by various sectors in Fort Collins.

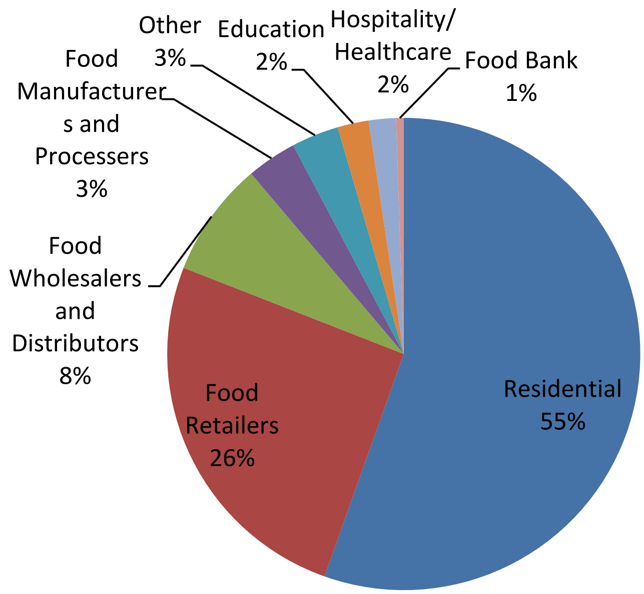

Figure 4: Food waste generated in Fort Collins by Sector.

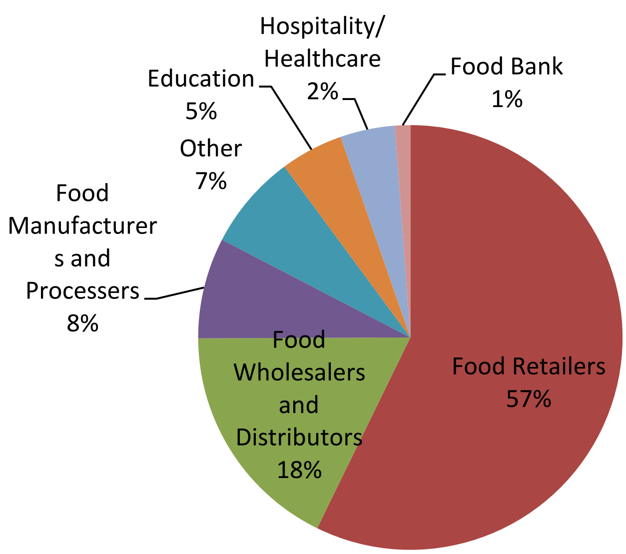

Figure 5: Food waste generated by just the commercial sector.

3.3 Summary of Previous Study on Anaerobic Digestion of Food Waste

Diverting food waste to anaerobic digesters is an area of interest for Fort Collins. A study conducted by city staff examined environmental impacts of food waste disposal at DWRF (See Appendix B for report summary). Delivery of food waste to DWRF consisted of two scenarios. The first, referred to as the residential scenario, involved sending residential food to DWRF via the sewer system. Woody materials such as yard waste are not well suited for the current anaerobic digesters at DWRF. The food waste would then go through the same treatment plant processes as regular wastewater, whereby the anaerobic digesters would produce biogas that would be combusted in a co-generation system, i.e. electricity generation from internal combustion engines and heat capture to be used for digester heating. The second scenario, referred to as the commercial scenario, assumed a truck transported commercial food waste to DWRF. The food waste would then be sorted to remove contaminants and then added directly to the anaerobic digesters with the biogas would again be used for co-generation. Of particular interest to Fort Collins, given limited digester capacity, was to assess which method of food waste delivery resulted in lower GHG emissions.

The results of this study found that the net GHG emissions of the commercial scenario was -89.8 kg CO_2 eq/Mg of food waste, whereas the residential scenario yielded 129.7 kg CO2 eq/Mg of food waste. The commercial scenario produced less GHG emissions for two primary reasons. The first is the production of a residential food waste processor, i.e. garbage disposal, creates surprisingly large GHG emissions from the manufacturing, packaging, and distribution of the unit. Also, residential food waste processors have relatively short lifespans (10 years). The commercial scenario also grinds and processes food waste, but it is likely that industrial food processors are more efficient than individual, smaller processors. This efficiency lowers the GHG emission to processed output ratio over the food processors lifespan. Secondly, adding food waste directly to the anaerobic digesters in the commercial scenario produces significantly more biogas than the residential scenario, as no losses occur in the sewer or during superfluous wastewater processing. Increased biogas per mass of food waste input results in more electricity and heat production, leading to a much larger energy credit for the commercial scenario. GHG emissions associated with truck transportation did not offset the benefits of the larger energy credit.

The commercial scenario resulted in net *negative* GHG emissions. The emission factor of -89.8 kg CO_2 eq/Mg of food waste was thus utilized for all anaerobic digestion scenarios in the subsequent analyses.

3.4 Carbon Footprint of Organic Waste Diversion Options in Fort Collins, CO

3.4.1 Objectives

The objective of this carbon footprint is to conduct a carbon footprint analysis of organic waste management in Fort Collins using results from Sections 3.1 and 3.2.

3.4.2 Scenario Description and Justification

GHG emissions for both compost and anaerobic digestion were compared to the status quo of landfilling organic waste. Several different scenarios were analyzed to create a more holistic view of the City's options which are depicted in Table 2 and shown graphically in Figure 6. The four scenario are: Scenario AD 1 (Anaerobic digestion of commercial food waste with co-generation, and the remainder of organic waste being composted regionally using a transfer station), Scenario AD 2 (Anaerobic digestion of commercial food waste with co-generation, with the remainder of organic waste being composted regionally without using a transfer station), Scenario Regional Compost with TS (Regional compost of all organic waste using a transfer station), and Scenario Regional Compost without TS (Regional compost of all organic waste without using a transfer station).

Transportation plays a key role in GHG emissions for each scenario. Transfer stations should always be considered when transportation of waste goes beyond city boundaries. This analysis includes scenarios that use a transfer station and scenarios that do not. In addition, the fact that Fort Collins has three different waste haulers was taken into account. The geographic scope is within the confines of Larimer and Weld Counties.

Anaerobic digestion of commercial food waste was shown to have a net negative GHG emission value in Section 3.3, and was thus deemed a suitable method of organic waste management. Residential food waste collection is not analyzed in the study, but represents another potential option should collection of commercial food waste prove favorable. Commercial food waste represents only a small fraction of total organic waste in Fort Collins. The remainder of the organic waste consists of residential food waste, residential yard waste, residential wet/contaminated paper, commercial yard waste, and commercial wet/contaminated paper. These fractions of organic waste were assumed to be composted regionally with a transfer station (Scenario AD 1) and without (Scenario AD 2).

Regional compost was chosen over local compost because there is currently no existing large scale, local compost facility. Difficulties in land permitting and funding logistics add complications to building a local compost facility, and thus the current regional facility is assumed to represent the most likely option for composting in Fort Collins. The regional facility is modelled based on an existing facility about 35 kilometers outside of Fort Collins. Similar to the anaerobic digestion scenarios, the compost analysis shows scenarios with a transfer station (Scenario Regional Compost with TS) and without a transfer station (Scenario Regional Compost without TS).

Table 2: Scenarios for Organic Waste Disposal

Scenario	Description
No Action	3 municipal trucks[1] take organic waste from both commercial and residential sources to be landfilled. This distance and emissions are based on the MSW split between the North Weld and Larimer County Landfills.
AD 1	3 municipal trucks take *only* commercial food waste to the anaerobic digesters at DWRF, and the biogas produced is used for co-generation. The remainder of the organic waste fraction is composted regionally utilizing a transfer station[2]
AD 2	3 municipal trucks take *only* commercial food waste to the anaerobic digesters at DWRF, and the biogas produced is used for cogeneration. The remainder of the organic waste fraction is composted regionally without utilizing a transfer station[2]
Regional Compost with TS (transfer station)	3 municipal trucks take organic waste to transfer station then a long-haul truck[1] takes organic waste to a regional compost facility (modelled at the current location of A-1 Organics)
Regional Compost without TS (transfer station)	3 municipal trucks take organic waste to regional compost facility (modelled at the current location of A-1 Organics)

1. See Transportation section for definition and assumptions
2. Currently, there is no existing transfer station. This analysis assumes the transfer station will be located at the Larimer County Landfill
3. See Compost section for definitions and assumptions

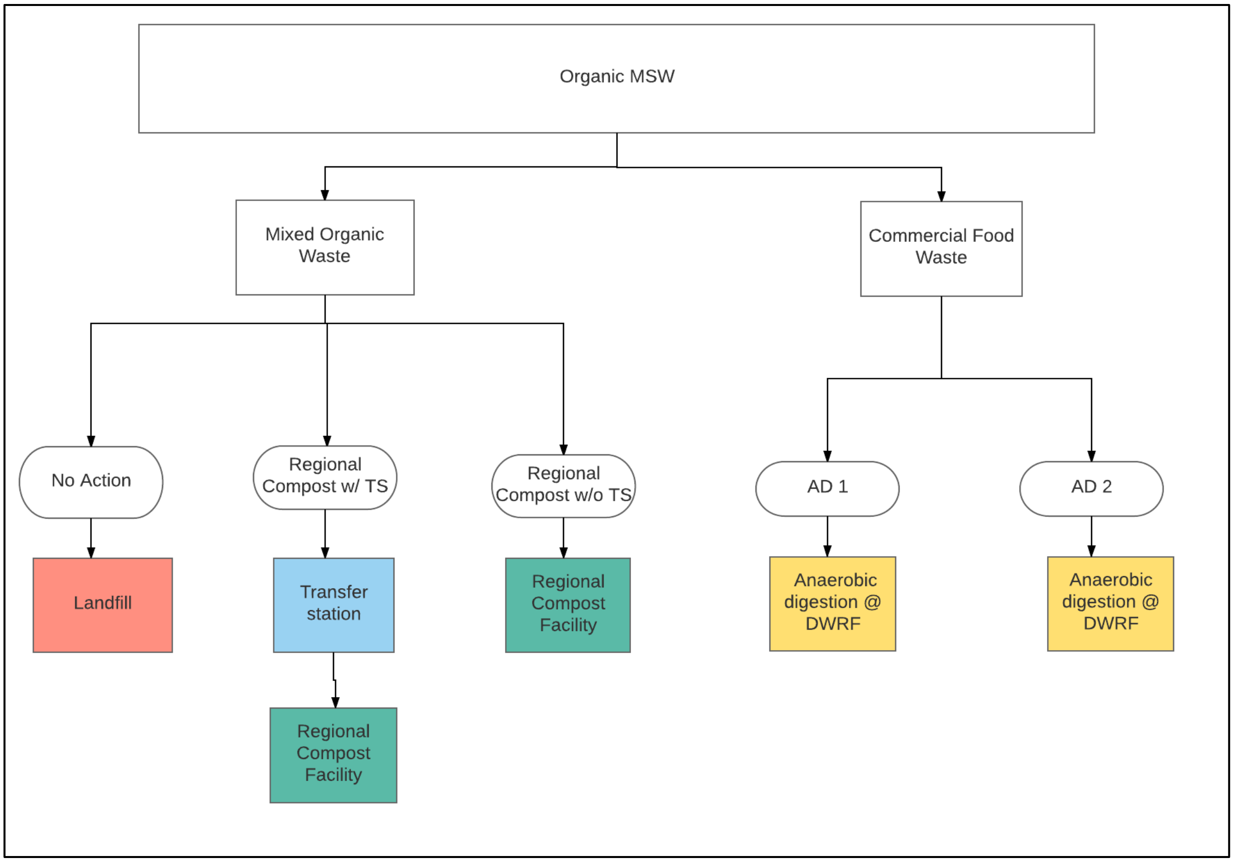

Figure 6: Schematic of organic diversion scenarios for Fort Collins.

3.4.3 Functional Unit

The functional unit is used as a normalizing value to compare different systems based on the service provided. In this case, the functional unit is one metric ton (Mg) of organic waste diverted from the landfill. For the purposes of this report, organic waste is made up of only food waste, yard waste (grass, leaves, and branches), and wet/contaminated fiber. Yard waste was modeled assuming an equal mixture of grass, leaves, and branches. Wet/contaminated fiber is defined as fiber including cardboard, chipboard, office paper, and shredded paper that has been soiled and cannot be recovered from a fiber mechanical sorting processes or sold as post-consumer fiber grade product (SloanVasquezMcAfee, 2016)

3.4.4 Impacts considered

This study was not a full ISO 1440 standard LCA in that the main impact category considered was GHG emissions reported in kg CO_2 equivalent (eq). Thus, the study is considered a carbon footprint study that incorporates an LCA methodology. Biogenic CO_2 sources were excluded from this analysis. Biogenic CO_2 emissions are defined as emissions related to the natural carbon cycle such as decomposition, fermentation, or metabolic digestion. In addition, any effects of carbon sequestration on GHG emissions have been neglected. This is done because there still lacks an overall consensus on the most suitable means to do so in LCA methods (Brandão et al., 2013). Assuming a 100-yr global warming potential timeframe, CH_4 has a CO_2 factor of 25 and N_2O has a CO_2 factor of 298 (IPCC, 2007). New values of CO_2 equivalents for both CH_4 and N_2O have been released by the IPCC as of 2014; however the values from the 2007 report are utilized for consistency purposes. Methane has been updated to a CO_2 factor of 28 and N_2O a CO_2 factor of 265 (IPCC, 2014). These values would increase all landfill emissions, while compost and anaerobic digestion emissions would only change slightly due to an increase in N_2O emissions and a decrease in CH_4 emissions.

3.4.5 System Diagrams

The system diagrams for the organic waste disposal options graphically display how the carbon footprint analysis was conducted. In the anaerobic digestion analysis, food waste is hauled to DWRF and is sorted and processed to remove contaminants before being added to the anaerobic digesters. The outputs of the anaerobic digestion process are biogas to be used in cogeneration, biosolids that are land-applied, and centrate that is re-treated at the DWRF (Figure 7).

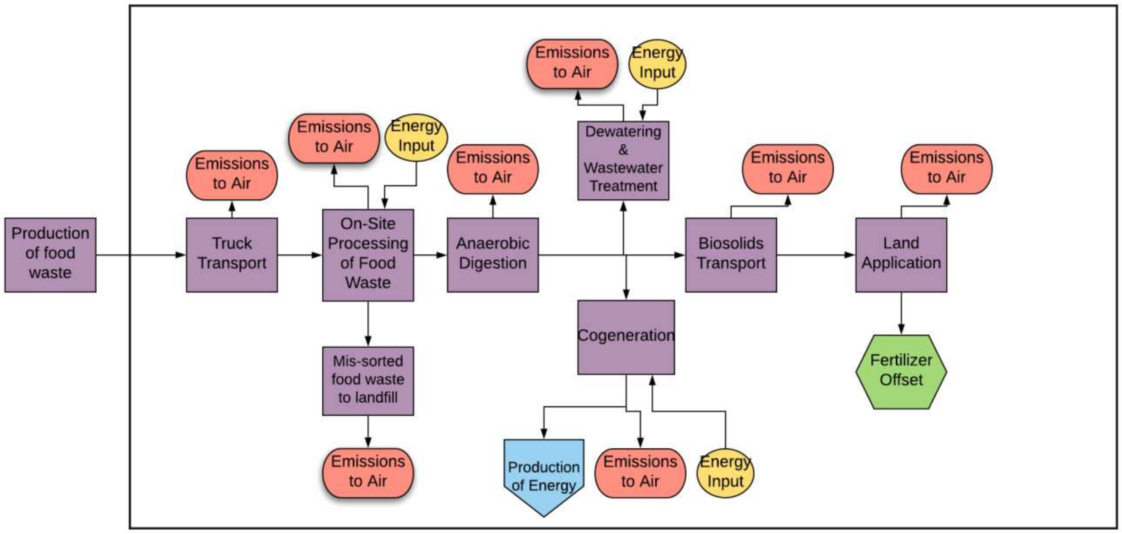

Figure 7: System diagram for anaerobic digestion.

As depicted in Figure 8, GHG emissions for composting are produced in truck transportation, the actual process of composting, and land application. In addition, creating compost requires energy for equipment, which will also contribute to GHG emissions. While there are GHG emissions associated with land application of compost, there is also the beneficial use of compost which replaces conventional fertilizers, and is thus a GHG offset. GHG emissions from the production of organic waste were not included.

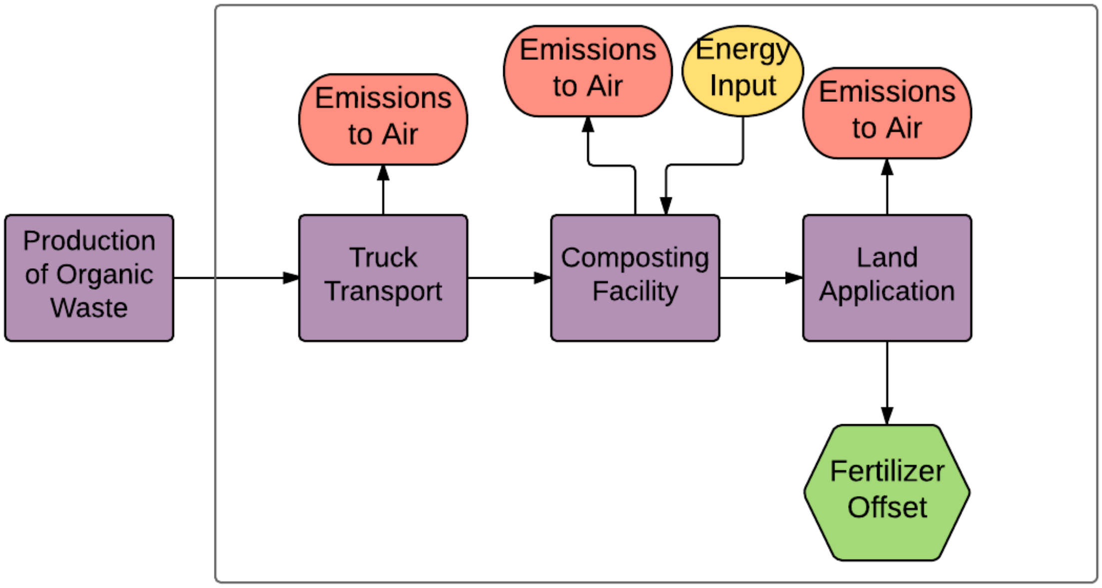

Figure 8: System diagram for compost.

GHG emissions for landfilling organic waste are generated from transportation of organic waste, as well as GHG emissions produced at the landfills from both anaerobic decomposition and combustion of fuel for heavy duty machinery (Figure 9). GHG emissions from the production of organic waste were not included.

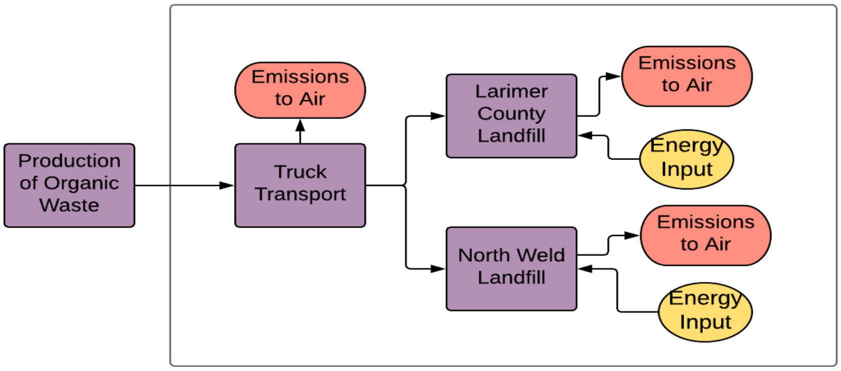

Figure 9: System diagram for both the North Weld and Larimer County Landfills.

3.4.6 Methods and Background

Organic waste management scenarios were created using site-specific data and logistics to analyze which scenarios produced the least GHG emissions. The scenarios include landfilling organic waste at both the Larimer County Landfill and North Weld Landfill Management Facility, anaerobic digestion at DWRF (assuming the commercial scenario is utilized), and windrow compost at a regional compost facility located about 35 kilometers outside of Fort Collins. A regional compost facility was modelled because there is currently no local compost facility. Different transportation scenarios and distances were also evaluated.

Construction and infrastructure were excluded from this study since the majority of literature on composting, anaerobic digestion, and landfilling excluded the emissions for infrastructure. In fact, capital equipment and infrastructure are often excluded from LCA studies due to the low impact in relation to other sources of emission (Aye et al., 2006; Saer et al., 2013; Sharma et al., 2007).

Using the already calculated GHG emission values for the commercial scenario of diverting food waste to DWRF, the remaining processes that were modeled are compost and landfilling. These two processes were modeled using site-specific data when possible, and literature values as needed. The transportation scenarios played a key role in this analysis and were modeled using site-specific distances.

3.4.6.1 Anaerobic Digestion

Concerning food waste, anaerobic digestion was more efficient when collecting food waste via truck than sewer (see Section 3.3). Woody materials such as yard waste and wet/contaminated fibers are not well suited for the current anaerobic digesters at DWRF. Thus, the only feasible option for anaerobic digestion is source-separated food waste from commercial sources such as grocery stores, restaurants, etc. Since the functional unit in this report is one Mg of total organic waste, treatment of the additional organic waste along with the digestion of food waste had to be considered. Commercial food waste accounts for 28% of the total organic stream (SloanVasquezMcAfee, 2016). Thus, all emissions for anaerobic digestion were multiplied by 28% and the remaining yard waste was assumed to be composted (see Compost Subsection of Section 2.1 for a detailed description of assumptions and emission factors). Therefore, the total emissions for anaerobic digestion at DWRF were calculated using Equation 1.

$$Emissions = [0.28(emissions\ at\ DWRF) + 0.72(emissions\ at\ regional\ compost\ facility)] \qquad (1)$$

Emissions at DWRF= -89.8 kg CO_2 eq/Mg of food waste

Emissions at regional compost facility= 96.7 kg CO_2 eq/Mg of feedstock

3.4.6.2 Windrow Compost

The compost system was modelled based on an existing regional compost facility located about 35 kilometers outside of Fort Collins. The raw inputs and outputs for this compost system are summarized in Table 3.

The existing regional facility utilizes large windrow composting piles to compost organic waste such as food waste and yard waste. According to operators of the facility, the material they receive is well balanced with carbon and nitrogen, so they do not purchase additives or bulking material. Therefore, there is no need for a system expansion to incorporate the addition of bulking material.

Diesel combustion-The combustion of diesel for composting operations plays a large role in the overall GHG emissions. A literature review was conducted, and based on seven different sources, an average diesel use per Mg of organic waste composted was calculated. The A-1 Organics facility utilizes standard diesel burning equipment such as a tub grinder, front end loader, and a windrow turner for their composting operations. Due to the lack of data on diesel usage for each type of machine described above, an aggregate fuel use was calculated based on literature that analyzed similar windrow composting facilities. The results of this literature review are summarized in Table 35 . The average CO_2 emission per liter of diesel combusted in industrial equipment was calculated using GaBi life cycle assessment software and National Renewable Energy Laboratory (NREL) life cycle inventory data.

Electricity usage- Per A-1 Organics operators, no electricity is used for their composting process.

GHG emissions-Emissions from composting vary across the literature. A literature review of compost emissions was conducted (see Appendix D: Table 35) and highlighted that methane, N_2O, and ammonia can be produced during windrow composting. As ammonia is not considered a GHG by the

Intergovernmental Panel on Climate Change (IPCC), ammonia was not included in this analysis. N_2O is a long-lived GHG has a CO_2 equivalent of 298.

Based on the large range of emission values, outliers were identified by calculating upper and lower fences. By calculating the first, second, and third quartiles along with inner quartile range the lower fence was calculated using Equation 2 and the upper fence was calculated using Equation 3 (Mendenhall et al., 2012). All data points that were above the upper fence were excluded and an average was calculated from the remaining values (see Appendix C: Table 36 for further details). The same procedure was utilized for N_2O emissions (see Appendix C: Table 36). Ammonia plays a large role in the acidification and eutrophication impacts of LCA, but was not considered in this study since this particular LCA is designed to analyze GHG emissions.

$$Lower\ Fence = Quartile\ 1 - (1.5 * Inner\ Quartile\ Range) \tag{2}$$

$$Upper\ Fence = Quartile\ 3 + (1.5 * Inner\ Quartile\ Range) \tag{3}$$

Mass reduction- The composting process significantly reduces the initial mass of the feedstock. An average mass decrease from initial feedstock to mature compost was taken from three different sources (see Appendix C: Table 33) and resulted in 29% of the initial feedstock.

Transportation of Compost to Clients- The facility delivers finished compost to various customers. The distance can be seen in Table 3 and is a best estimate based on communication with facility operators. OpenLCA was utilized to estimate emissions from transportation of the compost. For the municipal truck, NREL's diesel fuel single unit short haul truck (southwest) was used along with Recipe midpoint H impact categories. The gross vehicle weight was increased to 27.2 Mg to reflect industry weights of typical garbage trucks. The average payload of these trucks was 10.43 Mg based on conversations with various waste haulers. Furthermore, the percentage of distance traveled empty was estimated to be 50%. This yielded a value of 0.49 kg CO_2 equivalent per Mg kilometer.

Land application of compost- Anthropogenic activities, such as fertilizer application, result in the emission of N_2O due to increased microbial denitrification and nitrification. Since the emission is not biogenic, N_2O was included for this analysis.

Table 3: Inputs and Outputs for Compost Model

Inputs	
Feedstock	1 Mg of feedstock
Diesel Use[1]	5.44 Liters of diesel/Mg of feedstock
Electricity	0 kWh
Outputs	
CH_4 Emission[2]	0.663 kg CH_4/Mg of feedstock
N_2O *Emissions*[3]	0.063 kg N_2O/Mg of feedstock
Finished Compost[4]	0.29 Mg of compost
Transportation of Compost to Clients[5]	60.4 km
Land Application of Compost (N_2O Emissions)[6]	0.1 kg N_2O/Mg of feedstock

1. See Table 31 in Appendix C for literature values cited
2. See Table 36 in Appendix D for literature values cited
3. See Table 36 in Appendix D for literature values cited
4. See Table 33 in Appendix C for literature values cited
5. Personal communication, B. Yost, 2016
6. Calculated based on equation for N_2O emissions from agricultural soil management (United States Environmental Protection Agency, 1995)

Fertilizer credit- Knowing the amount of compost produced from one Mg of feedstock (in this case, a mixture of food, yard waste, and wet/contaminated fiber) and taking values from literature, the percent mass of nitrogen, phosphorus, and potassium (NPK) was calculated. One study reports 2.0% nitrogen, 0.3% phosphorus, and 0.8% potassium (van Haaren et al., 2010) while another reports 1.84% Nitrogen, 0.51% Phosphorus, and 2.07% Potassium (Levis et al., 2013). These values were averaged (Table 4).

The ratio to which compost replaces conventional fertilizer was also considered. The ratio of compost to conventional nitrogen fertilizer is 0.4 (Levis et al., 2013). In other words, 1 unit of nitrogen fertilizer is the equivalent of 2.5 units of compost. Phosphorus and potassium are reported to replace conventional fertilizer on a 1:1 ratio (Levis et al., 2013). Once the ratio of fertilizer replacement was calculated, an average emission rate per kg of fertilizer was used to calculate emissions for NPK (Table 4).

Table 4: Fertilizer Credit Assumptions

Fertilizer Credit	**Value**
Average nitrogen content of compost	1.92%
Average phosphorus content of compost	0.41%
Average potassium content of compost	1.44%
Average CO_2 emissions per kg nitrogen fertilizer[1]	3.80 kg CO_2/kg nitrogen fertilizer
Average CO_2 emissions per kg phosphorus fertilizer[2]	1.81 kg CO_2/kg phosphorus fertilizer
CO_2 emissions per kg potassium fertilizer[3]	0.41 kg CO_2/kg potassium fertilizer

1. See Table 32 in Appendix C for literature values cited
2. See Table 34 in Appendix C for literature values cited
3. (Levis et al., 2013)

The overall GHG emissions from the entire composting process can be seen in Figure 10. Diesel use, land application of compost, and transportation of compost to customers represent the largest emissions. The calculated fertilizer offset is negative, as it replaces the need for conventional fertilizers and reduces the total emissions of composting.

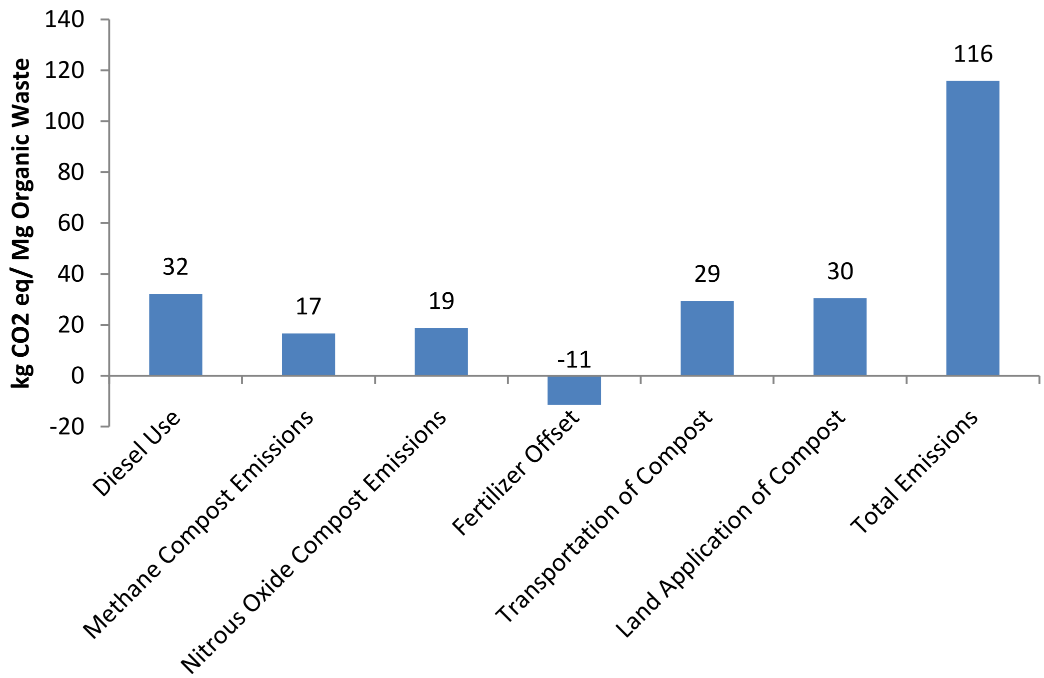

Figure 10: GHG emissions associated with each phase of the compost process.

3.4.6.3 Landfill

The City of Fort Collins disposes MSW in two landfills. One is the Larimer County Landfill and the other is the North Weld Landfill, a privately-owned landfill in Ault, Colorado. According to the City, approximately 56% of MSW generated in Fort Collins goes to the Larimer County Landfill, and the remaining 44% goes to the North Weld Landfill. Major components of landfill design include the landfill liner and landfill gas (LFG) collection system, which can vary from landfill to landfill. The liner is used to prevent leachate from draining into water sources through runoff. The LFG system is used to collect gas produced from the degradation of organic waste. The Larimer County Landfill has a LFG collection system whereby the gas is collected and flared. Flaring landfill gas oxidizes methane, and the remaining

CO_2 emissions are biogenic. The North Weld Landfill does not collect landfill gas for flaring or recovery (R3 Consulting Group, 2016) .

Diesel emissions- The Larimer County Landfill reported using 293,819.1 liters of diesel fuel in 2004 and accepted 130,983 Mgs of waste (Santin, 2013). Normalizing this value to liters of diesel per Mg of waste resulted in 2.2 liters of diesel per Mg of waste. This value was also applied to the North Weld Landfill since operations are assumed to be similar to that of the Larimer County Landfill.

Landfill emissions- In landfills, organic waste often undergoes anaerobic decomposition, which produces landfill gas (LFG) comprised primarily of methane and CO_2. For the purposes of this LCA, the CO_2 is considered biogenic, since CO_2 production is part of the natural carbon cycle. However, methane production is counted as an emission source, due to anaerobic conditions created due to anthropogenic activities (i.e., landfilling). Methane emissions due to food waste and yard waste were calculated assuming a 100 year timespan. This is the approximate amount of time for 95% of the possible LFG to be produced under a dry landfill scenario (U.S. EPA, 2015). The additional 5% of potential LFG production was not included, as it results in a negligible increase in landfill GHG emissions. Therefore, this study assumed 100% biodegradation of organic waste over 100 years. Fort Collins falls under a dry landfill category, which is classified as receiving fewer than 508 mm of annual precipitation (U.S. EPA, 2015).

The Larimer County Landfill has a landfill gas collection system while the North Weld Landfill does not. The EPA's WARM Version 13 reports typical collection efficiencies to be 68.2% for landfills (U.S. EPA, 2015). The methane emitted from the two landfills was calculated using Equation 4 (Di Bella et al., 2011) where P = production of methane, R = landfill gas recovery efficiency, and O = oxidation of methane.

$$E = P - R - O \tag{4}$$

The methane production associated with landfilling food waste is 1.93 $MgCO_2$ eq/Mg (U.S. EPA, 2015). Yard waste was calculated by averaging the methane generation of grass, leaves, and branches, which yielded 0.76 $MgCO_2$ eq/Mg (U.S. EPA, 2015).The wet/contaminated fiber was assumed to be primarily soiled paper waste, and as such, the methane generation of corrugated containers, newspaper, and phone book were averaged resulting in 1.73 $MgCO_2$ eq/Mg (U.S. EPA, 2015). The functional unit of 1 Mg of organic waste consists of 49.6% food waste, 33% yard waste and 17.4% wet/contaminated fiber (SloanVasquezMcAfee, 2016). Based on these values, the "P" in Eq. 4 is calculated to be 1,509.6 kg CO_2 eq/Mg of organic waste

As can be seen in Table 5, there is a large difference between emissions at the Larimer County Landfill and emissions at the North Weld Landfill, which reflect North Weld's lack of collection system. For the purposes of modelling landfill emissions, the percentage of waste landfilled at each location (56% in Larimer County Landfill and 44% in North Weld Landfill) was used to calculate an aggregate emission factor. This factor was used to calculate the aggregate landfill GHG emissions for Fort Collins, and can be seen in Figure 11 . The inputs and outputs are summarized for the Larimer County and the North Weld Landfills (Table 6). While the inputs for both landfills are the same, the methane emissions differ significantly due to the difference in LFG capture.

Table 5: Larimer County and North Weld Landfill Parameters

	Larimer County Landfill	North Weld Landfill
E	178.1 (kg CO_2 eq/Mg of organic waste)	1358.6 kg CO_2 eq/Mg of organic waste
P	1509.6 (kg CO_2 eq/Mg of organic waste)	1509.6 kg CO_2 eq/Mg of organic waste
R	68.2%[1]	0%
O	20%[2]	10%[3]

1. This value reflects a "dry landfill", i.e. less than 20 inches of annual precipitation (U.S. EPA, 2015)
2. With gas collection system before final landfill cover placement (U.S. EPA, 2015)
3. Without gas collection system or final cover (U.S. EPA, 2015)

Table 6: Inputs and Outputs for Larimer County Landfill

Inputs		
	Larimer County Landfill	*North Weld Landfill*
Waste	0.56 Mg of organic waste	0.44 Mg of organic waste
Diesel Use	2.2 Liters of diesel/Mg of organic waste	2.2 Liters of diesel/Mg of organic waste
Outputs		
	Larimer County Landfill	*North Weld Landfill*
Methane emission	178.1 kg CO_2 eq/Mg of organic waste	1,358.6 kg CO_2 eq/Mg of organic waste

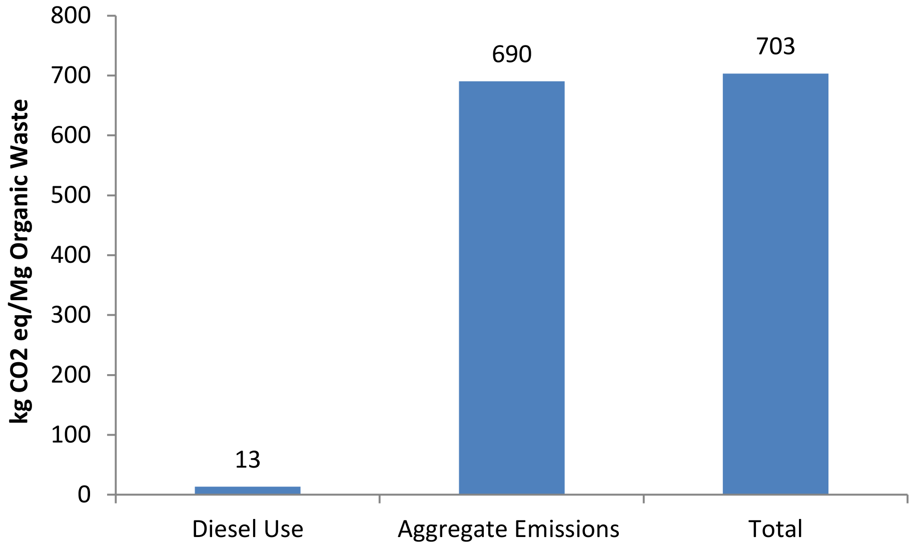

Figure 11: Aggregated GHG emission sources for landfilling organic waste.

3.4.6.4 Transportation

The assumptions made for the transportation analysis are summarized in Table 7. Transportation plays an important role in this analysis due to the City's interest in the different disposal scenarios. Also, the fact that the City has three independent waste haulers adds inefficiencies that exacerbate CO_2 emissions.

Organic waste pickup routes were modeled assuming 21 km per Mg of organic waste, which is typical of municipal waste collection routes where there is only 1 waste hauler (City of Loveland Solid Waste Division, Personal Communication, October 3, 2016). Due to the fact that Fort Collins has three independent waste haulers, the overall distance travelled was assumed to be three times greater. For the two local anaerobic digestion scenarios, an additional 8 km was added to the route due to the fact that the trucks have to return back to where they started after being emptied. The 8 km reflects the distance from DWRF to the relative center of Fort Collins (identified at 40.560240, -105.076670).

Table 7: Description of Transportation Distances for Each Scenario

Scenario	Distance (municipal truck)	Distance (long-haul truck)	Assumptions
No Action	158.1 km	0 km	• Three waste haulers take organic waste to landfill using municipal truck • Assumed distance of 21 km per truck for organic waste pickup • 32 km round-trip from the center of Fort Collins to Larimer County Landfill and North Weld Landfill based on MSW split to each landfill.
AD 1	115.3 km	53.4 km	• Three waste haulers take commercial food waste to DWRF using municipal truck. • Assumed distance of 21 km for food waste pickup • 13 km round-trip from center of Fort Collins to DWRF. • The remainder of organic waste is collected and transported based on the Regional Compost with TS scenario
AD 2	226.7 km	0 km	• Three waste haulers take commercial food waste to DWRF using municipal truck. • Assumed distance of 21 km for food

			waste pickup • 13 km round-trip from center of Fort Collins to DWRF. • The remainder of organic waste is collected and transported based on the Regional Compost without TS scenario.
Regional Compost with TS	120.7 km	74.03 km	• Three waste haulers collect organic waste using a municipal truck and transport waste to transfer station at Larimer County Landfill. • One long haul truck transports waste from transfer station to regional compost facility.
Regional Compost without TS	275.2 km	0 km	• Three waste haulers collect organic waste using a municipal truck and transport waste to regional compost facility

Transportation emission factors- OpenLCA was utilized to estimate emissions from transport. For the municipal truck, NREL's diesel fuel single unit short haul truck (southwest) was used along with Recipe midpoint H impact categories. The gross vehicle weight was increased to 27.2 Mg to reflect industry weights of typical garbage trucks. The average payload of these trucks was 10.43 Mg based on conversations with various waste haulers. Furthermore, the percentage of distance traveled empty was estimated to be 50%. This yielded 0.49-kg CO_2 equivalent per Mg kilometer.

For the long haul truck, NREL's diesel fueled combination short haul truck (southwest) was used along with Recipe midpoint H impact categories. The gross vehicle weight of this truck is 29.3 Mg and the payload is 19.55 Mg. These values are similar to what industry experts estimate the typical transfer truck weighs and delivers. The percentage of distance traveled was increased to 50%. This yielded a value of 0.3-kg CO_2 equivalent per Mg kilometer. Scenario Regional Compost without TS produced the highest GHG emissions (Figure 12) because three municipal trucks travelled the whole distance, instead of just one.

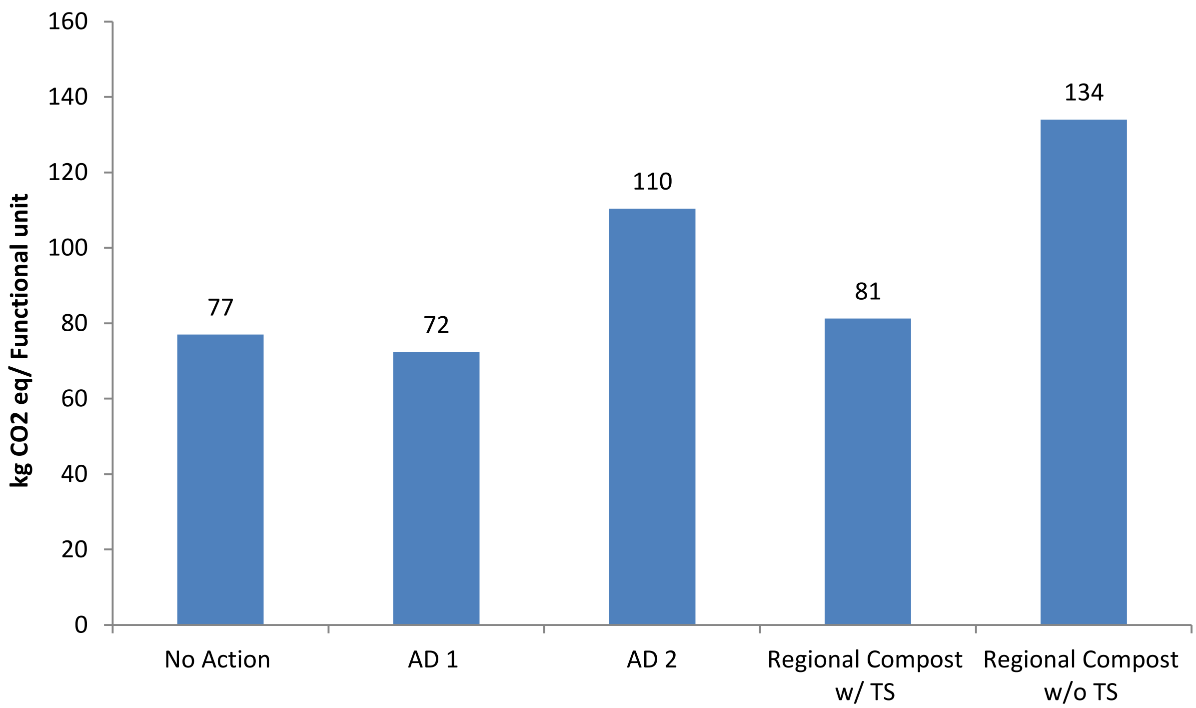

Figure 12: Emissions for different transportation scenarios.

3.4.5 Results

The side by side comparison of the GHG emissions for all five scenarios can be seen in Figure 13. Comparing emissions provides a useful illustration of the various organic waste disposal options. Landfilling produces the most GHG emissions, which is consistent with results of similar studies (Parry, 2012; PE Americas, 2011). AD1 contributed the lowest GHG emissions, expressed as kg CO_2 equivalent. Transportation efficiencies associated with organic waste transfer stations led to lower GHG emissions. However, the AD2 scenario, which did not make use of a transfer station, still had lower GHG emissions than the regional compost with transfer station scenario.

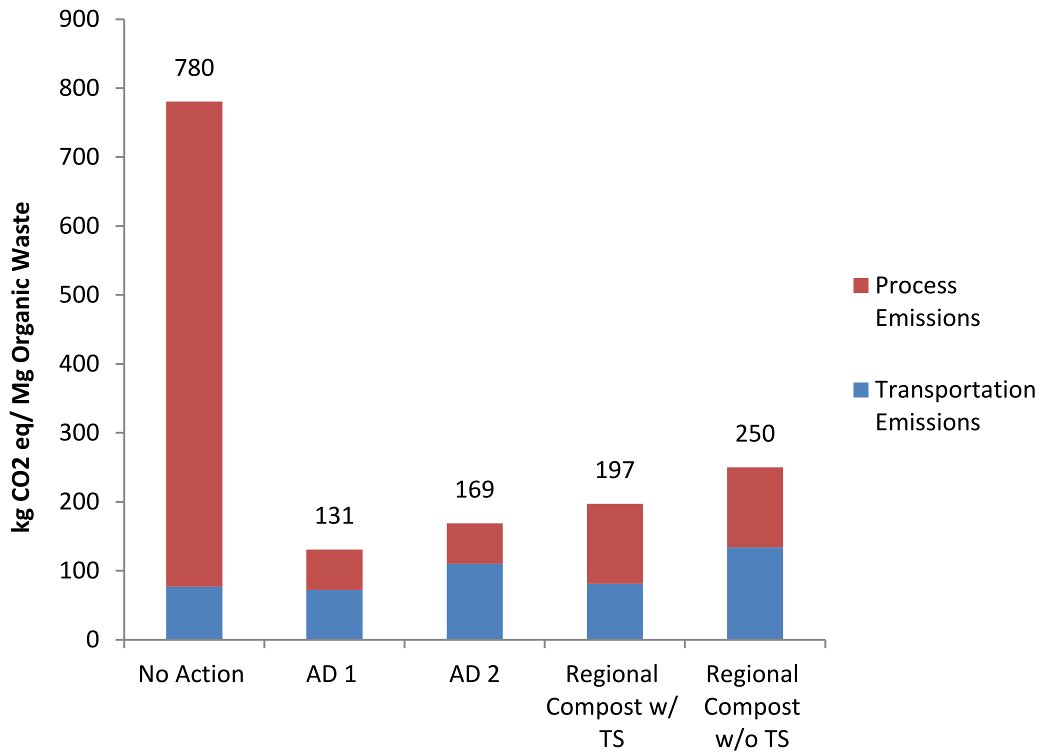

Figure 13: Overall GHG emissions for each scenario.

The results of this analysis were scaled up to theoretical waste diverted from the landfill per year (assuming 100% of the organic waste that is currently landfilled can be diverted), and can be seen in Table 8. In 2015, Fort Collins produced a total of 81,949 Mg of total MSW, of which residential sources contributed 41,272 Mg and commercial sources contributed 40,677 Mg (City of Fort Collins Environmental Services, Personal Communication, C. Mitchell, January 8, 2018). Yard waste, food waste, and wet/contaminated fiber constituted 44.3% of the residential MSW stream, and 41% of the commercial MSW stream (SloanVasquezMcAfee, 2016). These percentages were utilized to estimate the total mass of organic waste going to AD, compost, or landfill and the total GHG emissions for each scenario.

Table 8: Organic Waste End of Life Breakdown*

Scenario	Food Waste Sent to AD (Mg/year)	Organic Waste Sent to Compost Facility (Mg/year)	Organic Waste Sent to Landfill (Mg/Year)	Total GHG Emissions (kg CO_2 eq/year)
AD1	9,763	25,198	0	4,088,253
AD2	9,763	25,198	0	5,417,979
Regional Compost with TS	0	34,961	0	6,219,985
Regional Compost without TS	0	34,961	0	8,064,883
No Action	0	0	34,961	27,282,994

* Assumes that 100% of the available organic waste can be diverted from the landfill. The results of this analysis can be scaled based on expected participation rates and future regulation.

3.4.6 Scenario Analysis

The first scenario analysis assumes all organic waste is landfilled at the Larimer County Landfill and no organic waste is sent to the North Weld Landfill. As can be seen from Figure 14, landfilling all organic waste at the Larimer County Landfill decreased GHG emissions by about 70% compared to the No-Action Scenario. A 68.2% LFG efficiency and 20% oxidation of methane was assumed for Larimer County Landfill. Interestingly, if organic waste is only brought to the Larimer County Landfill, emissions are more similar to the other scenarios, especially the regional compost without a transfer station scenario. In fact, if all organic waste is brought to the Larimer County Landfill, the overall GHG emissions are lower than the regional compost without a transfer station. This is due to the large transportation GHG emissions in the regional compost without a transfer station. Due to the closeness of these various scenarios, an uncertainty analysis is an area for future study. However, this scenario analysis quickly illuminates how the City could reduce GHG emissions. The policy implications of either installing landfill gas collection with flaring at North Weld Landfill or only allowing organic waste to be disposed of in Larimer County Landfill are outside the scope of this analysis, but are considerations for the City leaders to consider.

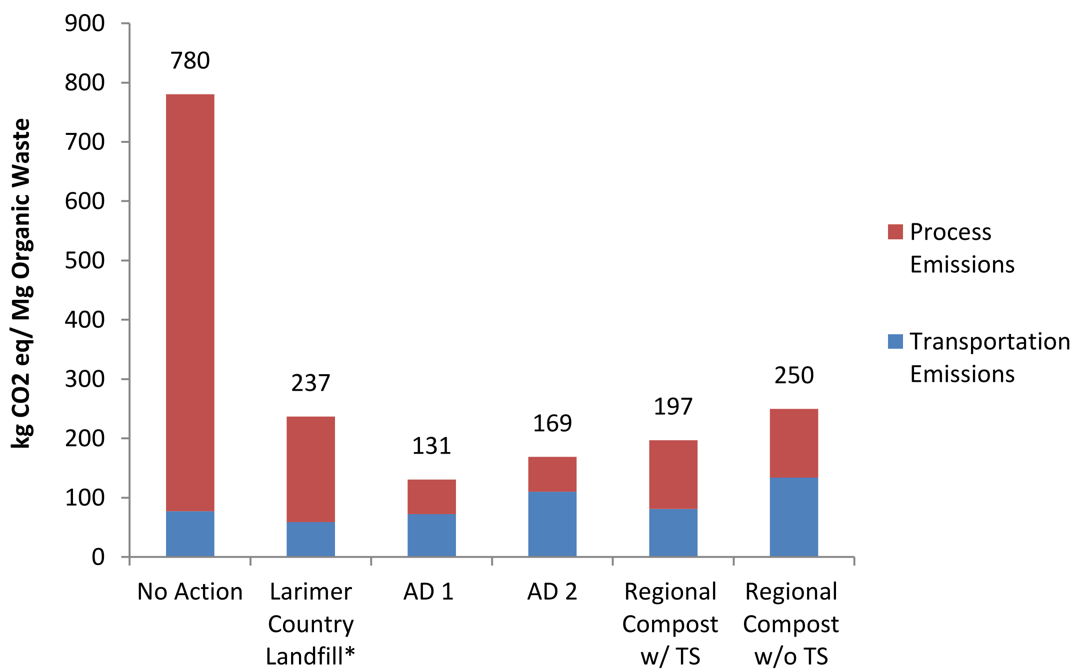

Figure 14: Scenario analysis showing a scenario, called Larimer County Landfill*, in which all organic waste is sent to the Larimer County Landfill, instead of being split between the North Weld and Larimer County Landfills.

The second scenario analysis assumes a more streamlined and efficient system of waste collection. Instead of three waste haulers, all scenarios were assumed to only utilize one truck. This reduced GHG emissions amongst all scenarios, as can be seen in Figure 15. The No-Action Scenario decreased by 7%, the AD 1 Scenario decreased by 29%, the AD 2 Scenario decreased by 44%, the Regional Compost with TS Scenario decreased by 20%, and the Regional Compost without TS Scenario decreased by 36%. The scenarios without a transfer station are more impacted by the reduction in waste haulers than the scenarios with a transfer station. However, scenarios that make use of a transfer station will still have slightly lower transportation emissions due to the increased efficiency of the long haul truck. Reducing the number of waste haulers is another area that the City could focus on to reduce GHG emissions, but once again the policy implications are outside the scope of this analysis.

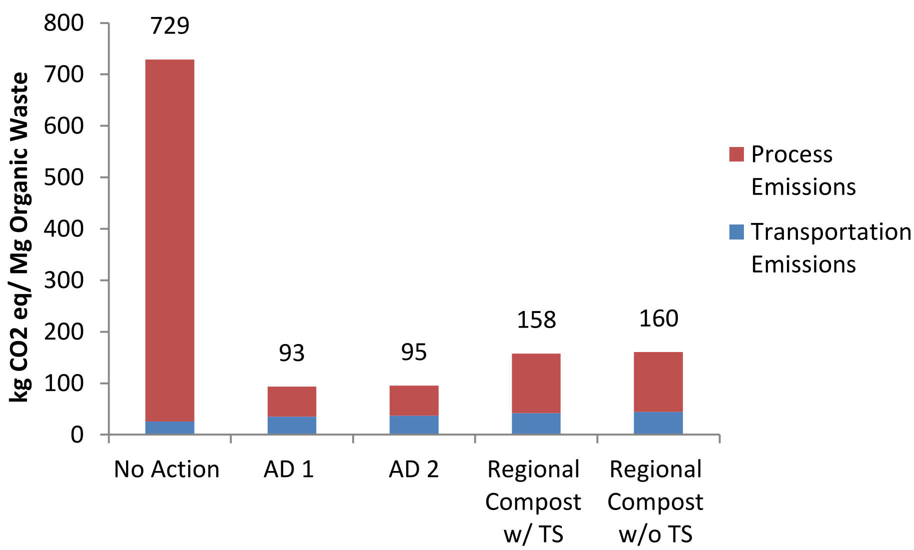

Figure 15: Net emissions assuming the number of waste haulers in Fort Collins is reduced from three to one.

3.4.7 Conclusions

Utilizing commercial food waste for anaerobic digestion at DWRF and transporting the remaining organic waste to a regional compost facility using a transfer station produced the lowest GHG emissions. Although this study shows a trend favoring anaerobic digestion and compost, the lack of an uncertainty analysis would bolster the results. This illuminates an area of future work in addressing the uncertainty of the emissions associated with these technologies. As mentioned earlier, many of the biological emissions vary substantially throughout the literature, which could have implications on the analysis. Although a statistical study was conducted for compost emissions, more advanced software or a more in-depth statistical review of the literature would most likely yield a stronger uncertainty analysis.

The results of this carbon footprint are in line with the vast majority of literature related to GHG emissions of landfills, compost, and anaerobic digestion. Utilizing the updated 2014 IPCC global warming potential for CH_4 and N_2O would not change the overall rank of the scenarios when comparing GHG emissions. The No Action scenario would still produce the highest GHG emissions, followed by AD 1, AD2, Regional Compost with TS, and finally Regional Compost without TS. The 2014 IPCC global warming potentials would lead to an increase in landfill emissions, a very slight decrease in the AD 1 and AD 2 scenario, and a slight increase in the Regional Compost with TS and Regional Compost without TS.

The various transportation scenarios show that transfer stations result in lower overall emissions when transporting waste long distances. This is useful for decision makers when considering the costs of building and staffing a transfer station. Furthermore, if the City is interested in ways to reduce GHG emissions without using the wastewater treatment plant or building new infrastructure, eliminating organic waste sent to the North Weld Landfill results in a 69% decrease in landfill emissions associated with Fort Collins' solid waste.

Chapter 4: Carbon Footprint and Cost Analysis of Organic Waste Management Option in Todos Santos, Baja California Sur, Mexico

4.1 Introduction

The municipality of Todos Santos, Baja California Sur, Mexico has identified improved waste management as a community need. The negative aesthetics of waste accumulation, lack of awareness for appropriate waste disposal, and public and environmental health related to open dumping and burning were identified as chief concerns (Pickering et al., 2015).

Assessing the current landfill composition is critical when building alternative scenarios to divert organic waste. Unlike Fort Collins, there have been no studies conducted on the current landfill composition in Todos Santos. Therefore, due to limited available data, the average waste composition for Mexico (Figure 16) was assumed representative of Todos Santos. Organic waste constitutes 51% of total waste, and developing sustainable waste management alternatives for this fraction will decrease the amount of waste landfilled and decrease GHG emissions compared to current waste management practices. Furthermore, depending on financial markets, compost facilities could be developed to provide a source of revenue and job creation.

To highlight best organic waste management strategies to achieve carbon footprint benefits, a site visit to Todos Santos was conducted in June 2017. The site visit illuminated both the lack of an engineered landfill, and any large scale compost facilities. Speaking with several stakeholders both at Colorado State University and in Todos Santos, it was apparent that compost is the most feasible organic waste management in Todos Santos.

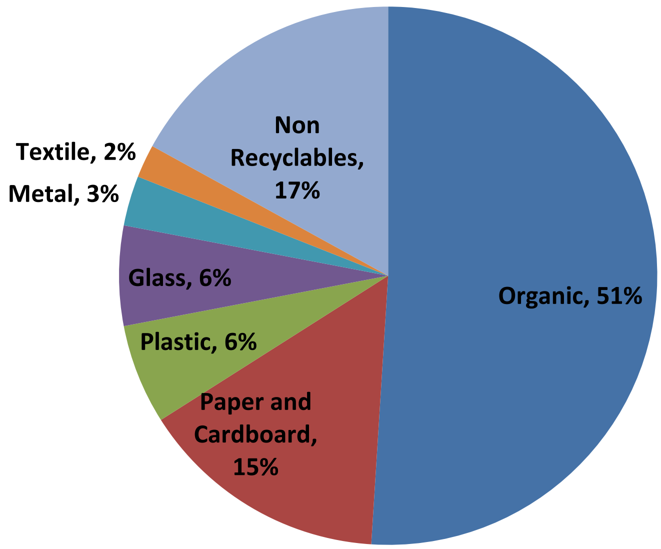

Figure 16: Waste Stream for Mexico. Values taken from (Dirección de Planeación Urbana y Ecología, 2011). The values are applied to Todos Santos' waste composition.

4.2 Objectives

The goal of this study was to quantify the carbon footprint of organic waste management in Todos Santos. Furthermore, a capital cost analysis comparing static aerated composting and windrow composting was conducted. The cost assessment and carbon footprint analysis were considered together when proposing best organic waste management options for Todos Santos.

4.3 Scenario Description and Justification

Several different scenarios were analyzed to create a more holistic view for organic waste management, and are summarized in Table 9. GHG emissions for windrow composting and static aerated compost were compared to the status quo of landfilling organic waste. The small population of Todos Santos and lack of anaerobic digesters at the municipal wastewater treatment plant, rendered anaerobic digestion as an impractical organic waste alternative. Currently, there is no large scale compost facility in Todos Santos, so assessing the GHG emissions and cost of both static aerated and windrow composting techniques is beneficial. Both the static aerated compost facility and windrow compost facility were assumed to be located at the current landfill. Due to the small geographic size of Todos Santos, the impact of transportation on GHG emissions would be very small, provided organic waste is not transported outside of city boundaries.

Table 9: Description of Organic Waste Management Options

Scenario	Description
No Action	1 municipal truck takes organic waste to the landfill in Todos Santos
Local Windrow Compost (WC)	1 municipal truck takes organic waste to a windrow facility hypothetically located at the current landfill
Local Static Aerated Compost (SAC)	1 municipal truck takes organic waste to a static aerated compost facility hypothetically located at the current landfill

4.4 Functional Unit

The functional unit is used as a normalizing value to compare different systems based on the service provided. In this case, the functional unit was one Mg of organic waste diverted from the open dump site. For Todos Santos, organic waste is only considered to consist of food waste and wood waste, since data on wet/contaminated fiber was unavailable.

4.5 Impacts Considered

The case study on Todos Santos was not a full ISO 1440 standard LCA in that the main impact category considered was GHG reported in kg-CO_2 equivalent. Therefore, it is considered a carbon footprint study with LCA methodology. Furthermore, non-biogenic CO_2 sources and carbon sequestration were excluded from this analysis. Assuming a 100-yr global warming potential timeframe, CH_4 has a CO_2 equivalent factor of 25 and N_2O has a CO_2 factor of 298 (IPCC, 2007). New values of CO_2 equivalents for both CH_4 (28) and N_2O (265) have been released by the IPCC as of 2014; however the values from the 2007 report are utilized for consistency purposes. The most recent global warming potentials would increase landfill emissions, and slightly decrease compost emissions.

4.6 System Diagrams

The system diagram for composting in Todos Santos is the same as composting in Fort Collins. While two different types of composting are analyzed, Figure 17 adequately models both composting techniques. Landfilling organic waste in Todos Santos only consists of transportation and landfilling along with their associated emissions, as can be seen in Figure 18. There is no heavy, diesel burning machinery used at the Todos Santos landfill.

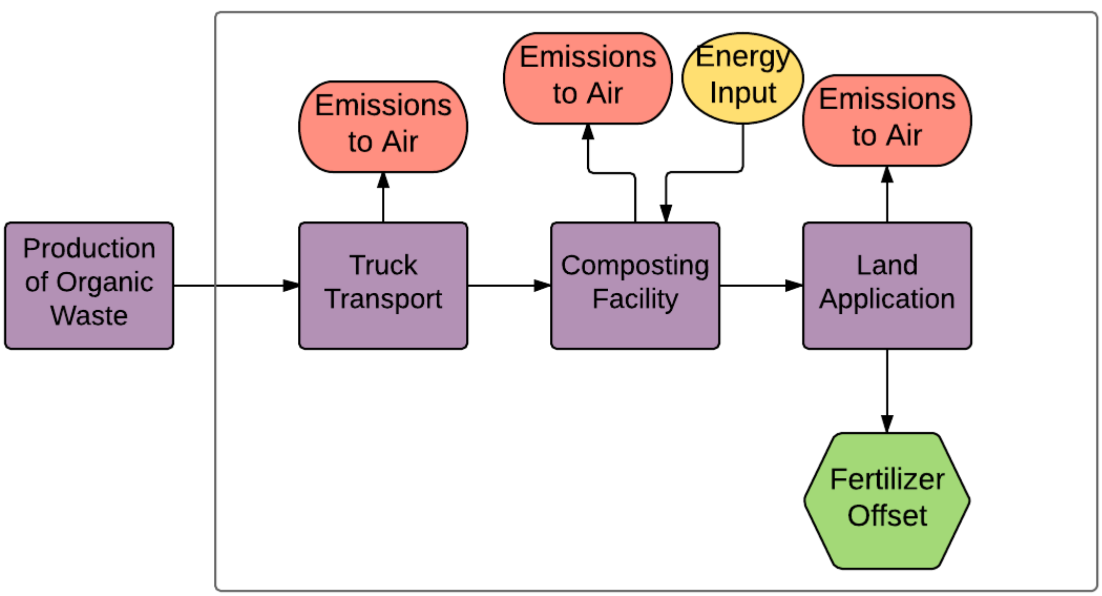

Figure 17: System diagram for static aerated compost and windrow compost.

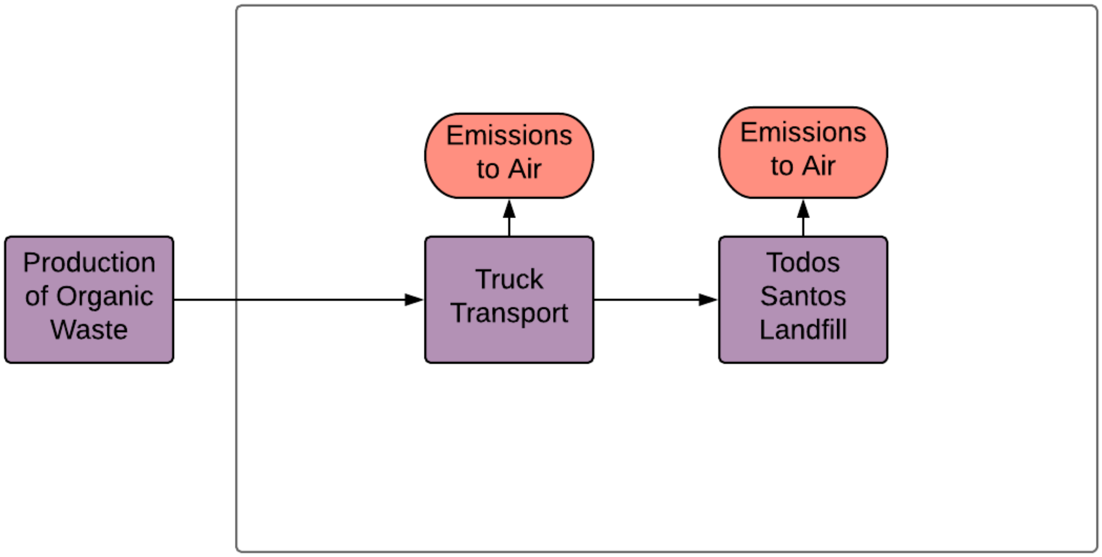

Figure 18: System diagram for landfilling organic waste in Todos Santos.

4.7 Methodology

The options for organic waste management in Todos Santos include windrow composing, static aerated composting, and landfilling at the exiting landfill near Todos Santos. Construction and infrastructure were excluded from this study since the majority of literature on composting, anaerobic digestion, and landfilling excluded the emissions for infrastructure. In fact, capital equipment and infrastructure are often excluded from LCA studies due to the low impact in relation to other sources of emissions (Sharma et al., 2007).

The MSW composition in Todos Santos was assumed to consist of 51% organic waste based on available data from Mexico (Figure 16). However, composition data pertaining to the organic waste stream within Todos Santos, (food waste, yard waste, wood, etc.) were not available. Pipatti et al. (2006) reported organic waste composition for North America and South America. Organic waste was assumed to only consist of food and wood waste. Pipatti et al. (2006) reported that the total amount of organic waste was 40.1% for North America and 49.6% for South America. The organic waste percentages for

South America match Todos Santos more closely than North America, so South American literature values were used in this analysis even though Todos Santos is in North America. Food and wood waste make up 44.9% and 4.7%, respectively, of the MSW stream in South American countries (Pipatti et al., 2006).

4.7.1 Compost

Currently, there are no large-scale composting facilities within the Todos Santos area. Thus, before any type of compost facility is to be constructed, the organic waste composition needs to be analyzed. Maintaining a proper carbon to nitrogen ratio is critical for achieving high quality compost. Using values from Pipatti et al. (2006), food waste makes up 90.5% of organic waste and wood waste makes up the additional 9.5%. For the purposes of this analysis, a 25 carbon-to-nitrogen ratio "R" was utilized. The mass of each type of feedstock was calculated using Equation 5 (Richard et al., 1996). Wood waste was assumed to be chipped into wood shavings for all modeled compost operations.

Using the values from Table 10, for every ton of compost feedstock, only 0.75% is required to be wood chips, which is much less than the existing 9.5%. In other words, food waste will be the limiting variable for creating an ideal organic waste mixture to compost. Therefore, based on the assumed waste characteristics and quantity, the target C:N ratio of 25 can be met without the addition of outside compost materials.

$$Q_2 = \frac{Q_1 * N_1 * \left(R - \frac{C_1}{N_1}\right) * \left(100 - M_1\right)}{N_2 * \left(\frac{C_2}{N_2} - R\right) * \left(100 - M_2\right)} \tag{5}$$

Where R= C:N ratio of compost mixture, Q_n= Mass of material n (in this case wood waste) as wet weight, C_n= Carbon (%) of material n, N_n= Nitrogen (%) of material n, M_n= Moisture content (%) of material n

Table 10: Chemical and Moisture Composition of Food Waste and Wood Shavings*

	Food Waste	Wood Shavings
Carbon (%)	47.4	54.5
Nitrogen (%)	2.0	0.08
Moisture (%)	87.8	20.0

*All values taken from Adhikari et al. (Adhikari et al., 2009)

4.7.2 Windrow Composting

The basic assumptions are the same as those modeled for Fort Collins windrow composting (see *Windrow Compost* in Section 3.2.7). However, the transportation of the finished compost was not modelled due to a lack of knowledge of the compost market in the Todos Santos region. This is an area of future research.

4.7.3 Static Aerated Composting

Static aerated composting is the process of pumping air through a compost pile. This alleviates the need to turn compost piles, which is needed in windrow composting. In general, static aerated compost piles are easier to operate as they do not require heavy turning equipment. In addition, static aerated compost piles have shorter processing times than windrow composting. However, due to the negation of physical turning, aerated static piles are often used to compost homogenous materials that do not need to be physically broken down (Composting Council of Canada, 2010). Furthermore, bulking agents such as wood chips are extremely important to include in the mixture to make sure that there is enough porosity in the pile. Thus, use of some type of mechanical grinder or chipper is recommended to homogenize the material before composting.

The two main types of static aerated composting are open and enclosed. Open aerated piles are often covered with finished compost or bulking agents such as sawdust or wood chips to help decrease odors. Negative air pressure is utilized in order to pull air down through the pile and pump the air to an odor control system. Enclosed aerated piles can either be located inside a structure (technically referred to as in-vessel composting) or covered with a heavy-duty plastic silage bag (technically referred to as non-vessel composting). The air is pumped from outside, blown into the bags, and exits through small openings on the sides of the bag. Newer systems, such as the GORE Cover System, allow for the escape of CO_2, increased odor mitigation by controlling condensation on the interior of the cover, and protects the compost pile from weather and temperature variations (W.L Gore & Associated, n.d.).

The raw inputs and outputs for the static aeration compost system can be seen in Table 11. The overall GHG emission from the entire composting process can be seen in Figure 19. Due to uncertainty in what type of static aeration system may be implemented, values for the carbon footprint analysis were taken based on a simple, open static aeration pile with positive pressure and finished compost/wood chips used as odor control.

Diesel combustion- The only diesel combustion for this process will be from shredding the organic waste and the use of a front loader for moving the organic waste. The average CO_2 emission per liter of diesel combusted in industrial equipment was calculated using GaBi life cycle assessment software and NREL life cycle inventory data.

Electricity usage- Electricity will be required to pump air through the compost pile. For a general static aerated pile it takes 0.69 kWh/Mg (Levis et al., 2013). The conversion from kWh to kg CO_2 equivalent in Mexico is 0.689 kg CO_2eq kWh^{-1} (Metz et al., 2005).

GHG emissions- Methane and N_2O emissions from static aerated composting are higher compared to windrow composting (Levis et al., 2013). According to Levis et al. (2013), the portion of emitted carbon that is methane is 1.59 times higher for static aerated compost than windrow composting. In addition, Levis et al. (2013) found that the portion of emitted nitrogen that is N_2O is 4.5 times higher for static aerated compost than windrow compost. Windrow composting and static aeration composting were both assumed to emit the same amount of carbon and nitrogen. Thus, CH_4 emissions for windrow composting (see *Windrow Composting* in Section 3.2.7) were multiplied by 1.59. The same technique was utilized to calculate N_2O emissions.

Mass reduction- Mass reduction from static aerated composting was assumed to be same as *Windrow Compost* (Section 3.2.7).

Land applications of compost- N_2O emissions resulting from land application of static aerated compost were assumed to be the same as windrow compost. Therefore, the emissions are calculated in the same manner as described in *Windrow Compost* (Section 3.2.7).

Table 11: Inputs and Outputs for Static Aerated Compost Model

Inputs	
Feedstock	1 Mg of feedstock
Diesel Use[1]	1.5 Liters of diesel/Mg of feedstock
Electricity[2]	3.8 kWh/ton of feedstock
Outputs	
Methane Emission[3]	1.05 kg CH_4/Mg of feedstock
N_2O Emissions[4]	0.309 kg N_2O/Mg of feedstock
Finished Compost[5]	0.29 Mg of compost
Land Application of Compost (N_2O Emissions)[6]	0.1 kg N_2O/Mg of feedstock

1. (Andersen et al., 2010)
2. (Levis et al., 2013)
3. See Table 35 in Appendix D for literature values cited
4. See Table 36 in Appendix D for literature values cited
5. See Table 33 in Appendix C for literature values cited
6. Calculated based on equation for N2O emissions from agricultural soil management (United States Environmental Protection Agency, 1995)

Fertilizer credit- The compost produced from static aeration was assumed to consist of the same chemical and physical properties as that produced in windrow composting. See *Windrow Compost* (Section 3.2.7) for detailed assumptions.

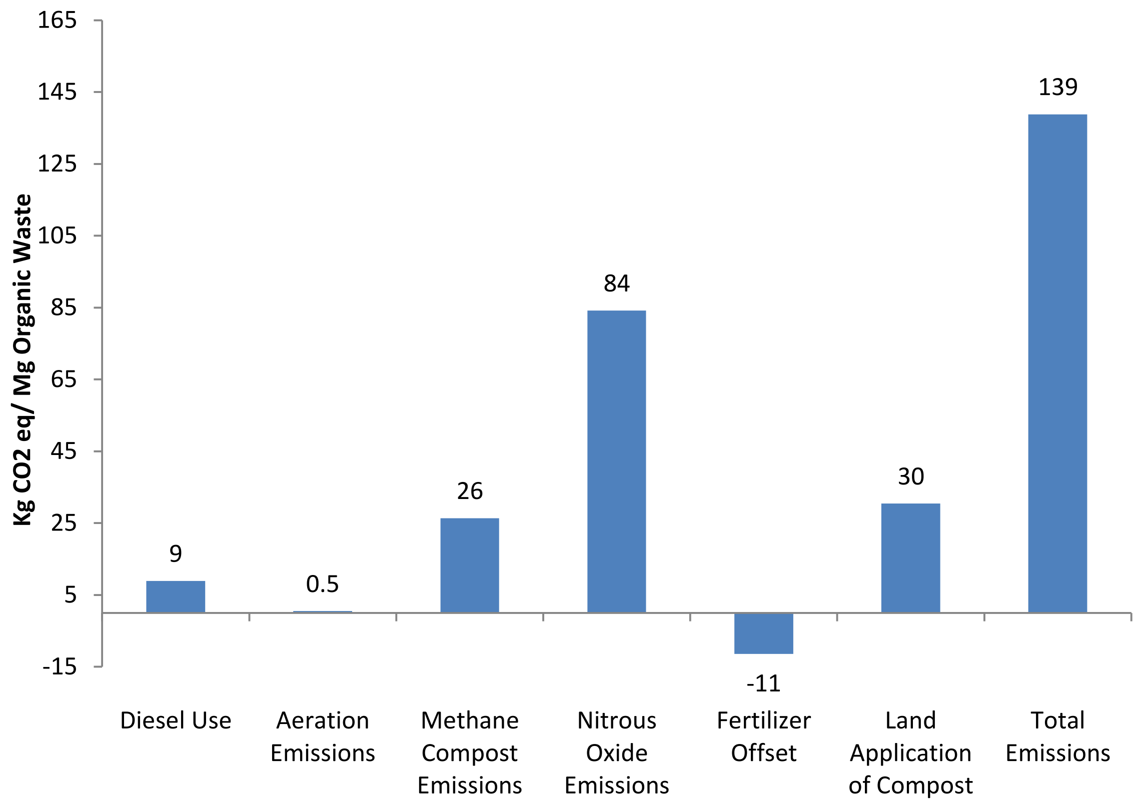

Figure 19: Emissions for each process of static aeration composting.

4.7.4 Landfill

Todos Santos disposes MSW in an open dump style landfill with no LFG capture. There is no on-site management of the waste, so no heavy equipment is utilized.

Diesel use- There is no diesel fuel combustion at the Todos Santos landfill.

Landfill emissions- Landfill GHG emissions for food and yard waste are assumed to be the same as emissions at the North Weld Landfill for the Fort Collins carbon footprint, see *Landfill* (Section 4.1.7) for detailed assumptions and values. Emissions from wet/contaminated paper were excluded due to lack of data. According to the EPA, a 100-yr time period is roughly the amount of time needed to produce 95% of the potential landfill gas for a dry climate landfill (U.S. EPA, 2015). Since both landfills are in climates classified as dry, the assumed 100 year global warming time frame is an appropriate assumption. Furthermore, it was assumed that 100% of the organic waste will biodegrade after the 100 years. Equation 4 was used to calculate total methane emissions.

Table 12 shows the inputs and outputs for the Todos Santos landfill. Due to a lack of gas collection system, the oxidation rate at the Todos Santos landfill is 10% (U.S. EPA, 2015). The GHG emission for the landfill is 1,472.8 kg CO_2 eq/Mg of organic waste.

Table 12: Inputs and outputs for Todos Santos Landfill

Inputs	
Waste	1 Mg of organic waste
Outputs	
Methane emission	1,472.8 kg CO_2 eq/Mg of organic waste

4.7.5 Transportation

Collection and transportation of organic waste in Todos Santos is difficult to model, as there are no existing compost facilities. For the purposes of this analysis, either a windrow or static aerated compost facility was assumed located at the current landfill. The various scenarios are summarized in Table 13. Organic waste pickup routes were assumed to be the same as the Fort Collins scenario (21 km per Mg of organic waste). The trip to the current landfill was measured to be 10 km from the center of Todos Santos (identified at 23.447787, -110.225188).

Table 13: Description of Transportation Distances for Each Scenario

Scenario	Distance (municipal truck)	Assumptions
No Action	31 km	One waste hauler takes organic waste to current landfill
Localized Windrow Compost	31 km	One waste hauler takes organic waste to windrow compost facility located at the current landfill
Localized Static Aerated Compost	31 km	One waste hauler takes organic waste to static aerated compost facility located at current landfill

Emission factors- The municipal truck used for waste collection in Todos Santos was assumed to be the same as the truck used in the Fort Collins analysis. The municipal truck contributes 0.49 kg CO_2 equivalent per Mg kilometer (see *Transportation emission factors* in Section 3.2.7.4 for more details). Due to the fact that all scenarios transport organic waste the same distance, each scenario produced 15.1 kg CO_2 eq/MG of organic waste.

4.8 Results

The side by side comparison of the GHG emissions for all three scenarios can be seen in Figure 20. Similar to the Fort Collins analysis, landfilling produces the largest GHG emissions, followed by static aerated compost, and windrow compost. The primary reason windrow compost resulted in lower GHG emissions was due to lower N_2O and CH_4 emissions than static aerated compost operations. Small differences in CH_4, and especially N_2O emissions, correlate to large differences in total GHG emissions, expressed as kg CO_2 equivalent. Unfortunately, there is not an abundance of literature on emissions for static aeration compost so a statistical analysis was not possible.

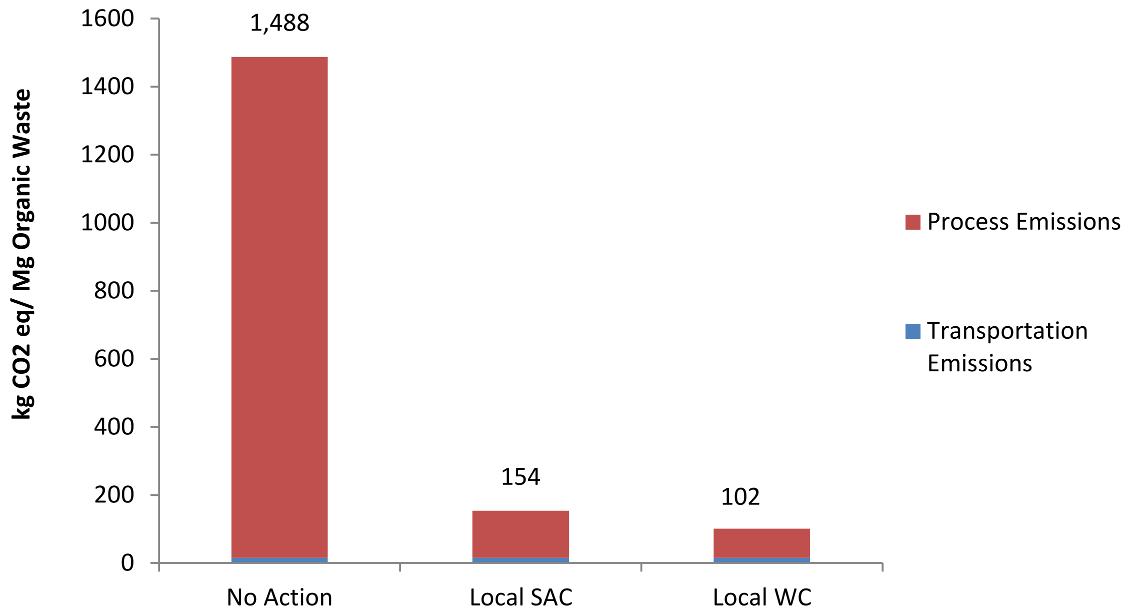

Figure 20: GHG emissions associated with each scenario. See Table 13 for detailed description of each scenario.

4.9 Capital Cost Analysis

The cost of establishing new compost facilities was analyzed. Although the cost of a windrow compost system compared to a static aerated compost system will vary by location, the breakdown of default costs in the U.S. can be seen in Table 14. Lacking other data, these costs were a suitable proxy for an overall estimation of what a compost facility may cost in Todos Santos. An annual feedstock of 2,144 Mg (5.87 Mg per day) was assumed for composting operations.

Table 14: Equipment Cost Breakdown of Windrow and Static Aerated Compost

Equipment	Equipment Cost[1] (Dollars/Unit)	Windrow[1] (units/Mg per day)	Static Aerated[1] (units/Mg per day)	Windrow Cost (Dollars)	Static Aerated Cost (Dollars)
Windrow Turner	26,700	0.173	.0865	27,130	13,570
Tub Grinder	370,843	0.0038	.0038	8,280	8,280
Screens (remove contaminants)	148,337	0.0025	.0025	2,180	2,180
Front end loader	222,506	0.003	.003	3,920	3,920
Blower	323	0 (assuming no aeration is used)	0.1	0	190
Optional Cover[2]	75,000	0	.0009	0	400
Total Cost (Dollars)				**41,510**	**28,540**

1. All values taken from (Levis et al., 2013)
2. Optional cover is modelled after GORE cover systems mentioned in chapter 4.7.1.3

Operations and maintenance for static aeration and windrow composting are not expressly examined in this study. However, a simple static aerated compost facility will likely be less complicated to operate than a windrow compost facility, due to the decreased need to turn organic waste piles. In addition, static aerated composting will require less and/or smaller heavy-duty equipment compared to windrow composing, so overall maintenance of the facility will be less difficult. Some static aerated compost facilities can be quite complicated as blowers, sensors, and monitoring equipment become more sophisticated, but for the purposes of this analysis static aeration is assumed to be very simple. If composting in Todos Santos proves to be successful, more complicated methods of static aeration could be analyzed and compared to windrow composting. In addition, the use of a cover (See Table 14 for description) will aid in operations by preventing water from evaporating. This will likely be critical in Todos Satos' arid climate.

The market for compost in Todos Santos has not been analyzed. This is an area for future research as the sustainability of a compost operation will depend on revenue obtained from selling compost. There is agricultural in and around Todos Santos, which suggests that there would be a market for compost. Quantifying that demand will be necessary before any city-wide compost facility is established.

4.10 Scenario Analysis

If a new landfill is to be built in Todos Santos, the possibility of adding a LFG capture system should be analyzed. As can be seen in Figure 21, the creation of a new landfill with LFG capture significantly reduces the GHG emissions of landfilling organic waste. However, static aerated compost and windrow compost still emit lower GHG emissions. The theoretical new landfill was assumed to have a LFG capture efficiency of 68.2% and an oxidation rate of 10% (U.S. EPA, 2015).

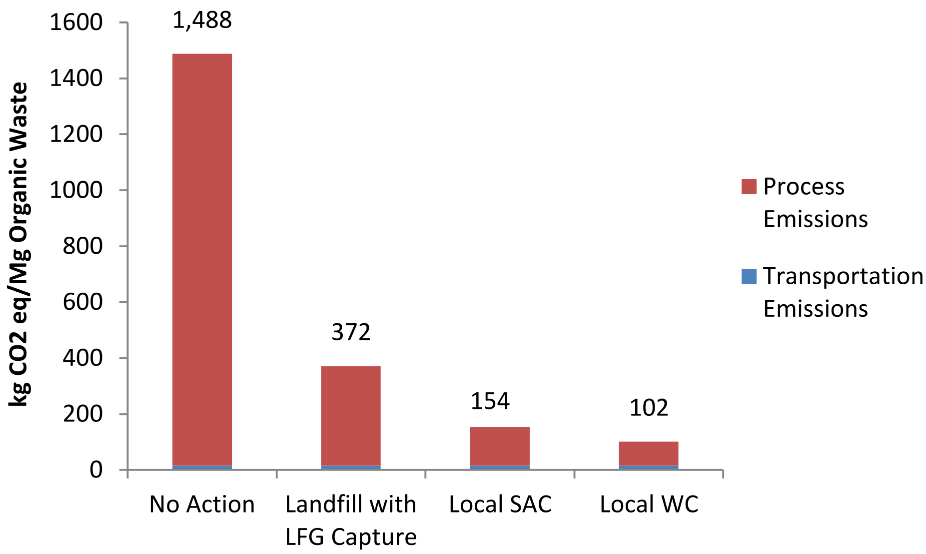

Figure 21: Comparison of GHG emissions of a theoretical new landfill with LFG capture to the No Action, Static Aerated Compost, and Windrow Compost Scenarios.

4.11 Conclusions

Despite the fact that GHG emissions are slightly higher for static aerated compost than windrow compost, static aerated compost represents a more feasible option for composting in Todos Santos. With static aerated compost, a windrow turner does not need to be purchased, and in general, static aeration compost has less management requirements. Furthermore, the cost analysis showed that a static aerated facility would be less expensive than a windrow facility.

The results of this analysis were scaled up to represent hypothetical organic waste diverted from the landfill per year. Todos Santos has a waste generation rate of 2.3-kg of waste per person per day (Dirección de Planeación Urbana y Ecología, 2011), and based on 2010 census data, Todos Santos has a population of 5,148. These numbers yield approximately 4,322 Mg of MSW per year. Assuming 49.6% of that waste is food and wood waste (Pipatti et al., 2006) results in 2,144 Mg of available organic waste. Figure 22 shows the current GHG emissions per year and also displays how various levels of static aerated composting could decrease emissions. For example, if 50% of organic waste is composted and the remaining 50% is disposed in the current landfill, the resulting emissions are 1,786,149 kg CO_2

equivalent per year. This represents a 55% decrease in emissions compared to the No-Action Scenario. If even 10% of total organics are composted in Todos Santos, the town can reduce overall emissions associated with landfilling organic waste by about 8.9%.

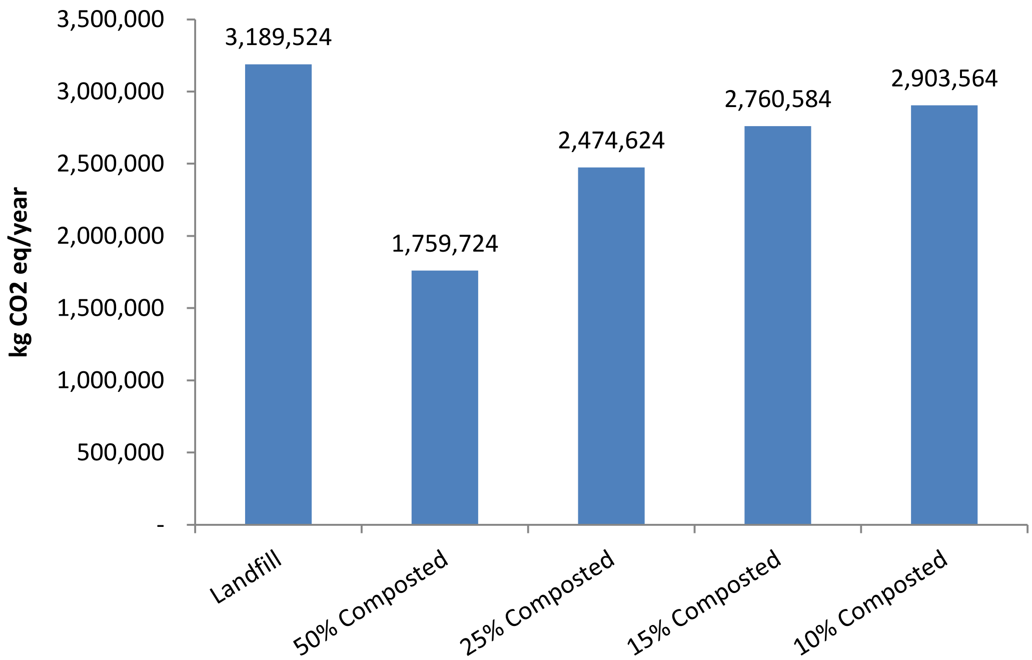

Figure 22: GHG emissions associated with different levels of composting organic waste using a static aerated system.

This analysis has shown that composting is favorable to landfilling organic waste concerning GHG emissions. Utilizing the most recent global warming potential relative to CO_2 released by the IPCC will result in different GHG emissions, but would not change the rank of scenarios when comparing GHG emissions. In fact, the No Action scenario wouldl have higher emissions, while both Local SAC and Local WC would have slightly lower emissions. Therefore, even with the 2014 IPCC global warming potentials, the No Action scenario wiould produce the highest GHG emissions, followed by Local SAC, and finally Local WC. In addition, composting organic waste will help to decrease litter, increase landfill lifetime, and create a beneficial soil amendment for Todos Santos. However, that is likely not enough to spur the advancement of compost in Todos Santos. To make composting a reality in Todos Santos, there needs to financial incentives, community leadership, and political leadership. Future research is required to fully understand the economic market for compost in Todos Santos and even the greater Baja California Sur area. To display the potential feasibility of composting, a hotel in Pescadero (neighboring community located 13 km from Todos Santos) has started a small, pilot-scale compost operation to manage their own organic waste (T. Molines, personal communication, December 12, 2017). This is designed to show political leadership that composting is a viable means of disposing of organic waste and can also produce a useable soil amendment. The pilot project is in the early stages, but the project represents the beginnings of a movement towards more sustainable organic waste management.

Chapter 5: Recycling Cost Analysis for Todos Santos

5.1 Introduction

Recycling programs not only help decrease materials being sent to the landfill and ease the pressure on virgin materials, but can also be a source for income and local job generation. Currently, Todos Santos has a small, grass roots recycling facility called Punto Verde (see Figure 23 for location). The facility is operated and owned by Alex Miro and is staffed primarily with volunteers. According to Miro, about 95% of the people that bring recyclables to Punto Verde are foreigners, while the vast majority of the native Mexican population in Todos Santos throws away their recyclables (A. Miro, personal communication, June 4, 2017). This culture is common in all of Baja California Sur, and organizations throughout the region are engaged in educational campaigns to increase recycling. In the nearby city of La Paz, there is a large-scale recycling facility that has five industrial balers and ships the majority of their materials to Guadalajara, Mexico (Operations staff, personal communication, June 8, 2017). From there, some of the materials are re-processed (e.g., paper into toilet paper). The majority of the materials are shipped to the U.S. and are finally recycled in China. According to staff at the La Paz facility, the reason more materials are not processed in Mexico is due to the delicate and easily compromised nature of recycling (e.g. contamination, impurities, etc.). In addition, governmental regulations concerning material quality make the process expensive.

Figure 23: Location of Punto Verde in reference to the CSU Center and the restaurant, Jazzamango.

Punto Verde is currently a fenced off, unpaved area where various types of recyclables are sorted and stored for future transport. As can be seen in Figure 23, Punto Verde is a small facility compared to the CSU Center. Several obstacles, including the lengthy transportation chain and the lack of waste management, make recycling in Todos Santos difficult. The distance between La Paz and Todos Santos alone (84 kilometers) creates barriers in cost efficiency. However, Miro believes that the most important way forward to create an efficient recycling program is through education. Punto Verde offers a hands-on approach to teach local children and adults the benefits of recycling, which in his opinion is the best way to encourage a culture change.

In order to provide an estimate of the current value of recyclables being thrown away, a cost analysis was conducted. In addition, potential improvements in facility efficiencies, such as utilizing a baler to increase densities of recyclables, were examined.

5.2 Methodology

Punto Verde accepts many different types of recyclables and has detailed records of materials recycled for 2016 and 2017. The various types of recyclables, weights collected, and monetary value of each recyclable according to Alex Miro can be seen in Table 15. All revenues were converted from Mexican pesos to U.S. dollars (exchange rate on November 26, 2017: 1 peso = $0.054)

Table 15: Recycling Data for Punto Verde

Type of Recyclable	Monetary Value (USD/Mg)	Collected at Punto Verde (Mg/Year)1	Revenue (USD/Year)2
# 1 PET or PETE plastic	54	2.06	111
# 2 HDPE plastic	54	1.10	59
ABS plastic	27	0.80	22
Cardboard and paper	32.4	3.44	111
Copper	3,510	0.05	161
Thin aluminum (beer or soda cans)	864	0.31	265
Iron cans	54	0.74	40
Scrap metal	81	1.19	96
Bronze	1,350	0.014	19
TOTAL		9.69	885

1. Data was collected from records on Punto Verde's website "https://www.ecorrrevolucion.org" and represents the year 2016.
2. The monetary value of recyclables fluctuates considerably depending on a multitude of factors. The dollar amounts reflected here are based on personal communication with Alex Miro and represent the average prices in 2016. Totals may not add up due to rounding.

The total value of recyclables currently being thrown away in Todos Santos is summarized in Table 16. Todos Santos produces 4,322 Mg of solid waste per year, which is broken down per Figure 16.

This represents a coarse breakdown of recyclables into paper and cardboard, plastic, glass, and metal. In order to develop a more granular analysis, plastic and metal compositions were scaled based on the breakdown from Punto Verde. For example, at Punto Verde, 52% of all plastic is #1 PET or PETE. Therefore, 52% of the total plastic in Todos Santos was assumed to be #1 PET or PETE. This method also applies to #1, #2, ABS plastics, copper, aluminum cans, iron cans and scrap metal, and bronze. These approximations represent a “best estimate” of recyclable materials in Todos Santos. As can be seen in Table 16, if 100% of recyclables are collected the revenue is estimated to be about $87,000 per year. This is significantly higher than the roughly $900 per year currently collected at Punto Verde.

Table 16: Potential Revenue of Recyclables in Todos Santos

Type of recyclable	Current value (collected at Punto Verde)	100% collection rate for all of Todos Santos
Units	Dollars/year	Dollars/year
Paper and Cardboard	111	21,004
#1 Plastic	111	7,279
#2 Plastic	59	3,879
ABS	22	1,422
Glass	N/A	14,002
Copper	161	10,622
Thin aluminum and aluminum cans	265	17,450
Iron cans and scrap metal	136	10,284
Bronze	19	1,243
TOTAL	**885**	**87,185**

5.3 Results

Currently, it is estimated that Todos Santos is landfilling about 99% of the available recyclable materials. Figure 24 portrays a revenue stream that could be generated if Todos Santos is to increase recycling efforts. Furthermore, if Todos Santos is to increase its recycling efforts, it could do so in incremental steps. Utilizing the results of this cost analysis, Todos Santos could set realistic goals for achieving increased recycling.

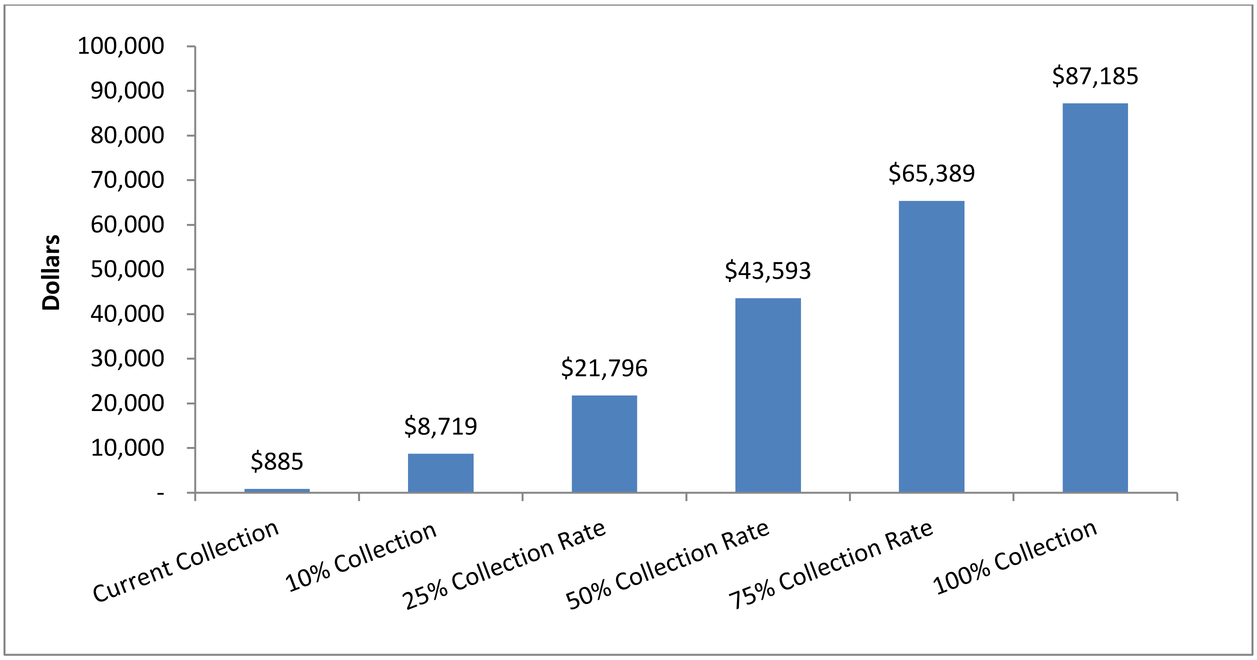

Figure 24: Theoretical revenue from different recycling collection rates. The current collection is based on values from Punto Verde.

Most large recycling facilities use bailers to increase material volumes and transportation efficiencies. Punto Verde has recently bought a bailer, but there have been difficulties in the actual implementation of the baler at Punto Verde. Assuming Punto Verde begins to use the bailer, paper and cardboard, plastic, and aluminum and iron cans were considered materials that can be baled. A semi-truck trailer is used to deliver recyclables to La Paz, and has a payload capacity of 30 Mg and a volume of 112 m^3 (A. Miro, personal communication, September 19, 2017). The increase in revenue per truck load (assuming the truck's volume is completely occupied for each material) can be as high as 16.7% (Table

17). In some cases, when the truck is fully loaded, the weight of some materials such as paper and cardboard, #1 plastic, and iron/tin cans exceeded the 30 Mg payload of the truck. In such instances the truck was assumed to only be loaded to 30 Mg.

Table 17: Revenue Comparison for Baling of Recyclables[1]

Material	Revenue with Baler (dollars/truck load)	Revenue without baler (dollars/truck load)	Increased Revenue Factor from Using Baler
Paper and Cardboard	972.0	441.3	2.2
#1	1620.0	107.6	15.0
#2	1435.3	86.1	16.7
ABS	717.6	89.7	8.0
Aluminum cans	14352.5	2870.5	5.0
Iron/tin cans	1620.0	538.2	3.0

1. Density values for materials that are loose vs. baled are taken from the EPA (United States Environmental Protection Agency, 1997)

5.4 Conclusion

The results of this analysis show that there is a market and possible revenue stream to support recycling efforts in Todos Santos. Table 16 shows that only small fractions of the recyclables in Todos Santos are collected at Punto Verde. Recycling collection policies either at a governmental or community level could allow for incremental increases in collection rates. However, there are many obstacles to overcome. Some are tangible obstacles such as lack of governmental support and lack of financial incentives. Other obstacles are harder to quantify such as a general lack of community culture surrounding recycling. For Punto Verde specifically, the current recyclable collection rates are not high enough to make the facility viable. Students at Colorado State University majoring in the Department of Design and Merchandising are currently working with Punto Verde to develop more awareness among the community. The main goals of this effort are to create educational billboards that can be placed around Todos Santos, develop a better work environment (e.g., bathroom, shade, etc.), and work with Punto Verde to develop the most streamlined collection and sorting operation possible. The recent addition of a baler is a possible way to increase revenue streams and make Punto Verde more financially sustainable.

When comparing recycling in Todos Santos to Fort Collins, the differences are stark. However, the success of recycling operations in Fort Collins is relatively new, and took years to foster. Some factors that led to the current success include strong leadership by City officials and education programs for residents, businesses, and even visitors (Zero Waste Associates, 2013). City staff have remarked that they feel the question among the majority of residents and businesses in Fort Collins is no longer "why should I recycle?" but instead "how should I recycle?" Achieving this same shift in Todos Santos will likely be even more challenging than for Fort Collins due to lack of political leadership, but collaborations between community leaders, universities, and volunteer organizations will help push the overall movement forward.

Chapter 6: Summary and Conclusions

A carbon footprint analysis of different organic waste management strategies was conducted for Fort Collins, Colorado, USA and Todos Santos, Baja California Sur, Mexico. Fort Collins is an environmentally progressive town that has the financial means to implement expensive organic waste management alternatives to landfilling. Todos Santos faces barriers for organic waste management due to economics and cultural attitudes. Both of the carbon footprint analyses used life cycle assessment methodologies to predict GHG emissions of various organic waste management scenarios. While these scenarios differed between Fort Collins and Todos Santos, it was found that landfilling organic waste produced the highest GHG emissions for both towns.

In Fort Collins, Scenario AD 1 was found to produce the least GHG emissions (130.7 kg CO_2 equivalents/functional unit), followed by Scenario AD 2 (168.8 kg CO_2 equivalents/functional unit), Scenario Regional Compost with TS (197.1 kg CO_2 equivalents/functional unit), Scenario Regional Compost without TS (249.8 kg CO_2 equivalents/functional unit), and finally the No Action Scenario, which produced the most GHG emissions (780.4 197.1 kg CO_2 equivalents/functional unit). The AD 1 scenario generated the least amount of GHG emissions due to the net negative emissions of the anaerobic digestion process and the utilization of transfer station to transport the remainder of the organic waste to a regional compost facility. In addition, a transfer station will always reduce overall GHG emissions when compared to a similar process scenario. For example, AD 1 and AD 2 have the same process emissions, but AD1 has a much lower transportation emission (Figure 13). This is mainly due to the fact that Fort Collins has three waste haulers, so combining organic waste at a transfer station, and only using one truck to transport waste will always decrease emissions.

While the AD 1 Scenario produced the lowest GHG emissions of all scenarios, the actual implementation of this scenario is very complicated. Engineering modifications to heat exchangers, pipes, pumps, etc. will need to be conducted in order to accommodate both increased food waste and a co-generation system. In addition, policy decisions regarding food waste collection participation rates and fees will need to be addressed in order to ensure a steady stream of food waste. Nevertheless, this analysis has shown that the AD 1 Scenario is the most environmentally favorable option (with regards to GHG emissions) and should be explored further to help the City meet its GHG reduction goals.

Generally speaking, an important discovery of this study was that if Fort Collins sends 100% of its waste to Larimer County Landfill instead of splitting it between North Weld Landfill, GHG emissions for the landfill decrease by about 69% (see Figure 14). This result illuminates the fact that in Fort Collins, a landfill with an LFG captures system produces similar, and in this case lower, GHG emissions to the Regional Compost without TS Scenario. The comparable emissions can be attributed to the high transportation emissions associated with the Regional Compost without TS Scenario. The process emissions for windrow composting organic waste are lower than landfilling with a LFG capture system, but the geographic distances and waste collection methods in Fort Collins display the importance of transportation in this carbon footprint analysis.

In Todos Santos, the carbon footprint analysis found that windrow composting produces the least GHG emissions. Landfilling organic waste produces 10 times more GHG emissions than either static aerated compost or windrow compost, due to the lack of any LFG capture system. Static aerated composting was found to produce more N_2O and CH_4 emissions than windrow composing, which due to the large CO_2 equivalents of CH_4 and N_2O, results in higher GHG emissions. Unlike the Fort Collins' carbon footprint, transportation does not play a key role in the Todos Santos analysis, as transportation distances were assumed to be the same for all scenarios. However, this assumption could change depending on a multitude of variables including available land, partnerships between towns, etc.

The IPCC 2007 global warming potentials for CH_4 and N_2O have been updated as of 2014. Methane has been updated to a CO_2 factor of 28 and N_2O a CO_2 factor of 265 (IPCC, 2014). The IPCC

2007 values were utilized for this study, however using the 2014 potentials would not change the ordinal ranking of scenarios. For Fort Collins, the No Action scenario will still produce the highest GHG emissions, followed by AD 1, AD2, Regional Compost with TS, and finally Regional Compost without TS regardless of whether the 2007 or 2014 global warming potentials are used. For Todos Santos, the No Action scenario will similarly produce the highest GHG emissions, followed by Local SAC, and Local WC produced the least GHG emissions, again irrespective of 2007 or 2014 global warming potentials.

The capital cost analysis of windrow versus static aerated compost facilities showed that a windrow facility is about 1.5 times more expensive than a static aerated facility, due primarily to the heavy equipment needed for windrow composting. Operation and maintenance requirements were not analyzed for windrow or static aerated composting. It is hypothesized that a simple static aerated compost facility will be easier to operate than a windrow facility, primarily due to the decreased necessity of organic waste turning. However a thorough operations cost analysis should be conducted for composting in Todos Santos. Despite the slightly higher GHG emissions that occur with windrow compost, the lower capital cost of static aerated compost make it a more feasible option.

A critical future area of study is an analysis of the current market for compost, i.e. demand, revenue streams, etc. It is hypothesized that due to the current agricultural areas within Todos Santos, there is the potential demand for compost, but this would need to be confirmed. Furthermore, the actual collection of organic waste is a complicated issue that would require further analysis. In order to assure that there is a steady stream of organic waste available for compost, there would need to be a dedicated collection service. Collection could be via municipality or independent entrepreneurs.

Recycling in Todos Santos is in its infancy stages, but has the potential to grow if community and government leaders can change existing cultural attitudes. This analysis has shown that only about 1% of the recyclables in Todos Santos are collected (Figure 24. In addition, in Todos Santos, there is an estimated $87,000 of recyclables produced per year. While it is unlikely to collect the full value of the available recyclables, small steps can be taken to incrementally increase recycling in Todos Santos. Similar to compost in Todos Santos, the financial logistics of recycling need to be considered to produce long lasting impacts. Through increased education, stakeholder leadership, and support from local government, incremental goals for sustainable waste management can be set and achieved.

The social aspects of sustainable waste management are usually more qualitative in nature, but equally important to address. Fort Collins and Todos Santos both require community participation to create a culture of sustainable waste management, be it organics or recyclables. Fort Collins has developed a strong practice of recycling and landfill diversion, while Todos Santos struggles with open dumping, disposal of garbage in natural areas, and lack of recycling. However, the culture in Fort Collins took time to develop, and was promoted through education, stakeholder leadership, and support from local government. Utilizing similar methods, Todos Santos can set incremental goals to compost organic waste and increase recycling rates.

Regardless of a city's economic, environmental, or social ethics, it is important to consider local waste management conditions that may impact transportation, feasible technologies, and stakeholder support. These local conditions were addressed before alternative solutions were created for Fort Collins and Todos Santos. Once feasible scenarios for organic waste diversion were identified, a carbon footprint analysis utilizing LCA methodology produced a holistic, comparative assessment that highlighted best organic management options for reducing GHG emissions in each city. Disposing of organic waste in landfills without LFG capture was the primary reason the landfilling scenarios produced the most GHG emissions for both Todos Santos and Fort Collins. In addition, the cost assessment of compost techniques conducted for Todos Santos showed that static aeration would be less expensive to implement than windrow compost. The recycling cost analysis illuminated that about 99% of the recyclables in Todos Santos are currently being disposed of in the open dump. This represents a lost opportunity for Todos Santos in the form of revenue, potential job creation, and an improved aesthetics/green connotation of Todos Santos.

Next Steps for Fort Collins

It is recommended that the City of Fort Collins conduct an analysis on the feasibility of both food waste and organic waste collection. When and if the City decides to move forward on organic waste diversion, collection will likely need to incorporate both residential and commercial sources. This will translate to increased costs for both collectors and customers. Furthermore, Fort Collins should analyze the possible tradeoffs between building a transfer station to transport organic waste and building their own local compost facility. A local compost facility would decrease GHG emissions associated with transporting organic waste regionally, but the land acquisition and permitting of compost facilities is often difficult.

Next Steps for Todos Santos

Fort Collins has a large amount of both accurate and granular data surrounding solid waste composition. This data is extremely useful when comparing both GHG emissions and cost for different solid waste disposal options. Todos Santos would benefit from a comprehensive waste audit to determine actual waste composition, as opposed to the best estimates used in this analysis.

In addition, the results of this analysis have shown that the current organics in Todos Santos could support either a windrow or static aerated compost facility. However, a market analysis of compost demand in the Todos Santos or even the Baja California Sur area would provide crucial information regarding the financial logistic of large scale compost facilities. If a market analysis is conducted and reveals there is not enough demand for compost in Todos Santos, efforts can still be undertaken to promote small scale local composting that can be used on farms or even small residential gardens. Moreover, collection of organic waste should be planned and handled either by the municipality or by an independent business/entrepreneur.

Efforts to increase recycling rates in Todos Santos should continue. Figure 24 shows different levels of revenue from recyclables, and should be utilized as a template to set incremental recycling goals. Also, increased education campaigns and potential partnerships with neighboring cities should be highlighted to help decrease the costs associated with transporting recyclable materials.

There has been continued description of fires and air pollution at the Todos Santos landfill while writing this thesis. A proper analysis of the existing landfill should be conducted to highlight improvements that can be done in the near term. If a new landfill is going to be built in the future, a plan for landfill cover, gas collection, and other maintenance should be conducted.

The long term success of any waste management program will depend on the participation of the local community. To promote recycling and compost initiatives, continuous and well organized events should be held to educate and foster interest from the community. The goal of these events should be to not only display different methods of solid waste management, but to also explain why a change in historical practices could be advantageous. Local media such as papers or brochures should be utilized to help spread information whenever possible. In addition, it is important that the community perceives how they will directly benefit from increased compost and recycling. In smaller cities such as Todos Santos, creative incentives should be offered to citizens for participating in new waste management programs. For example, if a citizen transports or signs up for an organic waste collection service, they could receive a discount when purchasing the finished compost. Financial or other forms of incentives will help to develop a community culture that is not only interested in sustainable waste management, but will also take pride in it.

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Appendix A: Food Waste Material Flow Analysis Report

Introduction

Food waste in the United States is a complicated issue to understand, and harder still to mitigate. According to the United States Environmental Protection Agency (EPA), food waste is the second largest category of municipal solid waste (MSW) sent to landfills in the United States and makes up about 14.6 percent of the total waste stream (EPA, 2015), as shown in Figure 1. Furthermore, it is estimated that 31 percent of the edible and available food supply at the retail and consumer level goes uneaten (Buzby et al., 2014). There are obvious restraints and difficulties to reducing food waste due the nature of food itself, i.e. spoilage, supply and demand, shipping, etc. Opportunities still exist for waste reduction and waste-to-energy technologies. In order to identify opportunities for food waste diversion and reduction, a Material Flow Analysis (MFA) was conducted to better understand the food waste streams in Fort Collins, Colorado. MFA is an analytical way to quantify flows and stocks of materials through a defined geographical area and over a set period of time. In this case the geographical area was Fort Collins, Colorado and the time frame was one year. MFA is a useful tool because it helps to reduce the complexity of the system while still providing a basis for sound decision making. It also assists in establishing priorities regarding environmental protection, resource conservation, and especially waste management. When used in conjunction with tools such as Life Cycle Analysis, the results can yield waste streams with associated environmental impacts. This is an area for future study.

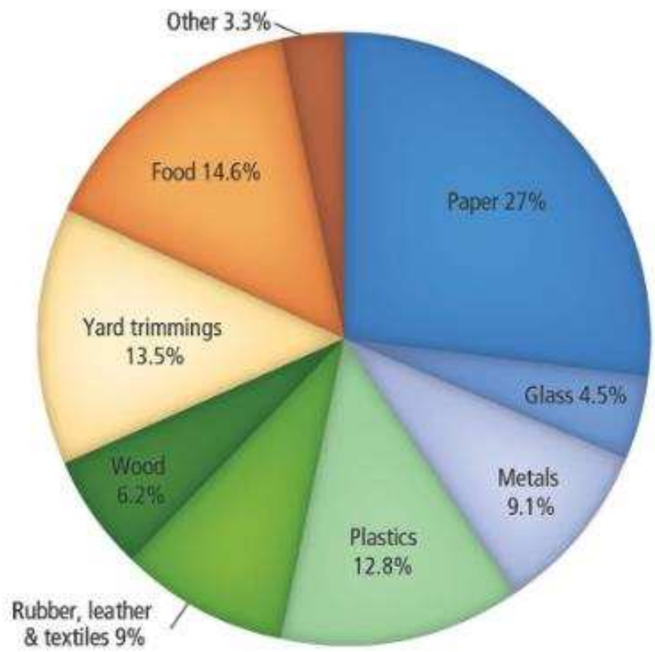

Figure 25. Total MSW Generation (By Material), 2013.

A useful first step in understanding food waste within a complicated system, such as a city, is creating a MFA that details the flows and stocks within that system. This MFA was conducted for the entire year of 2014 and the system boundary was the city of Fort Collins, Colorado. The various flows that occur, i.e. to grocery stores, restaurants, residents, etc. are important to understand because they illuminate the highest contributors to food waste. Data is represented in mass, and due to the law of conservation of mass, inputs should in theory equal outputs (see Figure 2). A full mass balance is difficult to conduct since human consumption, decomposition, and other factors make balancing the flows extremely difficult. However, MFA serves as a useful tool to gain a bird's eye view of where the various quantities of food waste are originating and how it is being disposed of.

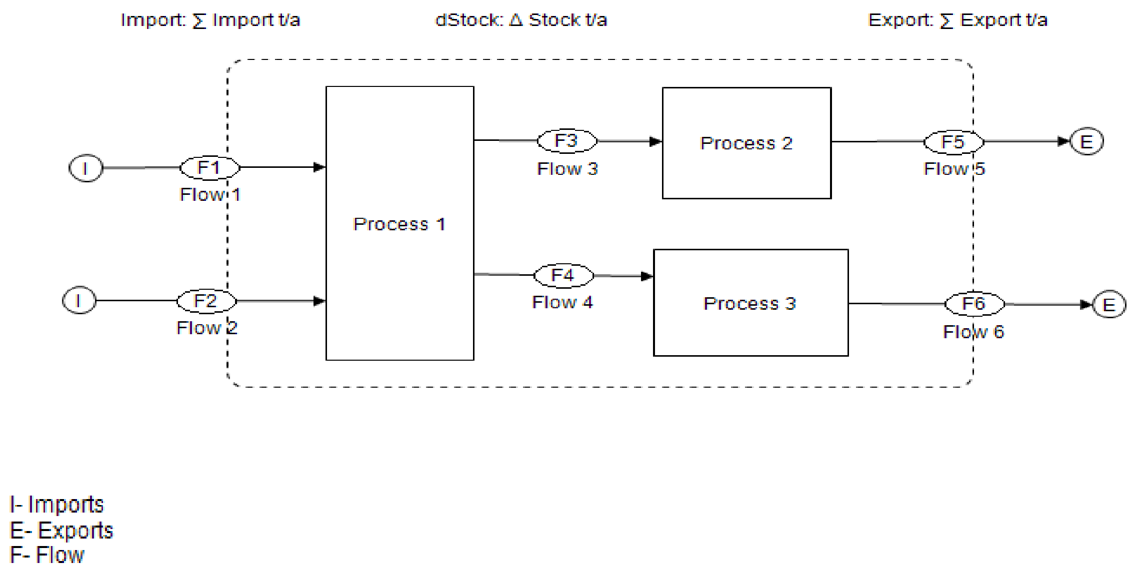

Figure 26. Generic Example of a Material Flow Analysis.

Due to the limited lifespan left at the Larimer County Landfill, there is a need to identify opportunities for material diversion. Food waste is a strong candidate due to the embodied energy within food which can be used for industrial uses. Diverting food waste from the landfill not only increases the landfill lifespan, but can also be a source of renewable energy.

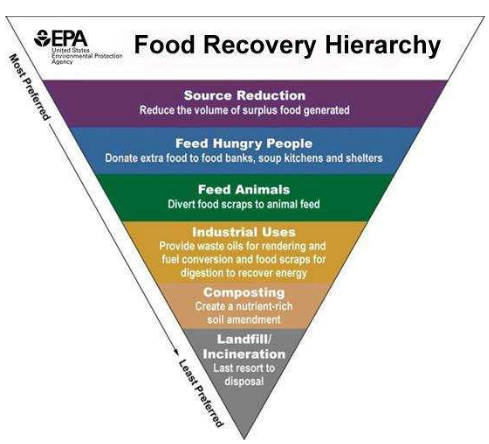

Figure 27. EPA Food Recovery Hierarch.

Goal of the Study

The goal of this study is to provide quality information for decision makers about the flow of food and food waste in and out the city of Fort Collins, as well as the associated impacts of disposal methods, by:

- Systematically estimating how much food moves through the community, organized by sector and disposal method.
- Offering insight into the highest and best use for organic, non-ligneous waste material (i.e. food scraps).
- Highlighting potential public and private partnerships.
- Sparking future research into the material management of organics.
-

Acronyms and Definitions

Food Loss – "The amount of edible food, postharvest, that is available for human consumption but is not consumed for any reason. It includes cooking loss and natural shrinkage (e.g., moisture loss); loss from mold, pests, or inadequate climate control; and plate waste" (Buzby, 2014).

Food Waste – "A component of food loss and occurs when an edible item goes unconsumed, such as food discarded by retailers due to undesirable color or blemishes and plate waste discarded by consumers" (Buzby et al., 2014).

MFA - Material Flow Analysis: a "map" quantifying the flow of materials in a defined situation and over a set period of time. The software used to conduct a MFA for food in Fort Collins is STAN (SubSTance flow ANalysis) and was developed by the University of Vienna in Austria.

MSW - Municipal Solid Waste

Methodology:

Food Input Estimation Methodology:

Data from the United States Department of Agriculture (USDA) was utilized to calculate total food supply. According to the USDA study 1,388 pounds of food was available per capita in 2010 (Buzby et al., 2014). This number was converted to tons and multiplied by the population of Fort Collins in 2014 (156,480 people) to estimate total food input. This yielded a total amount of 108,597 tons of available food per year.

Food Waste Estimation Methodology

The results of this study were calculated using a 2014 City of Fort Collins business database that included business name, North American Industry Classification System (NAICS) code, and number of employees (based on total employees as opposed to full-time employees). The database was further sorted to only include businesses with a food retail license. This resulted in a database containing 580 businesses.

The California Department of Resources Recycling and Recovery commissioned an extensive study conducted by Cascadia Consulting Group. This study broke down waste generation rates for businesses on a per employee per year basis using NAICS codes (Cascadia Consulting Group, 2015). Equation 1 displays a generic version of the California method formula.

Food Waste/year= $W_e \times\ N_e \times\ F_w$ (1)

W_e= tons of waste per employee per year according to specific NAICS (based on total employees)

N_e= Number of employees

F_w= Percentage of food waste out of total waste (based on total employees and NAICS number)

This method was useful for the Fort Collins project because it included all relevant businesses as well as provided a means of calculating food waste based on data that was readily available, i.e. number of total employees per business. The California study methodology was used to calculate food waste for the majority of businesses in Fort Collins.

The Environmental Protection Agency (EPA) has recently been designing a tool for calculating food waste (U.S. Environmental Protection Agency, 2015b) . The EPA study does not include as many NAICS codes, since it is intended for national use and cannot afford to be as detailed. It was useful for this project to cross check different methodologies to produce as much accuracy in predictions as possible.

The organizations with a food retail license in Fort Collins were lumped into 8 sectors. The breakdown is as follows:

- Education
- Food Wholesalers and Distributors
- Food Manufacturers and Processors
- Hospitality/Healthcare
- Food Retailers

- Residential
- Food Bank
- Other

Education Sector

When it came to education, the two methodologies were compared based on very few known values of food waste provided by Colorado State University (CSU) and 12 schools in the Poudre School District (PSD). A percent error was calculated to decide which methodology to use. It was found that the EPA method for PSD had a 40.8 percent error while the California methodology had a 45.9 percent error. Therefore, the EPA method was used for the majority of educational institutions in Fort Collins. Table 1 shows the breakdown of NAICS code subcategories for education. The EPA method was utilized to calculate PSD, Front Range Community College, and the Institute of Business and Medical Career based on the values in Table 2. When the number of students could not be found (i.e. private schools), the California method was used.

Table 18. Educational Sector Subcategories

NAICS Code	**NAICS Code Description**
611110	Elementary and Secondary School
611210	Junior College
611430	Professional And Management Development Training

611620	Sports and Recreation Instruction
611310	Colleges, Universities, and Professional Schools

Table 19. EPA Parameters used to Estimate Food Waste for Educational Institutions

Educational Institution Type	**Variable**	**Wasted Food Generation Factors**
Colleges and Universities		
Residential Institution	Number of Students	0.35 lbs/meal 40 meals/student/year
Non-Residential Institution	Number of Students	0.35 lbs/meal 108 meals/student/year
All Colleges and Universities	Number of Students	1.13 lbs/student/week 31 weeks/year
Private Elementary and Secondary Schools		
Primary/Secondary	Number of Students	0.35 lbs/meal
Public Elementary and Secondary Schools		
Primary/Secondary	Number of	0.5 lbs/student/week

	Students	
		40 weeks/year
	Number of	
Elementary School	Students	1.13 lbs/student/week
		40 weeks/year
	Number of	
Middle School	Students	0.73 lbs/student/week
		40 weeks/year
	Number of	
High School	Students	0.35 lbs/student/week
		40 weeks/year
	Number of	
Pre-K	Students	1.13 lbs/student/week
		40 weeks/year
	Number of	
K-12	Students	0.72 lbs/student/week
		40 weeks/year

CSU is a difficult institution to calculate due to its numerous food sources. These include the dining halls, Lory Student Center (LSC), Hughes stadium, Moby arena, and Morgan library. Some businesses at the LSC were listed in the city database but not all (see Table 3). For the current study, it was decided to use the known values of food waste coming from the dining halls as the total waste from CSU. This may have resulted in an underestimate of food waste generation and a more rigorous estimate should be conducted if this work is continued in the future.

Table 20. Food Retailers at the Lory Student Center

Businesses Captured at the LSC	**Businesses Not Captured at the LSC**
Carl’s Jr.	Aspen Grille
Taco Bell	Bagel Place
Panda Express	Spoons
Subway	Intermissions
	Ramskeller Pub
	That’s A Wrap
	Sweet Sinsations
	Sweet Temptations
	The Bean Counter
	University Club

Food waste generation was estimated at Front Range Community College after talking to dining staff who stated that at most 20 percent of the students enrolled in courses use the dining facilities. This percentage was used to calculate the total food waste using the EPA method (U.S. Environmental Protection Agency, 2015b). See Equation 2 for the formula.

$$\text{Food Waste}\left(\frac{\text{tons}}{\text{year}}\right) = \text{Number of students} \times \frac{1.13\frac{\text{lbs}}{\text{student}}}{\text{week}} \times 31\,\frac{\text{weeks}}{\text{year}} \times \frac{tons}{2{,}000\ lb} \qquad (2)$$

A similar method was utilized to estimate the waste at the Institute of Business and Medical Careers. Campus staff estimated that approximately 50 percent of the student body uses the cafeteria, therefore that value was used in Equation 2. For the other educational institutions food waste was calculated using the California method since number of students could not be found and time did not allow for original research.

Food Wholesalers and Distributors Sector

Food waste generation for the Food Wholesaler and Distributors Sector was calculated using the California method. The total number of employees was multiplied by the generation rate per employee and then multiplied by the percent of food waste within that sector's waste stream as shown in Equation 1. Equation 3 displays an example for businesses classified as NAICS code 445110 that generate 5.08 tons of waste per employee per year using the California method. Of that waste, 30.4 percent is considered food waste(Cascadia Consulting Group, 2015).

$$\text{Food Waste}\left(\frac{\text{tons}}{\text{year}}\right) = 5.08 \times N_e \times 30.4\% \qquad (3)$$

N_e= Number of Employees

Table 4 lists the NAICS subcategory codes within this sector.

Table 21. Food Wholesalers and Distributors Sector Subcategories

NAICS Code	**NAICS Code Description**
423620	Household, Consumer Electronics Merchant Wholesalers
424210	Drugs Sundries Merchant Wholesalers
424450	Confectionary Merchant Wholesalers
424490	Other Grocery and Related Products Merchant

	Wholesalers
424910	Farm Supplies Merchant Wholesalers
442299	All Other Home Furnishings Store
445110	Supermarkets and Other Grocery (except Convenience) Stores
445120	Convenience Stores
445210	Meat Markets
445291	Baked Goods Stores
445299	All Other Specialty Food Stores

Food Manufacturers and Processors Sector

Food waste generation for the Food Manufacturers and Processors Sector was calculated using Equation 1 (Cascadia Consulting Group, 2015). Table 5 lists the NAICS subcategory codes within this sector.

Table 22. Food Manufactures and Processors Sector Subcategories

NAICS Code	**NAICS Code Description**
311340	Nonchocolate Confectionery Manufacturing
311352	Confectionery Manufacturing from Purchased Chocolate
311421	Fruit and Vegetable Canning
311513	Cheese Manufacturing
311612	Meat Processed from Carcasses

311811	Retail Bakeries
311821	Cookie and Cracker Manufacturing
311911	Roasted Nuts and Peanut Butter Manufacturing
311920	Coffee and Tea Manufacturing
311942	Spice and Extract Manufacturing
311991	Perishable Prepared Food Manufacturing
312120	Breweries
312130	Wineries
312140	Distilleries
325412	Pharmaceutical Preparation Manufacturing

Hospitality/healthcare Sector

Food waste generation for the Hospitality Sector was calculated using Equation 1 (Cascadia Consulting Group, 2015). Table 6 lists the NAICS subcategory codes within this sector.

Table 23. Hospitality Sector Subcategory

NAICS Code	NAICS Code Description
621420	Outpatient Mental Health and Substance Abuse Center
621498	All Other Outpatient Care Centers
622110	General Medical and Surgical Hospitals
623110	Nursing Care Facilities

623220	Residential Mental Health and Substance Abuse Facilities
623311	Continuing Care Retirement Communities
623312	Assisted Living Facilities for the Elderly
721110	Hotels

Food Retailers Sector

Food waste generation for the Food Retailers Sector was calculated using Equation 1 (Cascadia Consulting Group, 2015). Table 7 lists the NAICS subcategory codes within this sector.

Table 24. Food Retailers Sector Subcategories

NAICS Code	**NAICS Code Description**
722310	Food Service Contractors
722320	Caterers
722330	Mobile food Services
722410	Drinking Places (Alcoholic Beverages)
722511	Full-Service Restaurants
722513	Limited-Service Restaurants
722515	Snack and Nonalcoholic Beverage Bars

Residential Sector

Understanding residential food waste is difficult due to limited data. Five studies detailing food loss per capita on a national scale were used. These rates were multiplied by the population of Fort Collins to estimate total residential generated food loss. Table 8 shows the different values for each study in tons per capita and also shows the tons of residential food waste scaled to the population of Fort Collins.

Table 25. Residential Food Waste

	USDA[1]	EPA[2]	FAO [3](low)	FAO [4](high)	Thyberg[5]	UNEP[6]	Average
Food loss (tons/capita)	.145	.065	.105	.127	.132	.12	.116
Fort Collins food loss (tons)	22,690	10,195	16,387	19,836	20,619	18,778	18,084

1. United States Department of Agriculture (Buzby et al., 2014)
2. Environmental Protection Agency (EPA, 2015)
3. Low end estimate for per capita food loss in Europe and North America according Food and Agriculture Organization of the United Nations (FAO, 2011)
4. High end estimate for per capita food loss in Europe and North America according Food and Agriculture Organization of the United Nations (FAO, 2011)
5. (Thyberg et al., 2015)
6. United Nations Environment Program (United Nations Environment Programme, 2015)

Food Bank Sector

Actual numbers for donations and waste used in the Food Bank Sector were obtained from staff at the food bank for Larimer County. This is proprietary data and is not referenced.

Other Sector

Food waste generation for the Other Sector was calculated using Equation 1 (Cascadia Consulting Group, 2015). Table 9 lists the subcategory codes within this sector.

Table 26. Other Sector Subcategories

NAICS Code	NAICS Code Description
112910	Agriculture
446110	Pharmacies and Drug Stores
446191	Food (Health) Supplement Stores
447110	Gasoline Stations with Convenience Stores
451120	Hobby, Toy, and Game Stores
451140	Musical Instrument and Supplies Stores
451211	Book Stores
452112	Discount Department Stores
452910	Warehouse Clubs and Supercenters
452990	All Other General Merchandise Stores
454111	Electronic Shopping (Fort Collins store sells loose leaf tea)
454390	Other Direct Selling Establishments
493190	Other Warehousing and Storage
512131	Motion Picture Theaters
541712	Research and Development in the Physical, Engineer, and Life Sciences
551114	Corporate, Subsidiary, and Regional Managing

	Offices
624190	Other Individual and Family Services
624210	Community Food Services
624221	Temporary Shelters
713120	Amusement Arcades
713910	Golf Courses and Country Clubs
713930	Marinas
713940	Fitness and Recreational Sports Centers
713950	Bowling Centers
713990	All Other Amusement and Recreation Industries
813410	Civic and Social Organizations
921140	Executive and Legislative Offices (Fort Collins jail)

It was a concern that if a large business had a food license for a small café or employee cafeteria there could be an overestimation of food waste. The methods used in this study were assumed to eliminate the majority of this problem, since the approach considers each sector's food waste separately. For example, in executive and legislative offices (NAICS code 921140) only 14.7% of waste generated is food waste compared to food retailers where 47.2% of total generated waste is food (Cascadia Consulting Group, 2015). However, in order to further ensure accuracy businesses within Other or Hospitality were sorted by eliminating businesses with less than 15 people. This was done because it was assumed that any business with less than 15 employees would be negligible as far as total generated food waste. The results of this sorting did not illuminate any obvious mistakes or overestimations. In fact, the businesses in question are only responsible for 3.5% of Fort Collins' total food waste. Nevertheless, in order to further validate the results original research was required. Unfortunately time and response rates from contacted individuals delayed quality checks. This is an area for future work if this study is continued.

Results

The final MFA shows that in 2014 a total amount of 32,616 tons of total food waste was generated in the city of Fort Collins. This corresponds to 30 percent of the total available food supply, which correlates with what the UDSA predicts. It can be seen that residential waste is the largest contributor to total food loss, which also corresponds to the literature. The final MFA (Figure 3) is presented as a Sankey diagram where the width of the arrow is proportional to the flow value. The food input value of 108,597 tons was not included because its large size skewed the overall figure, making the smaller flows difficult to distinguish. Figure 4 displays the overall breakdown of each sector by percent. For the purposes of this report all sectors excluding residential are classified as commercial. Figure 5 displays the breakdown of the commercial scenario.

Validation of Calculations

The City of Fort Collins commissioned a waste study of the Larimer County Landfill in June of 2016. The report was compiled by SloanVazquesMcAfee (SloanVasquezMcAfee, 2016) Municipal Solid Waste Advisors and detailed the breakdown of the materials in the Larimer County Landfill. The numbers were utilized to help validate the calculations made in this project.

An important distinction is that the MFA conducted for this project identifies **total generated food loss** and not just what ends up in the landfill. It is also worthwhile to identify the difference between food loss and food waste, which are defined in the Abbreviations and Definitions section above. In this paper the two are used synonymously since the goal of the study is to understand the total amount of food not being consumed.

According to SVM, 23.7 percent of residential MSW that ends up at the landfill is food waste(SloanVasquezMcAfee, 2016). Furthermore, 17.9 percent of commercial MSW that ends up at the landfill is food waste(SloanVasquezMcAfee, 2016). Values in Table 10 are taken from internal City of Fort Collins sources and display the total amount of landfilled material per year in Fort Collins. The total amount of food waste that ends up in the landfill per year was calculated and tabulated in Table 11.

Table 27. Residential and Commercial Contributions to Landfill

Sector	**Tons**
Residential (includes multi-family*)	44,715

Commercial	44,274

* In the SVM report, “commercial” is described as anything picked up from a dumpster, whereas “residential” is described as garbage picked up from plastic carts. Since many apartments and condos use dumpsters, they are counted as commercial. For the standards of this report, apartments and condos are considered residential. Thus, “multi-family” is allocated to residential instead of commercial.

Table 28. Food Waste Disposed to Landfill

	SVM Mean (tons)
Commercial	7,925
Residential	10,597
TOTAL	18,523

The values in Table 12 display the total food loss calculated in this study from both residential and commercial sources in Fort Collins. The total shown in Table 12 is the same as the total in Figure 3 and displays total generated food loss.

Table 29. Food Loss in Fort Collins, Colorado

Sector	**Tons**
Commercial	14,532
Residential	18,084
TOTAL	32,616

There are significant differences between Table 11 and Table 12 due to the discrepancies between the scopes of the studies. Table 11 details the tons of food that are sent to the landfill while Table 12 displays the total generated food loss in Fort Collins. According to the above tables about 57 percent of total food waste generated in Fort Collins ends up in a landfill. In both Table 11 and 12 more than 50 percent of the food waste is due to residential.

An attempt was made to empirically add up all sources of food loss in Fort Collins (see Table 13). Adding up the total estimates of landfill, compost, donations to the local food bank, and food disposed via garbage disposal amounts to 28,472 tons of total generated food loss. Comparing the totals in Tables 12 and 13, a percent error of 14.56 was calculated.

Table 30. Total Food Loss from Various Sectors

	Tons
Landfill	18,523
Compost[1]	1,512
Donations[2]	4,227
Sewer[3]	4,209
TOTAL	28,472

1. Food waste that currently gets composted from commercial sources in Fort Collins in addition to what the food bank for Larimer County composts.
2. Food donations received by the Food Bank for Larimer County
3. Average food waste to disposal per person per year taken from EPA estimate (U.S. Environmental Protection Agency, 2014)

Conclusions

Results of this study clearly show that residential food waste contributes more to total MSW than all sectors combined. This is a key conclusion of the study and illustrates the importance of residential food waste diversion. In some parts of the country, such as Boulder, Colorado, and other parts of the world, residential organics are collected in separate bins. In the vast majority of cases, organics includes both food waste and yard waste. Currently, this type of service does not exist in Fort Collins, but there has been expressed interest in the possibility by City staff. It should be noted that yard waste is not an ideal candidate for anaerobic digestion so a mixed stream of organics (yard and food waste) would be better suited for compost.

Another potential option for residential food waste diversion is utilizing the garbage disposal units that are currently installed in the majority of Fort Collins homes. This has obvious implications and is subject to numerous factors. A hotspot life cycle analysis is currently being conducted by the City of Fort Collins Environmental Services staff that attempts to understand these factors.

The results of the MFA also display the relative contributions of the commercial sector. It can be seen from Figure 6 that food retailers and food wholesalers and distributors are the two largest contributors to food waste. Thus, it would likely make the most sense to focus food waste diversion efforts on these two sectors. Potential public-private opportunities could be developed within these sectors to increase efficiencies. For example, there are waste water treatment plants in California such as Central Marin Sanitation Agency that accept commercial sources of food waste for use in their anaerobic digesters. These digesters produce methane and can be used as a renewable source of energy (Kennedy/Jenks Consultants, 2008).

This study has aided in the understanding of food waste in Fort Collins by showing the relevant stocks and flows in a reproducible, understandable, and transparent way. It provides a strong foundation for any other analyses that are done on food waste in Fort Collins.

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Appendix B: Food Waste Diversion: A Comparative Carbon Footprint Study using Life Cycle Analysis

Introduction:

The term “food waste” often implies negative connotations of being burdensome or undesirable. However, the inherent properties of food waste and even organic waste in general can create opportunities for sustainable practices, whereby it is transformed from a “waste” into a useful resource. Furthermore, diverting food waste from the landfill will not only help Fort Collins become a zero waste city, but can also aid in decreasing greenhouse gas emissions. The purpose of this report is to examine the advantages and disadvantages of several different options for food waste management in Fort Collins based on greenhouse gas emissions. In addition to reducing greenhouse gas emissions, food waste diversion from the landfill will help Fort Collins achieve its goal of zero waste by 2030.

Driver 1: Fort Collins as a Zero Waste City

The City of Fort Collins, Colorado is dedicated to becoming a “zero waste” city. A goal of 50% waste diversion from the landfill was set in 1999, and in 2014 Fort Collins achieved a 68.4 diversion rate. The current goal set by the Fort Collins City Council is to achieve zero waste by 2030. In 2016 the consulting firm Sloan Vazquez McAfee conducted a study to categorize the composition and characteristics of Fort Collins’ solid waste that is sent to the Larimer County Landfill. The analysis was conducted for residential, commercial, and construction and demolition waste for both Fall and Spring of 2016. The results of the two season study found that on average food waste accounts for 34.3% of residential organic waste, and 43.4% of commercial organic waste. Due to these large percentages, food waste diversion will be instrumental in helping Fort Collins achieve its zero waste goals.

Driver 2: Decreasing GHG Emissions

Fort Collins is also determined to decrease greenhouse gas (GHG) emissions. Ambitious goals have been set for reducing GHG emissions including a 20% reduction below 2005 levels by 2020, 80% below 2005 levels by 2030, and carbon neutral by 2050. When food waste is sent to a landfill, it decomposes to produce a mixture of various gases of about 50% carbon dioxide (CO_2) and 50% methane (CH_4). The CO_2 emissions are classified as biogenic, or in other words, emissions that are considered to be part of the natural carbon cycle. However, the CH_4 produced is not part of this natural cycle and is 25 times more potent than CO_2 on a 100 year timescale (recent reports from the GPC suggest it may be even higher). Thus, CH_4 emissions from food waste can have large implications on overall city GHG emissions. Diverting food waste from the landfill will help the City achieve their GHG reduction goals.

Food Waste Material Flow Analysis

Food waste in the United States is a complicated issue to understand, and harder still to mitigate. According to the United States Environmental Protection Agency (EPA) "food waste is the second largest category of municipal solid waste (MSW) sent to landfills in the United States" and makes up about 14.6% of the total waste stream. There are obvious restraints and difficulties to reducing food waste due the nature of food itself, i.e. spoilage, supply and demand, shipping, etc. but there still exist opportunities for waste reduction and waste to energy technologies.

Utilizing Food Waste at Drake Wastewater Reclamation Facility

The two season waste composition study found that food waste accounts for 34.3% of residential organic waste, and 43.4% of commercial organic waste. One particularly option that Fort Collins was interested in investigating is sending food waste to the anaerobic digesters at the Drake Wastewater Reclamation Facility (DWRF). Anaerobic digesters are utilized in wastewater treatment plants to reduce the amount of organic matter that will ultimately need to be transported to landfills or other disposal facilities. The bacteria responsible for breaking down organic waste produce CO_2, CH_4, and heat, collectively referred to as biogas, which can be used as a fuel source for generators, boilers, internal combustion engines, or other mechanisms for energy production. If no energy recovery equipment is in place, biogas is typically flared. Currently, the facility combusts the portion of the biogas required to heat its digesters and flares the surplus biogas. Opportunities have been identified by the City to add co-generation engines to generate renewable electricity as well as capture heat to utilize in the anaerobic digesters. The addition of food waste to the facility's anaerobic digesters will increase the amount of biogas produced, which will in turn increase the potential for energy production in a co-generation scenario.

Food Waste Diversion Scenarios

Delivery of food waste to DWRF consisted of two different scenarios. The first, referred to as the residential scenario, involved sending residential food to DWRF via the sewer system. The food waste would then go through the same treatment plant processes as regular wastewater (see Figure 2). The second scenario, referred to as the commercial scenario, assumed a truck transported commercial food waste to DWRF. The food waste would then be sorted to remove contaminants and then added directly to the anaerobic digesters (see Figure 3). Of particular interest to the City was, given limited digester capacity, which method of food waste delivery had lower GHG emissions.

Residential Scenario

The overall system of the residential scenario is presented in Figure 2. Food waste is processed within each home using an in-sink grinder (garbage disposal) and is sent to DWRF through the sewer system. It is then treated at the wastewater plant, and sent to the anaerobic digesters, i.e. the biomethane production picture in the figure. The outputs of the biomethane production process are heat and electricity production, water that is re-treated at the wastewater treatment plant, and organic solids that are applied to grasslands, i.e. Meadow Spring Ranch.

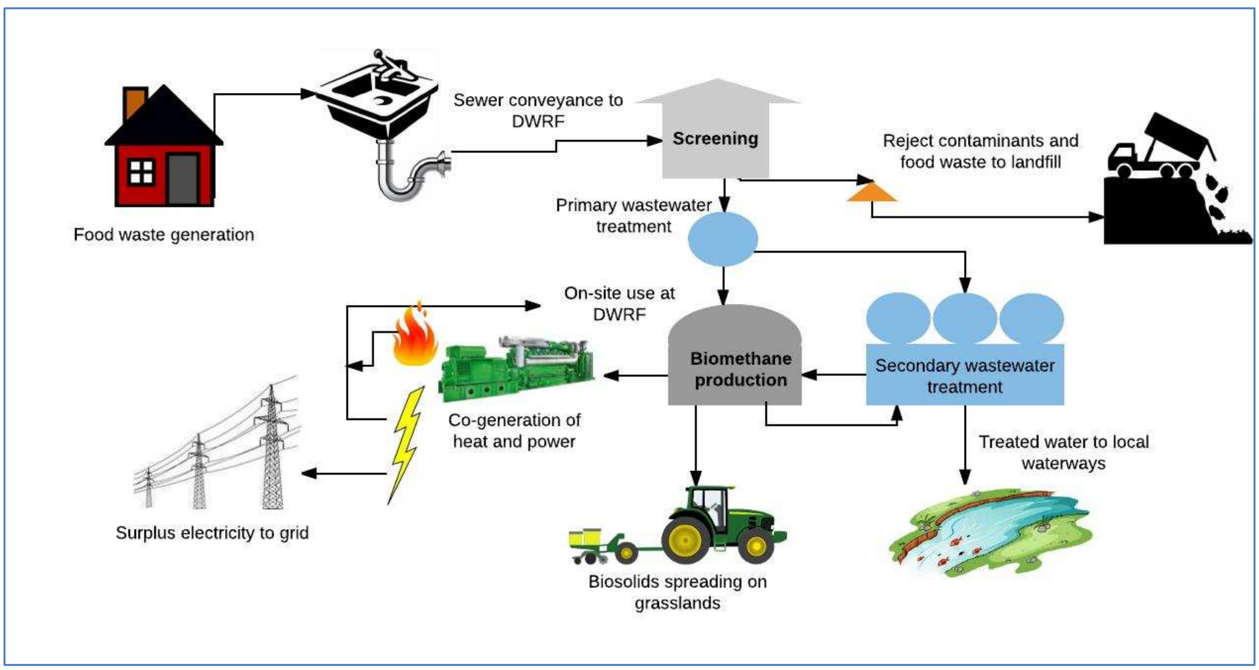

Figure 28: Overall process of the residential scenario. Food waste is initially generated in households, and is sent to the wastewater treatment plant via the sewer system.

Commercial Scenario

The commercial scenario is somewhat simpler due to the fact that the food waste does not go through the wastewater treatment process before entering the anaerobic digesters. As can be seen from Figure 3 food waste is hauled to DWRF and is sorted and processed to remove contaminants before being added to the anaerobic digesters, i.e. the biomethane production process. Similar to the residential scenario, the outputs of the biomethane production process are heat and electricity production, water that is re-treated at DWRF, and organic solids that are applied to grasslands, again referring to Meadow Springs Ranch.

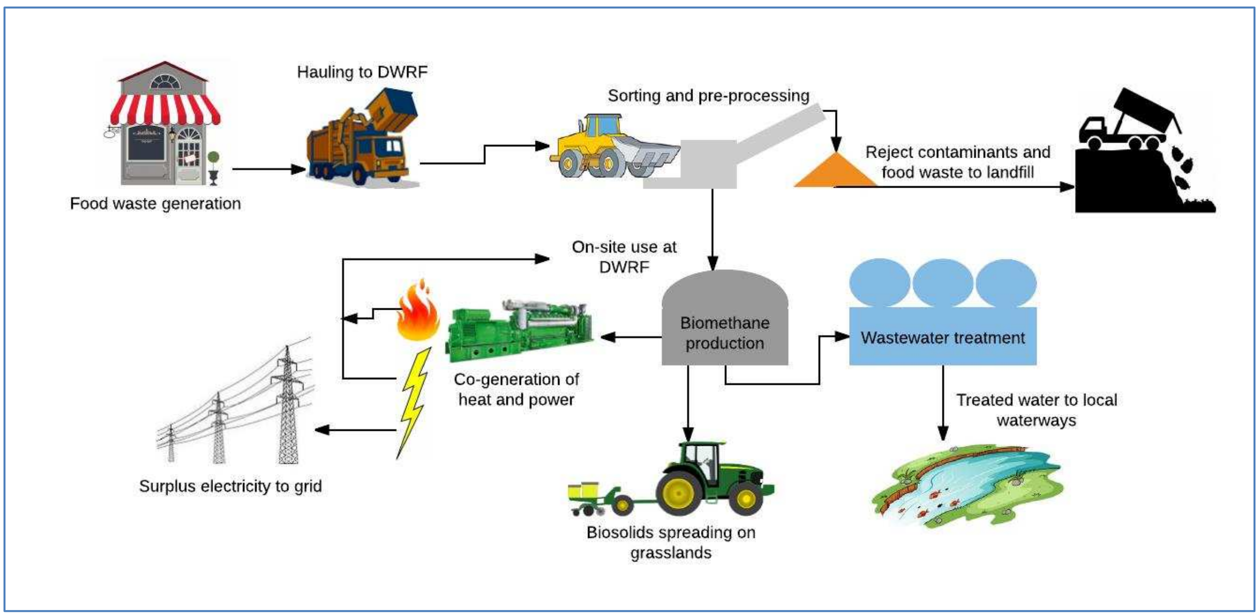

Figure 29: Overall process of the commercial scenario. Food waste is initially generated in households, and is sent to the wastewater treatment plant via the sewer system.

Life Cycle Analysis

In order to compare the two scenario's GHG emissions, the life cycle analysis (LCA) method was applied. A full LCA is essentially a cradle to grave system analysis that compares the environmental impacts of two or more processes/products. Environmental impacts often include global warming, acidification, eutrophication, human and eco-toxicity, and resource depletion. Due to data and budgetary constraints this report only analyzes global warming (GHG emissions) impacts, and net water demand. LCA is a useful resource for decision makers to compare the advantages and disadvantages of the two food waste management options.

To insure scenarios are compared on an equal basis, LCA utilizes a functional unit. A functional unit is a way to measure the service or function that the analyzed process provides. In the case of this study, the functional unit is one metric ton of food waste diverted from the landfill.

Results

GHG Emissions

Ultimately, the commercial scenario proved favorable to the residential scenario. The commercial scenario resulted in lower overall GHG emissions and lower water consumption. The net GHG emissions were $1.3*10^{-1}$ tons CO_2 eq/Metric ton of food waste for the residential scenario and $-8.98*10^{-2}$ tons CO_2 eq/Metric ton of food waste for the commercial scenario. It is significant to note that the commercial scenario produced net negative GHG emissions. Figure 4 displays an aggregated view of the various processes emissions and credits for each scenario.

Water Consumption

Water usage was calculated to be 10 times higher for the residential scenario. The authors utilized literature values from previous studies to arrive at this number. The residential scenario requires more water to dilute the food waste to a mixture where it can be ground down in a household garbage disposal. The commercial scenario does not require additional water due to the intrinsic moisture of food waste. In other words, adding food waste directly to the anaerobic digesters will not require any additional water.

Conclusion

The results of this analysis provided several interesting conclusions.

1. The production of a residential food waste processor, i.e. garbage disposal, creates surprisingly large emissions from the manufacturing, packaging, and distribution of the unit. The commercial scenario also grinds and processes food waste, but it is likely that industrial food processors are more efficient than individual, smaller processors and see higher volumes of food waste, lowering the resource to processed output ratio over their lifespan.
2. Adding food waste directly to the anaerobic digesters in the commercial scenario produces significantly more biogas than the residential scenario as no losses occur in the sewer or during superfluous wastewater processing. Increased biogas per food waste input results in more electricity and heat production, leading to a much larger energy credit for the commercial scenario. Truck transportation did not offset the benefits of the larger energy credit.
3. In contrast to the commercial scenario, the residential scenario saw lower resource and energy efficiency from equipment (mentioned in conclusion 1) and higher losses due to degradation during sewer transportation and wastewater treatment processes. While still much lower in terms of emissions than the landfill, given the limited digester capacity at DWRF, the commercial scenario provides more energy for the same initial amount of food waste.
4. Water consumption is 10 times higher for the residential scenario, due to the dilution of food waste required for a household garbage disposal.

Bottom Line Summary

The material flow analysis conducted provided an estimate of how much and where food waste is being generated in Fort Collins. To compare GHG emissions for two different food waste diversion strategies, LCA methodology was utilized. This carbon footprint study found that the commercial scenario was not only superior to the residential scenario, but also resulted in net *negative* GHG emissions. In addition, the commercial scenario resulted in 10 times less water consumption than the residential scenario.

Appendix C: Compost Background Data

Table 31 Sources Used for Diesel Use

Source	Total Diesel Use (liter diesel/Mg feedstock)
(Andersen et al., 2010)	3.04
(Komilis et al., 2004)	2.6
(Sharma et al., 2007)	5.02
(U.S. Environmental Protection Agency, 2016)	7.8
(PE Americas, 2011)	4.9
(Martínez-Blanco et al., 2010)	5.7
(Cadena et al., 2009)	9
Average	**5.44**

Table 32 Sources Used for Emissions of Nitrogen Fertilizer

Source	CO_2 equivalent emissions/kg Nitrogen fertilizer
NREL LCI database	1.288
GaBi database	1.46
(Boldrin, 2009)	8.85
(Levis et al., 2013)	3.4
(Brown et al., 2010)	4
Average	**3.8**

Table 33 Sources Used for Feedstock Decrease

Source	Percent Feedstock Decrease
(van Haaren et al., 2010)	20%
(Saer et al., 2013)	33.5%
(Levis et al., 2013)	33.2%
Average	**29%**

Table 34 Sources Used for Emissions of Phosphorus Fertilizer

Source	CO_2 equivalent emissions/kg Phosphorus fertilizer
NREL LCI database	0.45
(Boldrin, 2009)	1.8
(Levis et al., 2013)	3
(Brown et al., 2010)	2
Average	**1.8**

Appendix D: Compost GHG Emissions

Table 35: Literature Review of GHG Emissions Associated with Composting

Source	Feedstock	Min Methane Emissions (kg/Mg feedstock)	Max Methane Emissions (kg/Mg feedstock	Min N_2O Emissions (kg/Mg feedstock	Max N_2O Emissions (kg/Mg feedstock
(Saer et al., 2013)	Green Waste	0.049	0.604	0.025	0.178
(Saer et al., 2013)	Bio and green waste	N/A	1.51	N/A	0.252
(Saer et al., 2013)	Municiipal organic waste	0.03	N/A	0.0165	N/A
(Saer et al., 2013)	Yardwaste	N/A	0.08	N/A	0.054
(Saer et al., 2013)	Household organic wastes	0.021	0.2149	0.0003	0.003
(Saer et al., 2013)	Household organic wastes	N/A	3.6	N/A	N/A
(Saer et al.,	Household	N/A	11.9	N/A	0.1

2013)	organic wastes with yard waste				
(Saer et al., 2013)	Household organic wastes with leaves	N/A	0.172	N/A	0.022
(Saer et al., 2013)	Mixture of olive branches, leaves	N/A	7	N/A	N/A
(Saer et al., 2013)			4.8		0.08
(Saer et al., 2013)	Household organic wastes with leaves and branches	0.08	0.3	0.04	0.1
(Saer et al., 2013)	Household organic wastes with leaves and branches	N/A	0.2	N/A	0.11

(Saer et al., 2013)	Food waste	N/A	0	N/A	0
(van Haaren et al., 2010)	Yard waste	2.3 E -05	2.3 E -05	N/A	N/A
(Martínez-Blanco et al., 2010)	Organic form municipal solid waste	0.034	0.034	0.092	0.092
(Levis et al., 2013)	Miscellanous organic waste	3.7	3.7	0.0192	0.0192
(Andersen et al., 2010)	Garden waste	1.9	1.9	N/A	N/A
(U.S. Environmental Protection Agency, 2015)	Biowaste	0.2425	0.2425	0.1465	0.1465

Table 36: Statistical Values for GHG Emissions Associated with Composting

	Methane Emissions (kg/Mg Feedstock)	N_2O Emissions (kg/Mg Feedstock

Quartile 1	0.065	0.021
Quartile 2	0.240	0.054
Quartile 3	1.705	0.105
Inner Quartile Range	1.641	0.084
Lower Inner Fence	2.396	-0.106
Upper Inner Fence	4.166	0.232
Average with Outliers Eliminated	0.663	0.063