Decentralized management of urban food waste: A proof of concept with neighborhood-scale vermicomposting in Montreal, Canada

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Abstract

With growing urban populations, the management of organic waste in cities is becoming increasingly challenging. A large fraction of food waste is currently landfilled, where its decomposition leads to greenhouse gas emissions. Although composting is becoming more common in Canada, the conventional approach for collecting and managing municipal organic waste has typically been to construct large, centralized treatment facilities, which can be costly, time intensive, and may have negative environmental and social impacts for surrounding communities. Furthermore, due to logistical constraints, some industrial, commercial and institutional buildings either do not separate the organic fraction of their waste or are gaps in existing municipal organic waste collection. I investigate the potential for decentralized (neighborhood block level) urban organic waste collection and treatment in small- to medium-scale vermicomposting facilities. Vermicomposting is the process of breaking down organic waste with the use earthworms, which is quicker than conventional composting and yields a more valuable end-product. By using spatial and systems modelling, I examine the efficacy for such an approach in different urban and suburban neighborhoods across the densely populated Island of Montreal, Canada, focusing on food waste sources that are presently unrecovered or overlooked in Montreal's municipal waste collection (i.e., industrial-commercial-institutional, ICI, and large residential buildings). First, I estimate the potential magnitude and spatial distribution of unrecovered food waste across the Island of Montreal by spatially disaggregating existing city-wide food waste values by source type and their discrete locations using a geographic information system (GIS). The identified 10,882 source locations generate ~141,351 tonnes of potentially recoverable food waste annually, or about 120% of the total amount of organic waste recovered by the City of Montreal in the circa 2020-2021 period. Key 'hot spots' of recoverable food waste are mainly in high-population density central neighborhoods with clusters of residential buildings and restaurants, as well also throughout the Island in areas with single concentrated sources (e.g., a supermarket or hospital). Second, I create a systems model of a hypothetical vermicomposting operation to examine the economic feasibility and carbon offset potential depending on locating that facility in different representative types of neighborhoods (by gradients of population density and land value). I then discuss tradeoffs between food waste availability and rental rates when

determining which areas would be best suited for local food waste management with vermicomposting. Based on my systems modelling of facilities located in different neighborhood types, I conclude that decentralized vermicomposting for urban food waste management can be both profitable and reduce carbon emissions compared to landfilling. My study is therefore a proof-of-concept test of the potential of decentralized vermicomposting to divert urban organic waste streams, serving as the basis for the implementation of novel paradigms in urban organic waste management. Such an alternative, decentralized approach to organic waste treatment could complement existing waste management infrastructure, with co-benefits of reducing transport distances, added flexibility, potentially reduced operational costs, and allowing for nutrient recycling within urban neighborhoods. However, achieving this would require collaboration among various stakeholders, including careful consideration of potential end-users of worm castings, such as urban and peri-urban agricultural producers.

Résumé

La gestion des déchets organiques dans les villes devient de plus en plus difficile avec la croissance de la population urbaine. Une grande partie des déchets alimentaires est actuellement mise en décharge, où sa décomposition entraîne des émissions de gaz à effet de serre. Bien que le compostage soit de plus en plus courant au Canada, l'approche conventionnelle de collecte et de gestion des déchets organiques au niveau municipale a généralement consisté à construire de grandes installations de traitement centralisées, ce qui peut être coûteux, chronophage et avoir des impacts environnementaux et sociaux négatifs pour les communautés environnantes. De plus, en raison de contraintes logistiques, certains bâtiments industriels, commerciaux et institutionnels ne séparent pas la fraction organique de leurs déchets ou constituent des lacunes dans la collecte des déchets organiques municipaux existants. J'étudie le potentiel d'une collecte et d'un traitement décentralisés (au niveau des blocs de quartier) des déchets organiques urbains dans des installations de vermicompostage à petite et moyenne échelle. Le lombricompostage est le processus de décomposition des déchets organiques à l'aide de vers de terre, cette approche est plus rapide que le compostage conventionnel et donne un produit final plus qui a plus de valeur. En utilisant la modélisation spatiale et systémique, j'examine l'efficacité d'une telle approche dans différents quartiers urbains et périphériques densément peuplés de l'île de Montréal, dans la province du Québec au Canada, en me concentrant sur les sources de déchets alimentaires qui ne sont actuellement pas récupérées ou négligées dans la collecte des déchets municipaux (c'est-à-dire, industriel commercial institutionnel, ICI et grands immeubles résidentiels). En premier lieu, j'estime l'ampleur potentielle et la distribution spatiale des déchets alimentaires non récupérés sur l'île de Montréal en désagrégeant spatialement les valeurs existantes de déchets alimentaires à l'échelle de la ville par les types de sources et leurs emplacements discrets à l'aide d'un système d'information géographique (SIG). Les 10 882 emplacements sources identifiés génèrent annuellement environ 141 351 tonnes de déchets alimentaires potentiellement valorisables, soit approximativement 120 % de la quantité totale de déchets organiques récupérés par la Ville de Montréal au cours de la période 2020-2021. Les principaux « points chauds » de déchets alimentaires récupérables se trouvent principalement dans les quartiers centraux à forte densité de

population qui ont des regroupements de bâtiments résidentiels et de restaurants, ainsi que dans des zones de l'île avec des sources uniques et concentrées de déchets (par exemple, un supermarché ou un hôpital). En deuxième lieu, je crée un modèle de systèmes d'une opération hypothétique de lombricompostage pour examiner la faisabilité économique et le potentiel de compensation en carbone en fonction de la localisation de cette installation dans différents types de quartiers représentatifs (par gradients de densité de population et de valeur foncière). Je discute ensuite des compromis entre la disponibilité des déchets alimentaires et les coûts de location pour déterminer les zones les mieux adaptées à la gestion locale des déchets alimentaires en utilisant le vermicompostage. En me basant sur ma modélisation de systèmes d'installations situées dans différents types de quartiers, je conclus que le lombricompostage décentralisé pour la gestion des déchets alimentaires urbains peut être à la fois rentable et réduire les émissions de carbone par rapport à l'enfouissement. Mon étude est donc un test de preuve de concept du potentiel du lombricompostage décentralisé afin de détourner les flux de déchets organiques urbains, ceci servira de base à la mise en œuvre de nouveaux paradigmes dans la gestion des déchets organiques urbains. Une telle approche alternative et décentralisée du traitement des déchets organiques pourrait compléter l'infrastructure existante de gestion des déchets, avec des avantages connexes tels que la réduction des distances de transport, une flexibilité accrue, des coûts d'exploitation potentiellement réduits et la possibilité de recycler les nutriments dans les quartiers urbains. Cependant, y parvenir nécessiterait une collaboration entre les différentes parties prenantes et une attention particulière aux utilisateurs finaux potentiels des déjections de vers, tels que les producteurs agricoles urbains et ceux situés en périphérie.

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Preface

When I began this research, my plan was to conduct physical experiments with prototype vermicomposting systems that were paired with hydroponic agriculture. This builds out of preliminary experiments which I have conducted over several years in the context of a personal business venture. However, as a result of remote work during the Covid-19 pandemic, I had to pivot to a new project involving spatial analysis and modelling (despite never having worked with geographic information systems, GIS, nor having taken a course on that topic). Although challenging, the adaptation to a completely new research approach was a unique opportunity to learn many valuable skills and made me appreciate the endless possibilities of theoretical modelling.

This thesis is original, unpublished, independent work of the author, M. T. Schmid. It is presented in a traditional monograph format with six chapters, which are being reworked to a single journal manuscript at the time of submission. Graham MacDonald provided expert advice throughout my work, particularly on my spatial analysis, mentored me on geographic information systems and contributed to the editing process of the thesis. Grant Clark provided input on the overall structure and scope of my research and gave advice on the underlying technical aspects of my work. Graham MacDonald and Grant Clark will be co-authors on any subsequent manuscript. Michael Boh provided informal advice on the structure of my systems model in Chapter 4 and Christopher Leuderitz advised on the hypothetical market analysis in Chapter 5.

Chapter 1: Thesis Introduction

Efficiency is the absence of waste has long been an economic tenet. There is growing awareness across government, industry, and civil society about the need to rethink waste streams—particularly food waste—by shifting towards a more ecological model of waste management as part of a sustainable economy (e.g., EC, 2015; UN, 2015). Ecological systems are circular by nature and thus offer some insights on this. Within ecosystems, resources are continuously cycling through populations as the wastes of one are nourishment for the other. Through this process, a stable equilibrium can be reached and, unless destabilized by external factors, will be maintained through feedback loops (Masullo, 2017). Most economic systems on the other hand are linear. Industry extracts non-renewable resources and turns them into goods, which today predominantly end up in ever growing landfills once they have reached the end of their lifespan. This linear organization ultimately leads to scarcity of resources on the one hand and pollution by waste materials on the other (Andrews, 2015). To achieve economic sustainability and a higher degree of resource use efficiency, our economic systems will have to reflect natural ecosystems regarding their ability to reintroduce waste materials back into circulation.

To address opportunities for such sustainability transitions, there have been specific calls from researchers and advocates around the need for a shift towards a 'circular economy' (Prieto-Sandoval et al., 2018; Morseletto, 2020). As sectors of concentrated waste generation, urban areas can play a key role in the creation of a circular economy (Mohareb et al., 2017; Zeller et al., 2019). Urban centers also account for the bulk of population growth today, with 55% of humanity already living in cities and an expected rise to 68% by the year 2050 (United Nations, 2018). Canada is a highly urbanized country, with about 82% of the population residing in urban areas (World Bank, 2021). Growing output of municipal solid waste (MSW) is therefore a challenge for many cities around the world (e.g., Wilson et al., 2020). While urbanization is not directly linked to solid waste, it means that urban neighborhoods and city governments are increasingly important scales to focus on more sustainable waste management solutions.

Through circular economy principles, waste of resources and negative environmental impacts of MSW can be reduced, for instance by lowering the organic fraction of MSW through more efficient food supply chains and organic waste valorization (Kummu et al., 2012; Mohareb et al., 2017). End-of-pipe solutions, such as the composting of food waste, may be less desirable than reducing the amount of waste generated. For example, the ‘food recovery hierarchy’ identifies source reduction, food donations, use of food waste as animal feed and energy recovery as approaches to minimizing food waste, which can be employed prior to waste recycling whenever possible (U.S. Environmental Protection Agency OLEM, 2017). However, either due to the lack of the required policies and infrastructure that leads to waste being unrecovered (or certain waste being unsuitable) for these more beneficial uses, some fraction of food waste is often incinerated or discarded in landfills in North American cities. This portion of food waste can be valorized through composting (Papargyropoulou et al., 2014).

1.1. Investigating the feasibility of decentralized urban vermicomposting

In the face of growing waste generation and associated methane emissions from landfilling, urban organic waste management is a major sustainability challenge that requires innovative solutions. Conventional approaches to urban organic waste treatment in high-income cities has typically involved building large-scale and centralized facilities. While this may be an effective option, it comes with potential tradeoffs, such as high construction costs, considerable transportation distances and collection distances. Relatively little research has been done on the potential of mitigating these impacts by complementing large-scale facilities with decentralized, low-tech organic waste management (but see, e.g., Righi et al., 2013 and Pai et al., 2019). Due to its efficiency and capacity for waste valorization, vermicomposting could be a well-suited method of decentralized organic waste management. In vermicomposting, organic waste is broken down and digested by earthworm and microorganisms to yield vermicastings, which are high in nutrients and other substances beneficial for plants (Edwards et al., 2011).

In this thesis, I explore the feasibility and potential of urban food waste management employing decentralized vermicomposting with a case study of Montreal, Quebec, Canada. Whereas the main contribution of my study is around understanding the efficacy of this approach through spatial analysis and systems modelling, my work more broadly contributes to research on understanding the geography of urban food waste and the path towards a circular economy with alternative approaches to waste management.

1.2. Thesis structure

This thesis is comprised of six chapters. In Chapter 2, I provide a concise literature review of organic waste management globally, in Canada, and specifically in the context of Montreal. Here, I discuss the scope of the issue and present various conventional approaches to organic waste management. I also introduce the general practice of vermicomposting and the concept of a decentralized approach to managing urban food waste streams. The chapter concludes with an outline of my objectives, research questions and hypotheses. In Chapter 3, I present the geographical and temporal context of my study and outline the series of methodological steps I took in my research. I then provide a detailed description of the methods employed for the spatial analysis and systems modelling in two consecutive sections. My results are presented in Chapter 4. First, I depict the estimated amounts of currently ‘unrecovered’ food waste across Montreal (as defined in Chapter 2) by source type and their spatial distribution across the Island of Montreal. Next, I show how the spatial patterns and magnitude of unrecovered food waste compares with urban land values, which I used to strategically select the facility sites for my systems model and determined the amount of feedstock available for modelled vermicomposting sites. Finally, I provide the structure of my systems model and present a breakdown of expenses, the profits generated over time, and the relative GHG emissions of simulated vermicomposting operations in these different locations. Chapter 5 presents a discussion, where I contextualize my findings within the existing literature. First, I reflect on the efficacy of decentralized vermicomposting for urban food waste management and discuss the utility of the methods I employed to identify the spatial distribution of food waste. I then review how the location of a facility as well as the specific markets that are targeted could affect its profitability, as well as its effectiveness for realizing a circular economy. Finally, I conclude the chapter by discussing key limitations and uncertainties of my study. My thesis concludes in Chapter 6 in which I summarize my findings in the context of my original research questions and give recommendations for further work in the field.

Chapter 2: Literature review

In its most recent report, the UN estimated that 931 million tons of food waste were generated in 2019, suggesting that 17% of the total global food production may be wasted each year (UNEP, 2021). Further estimates report that waste comprises 9% of greenhouse gas emissions from the global food system, of which one-third of that originates from the decomposition of solid food waste in landfills, mostly as methane (Crippa et al., 2021; Tubiello et al. 2021). In the face of this issue, the United Nations has set a goal in 2015 to halve global food waste at the retail and consumer level by 2030 (UN, 2015). While reducing food waste at the source is preferable, once waste is created, composting and other approaches to recover valuable nutrients and energy resources can help divert food waste from landfills and generate beneficial re-use of these resources in society (Papargyropoulou et al., 2014). Despite a growing body of literature dedicated to the quantification of food waste in recent years, large uncertainties also remain in terms of the amount of food waste being generated globally, which have been attributed to inconsistent data, temporal and geographical blind spots, and a lack of comprehensive supply chain coverage (Xue et al., 2017).

2.1. Organic waste generation in Canada

When considering all waste generated across the total economy, Canada currently has the highest total per capita annual waste generation in the world (Kaza et al., 2018). The Commission for Environmental Cooperation (CEC) estimated that, in 2012, a total of 18.4 million tonnes of organic waste was generated in Canada, only about 30% of which is being diverted, meaning that the remaining 12.6 million tonnes is currently sent to landfills (CEC, 2017). They roughly categorized organic waste into food waste, yard waste, and paper; organic waste from the Canadian residential sector was estimated as 28% food waste, 38% yard waste and 34% paper, whereas the industrial, commercial, and institutional (ICI) sector had a distribution of 34%, 7% and 59% of the respective categories. In total, the residential and ICI sectors generated about 10.18 and 8.26 million tonnes of organic waste in 2012, respectively (CEC, 2017). Focusing just on the food fraction of OW, Gooch et al. (2019) estimated that as much as 35.5 million tonnes of food is being lost or wasted annually at different points in the Canadian food value chain by using surveys, interviews, and secondary data to inform their estimates. Focusing just on the food waste component, Von Massow and colleagues (2019) estimated that the average Canadian household generates about 229 kg of total food waste annually (including both available and unavoidable forms).

With about 70% of organic waste being sent to landfills in recent years (CEC, 2017), a large fraction of waste that is currently landfilled consists of material that could easily be diverted or recovered and valorized instead. The recovery of organic waste reintroduces valuable nutrient resources locked in biodegradable materials back into the economy (Roy, 2017). Numerous practices, such as composting or anaerobic digestion, can be implemented to recycle resources from organic waste directly back into urban and peri-urban food systems (Mohareb et al., 2017; Metson et al., 2018). However, despite such potentially cost-efficient methods to recycle urban food waste into organic fertilizer, landfills still receive a considerable share of food waste collected with municipal solid waste from large Canadian cities, such as Montreal (Treadwell et al., 2018) and Toronto (van der Werf et al., 2020). Dumping organic waste also reduces the potential lifespan of landfills, forcing municipalities to find new sites, which is becoming increasingly difficult (Leão et al., 2004; Tominac et al., 2020). Furthermore, as mentioned previously, the decomposition of organic waste has a negative environmental impact through the emission of methane (Adhikari et al., 2006). Methane has a global warming potential 25 times that of carbon dioxide (CO_2) (IPCC, 2007) and typically makes up 40-60% of landfill emissions (Yilmaz et al., 2021). Even in landfills that capture methane, as much as 25% of it still leaks into the atmosphere (Parsaeifard et al., 2020). Emissions from landfills currently account for 20% of methane emissions in Canada, or roughly 23 Mt CO_2-eq emitted from Canadian landfills annually (Environment Canada, 2019).

2.2. Municipal organic waste management strategies

Besides landfilling, the three most common methods used to deal with organic waste are incineration, composting, and anaerobic digestion (Slorach et al., 2020). In Canada, this usually occurs in large-scale centralized facilities, such as Calgary's organics in-vessel composting facility, which has a processing capacity of 145,500 tonnes per year (AIM Environmental Group, 2020). The treatment of organic waste in such composting facilities has potential environmental benefits, as it reduces methane emissions and allows for the beneficial reuse of processed waste. With 145 g of CO_2-eq per kg of waste, food waste treated by in-vessel composting facilities generates only around 16% of the emissions released from food waste decomposing in landfills (about 922 g of CO_2-eq per kg of waste from landfilling) (Lou and Nair, 2009; Colón et al., 2011; Dorward, 2012; Bernstad Saraiva Schott et al., 2016; Thomas et al., 2020).

Composting facilities treat organic waste through aerobic decomposition, which yields nutrient-rich, organic fertilizer, commonly applied in agricultural operations (e.g., as reviewed by Roy 2017 in the case of phosphorus). On the other hand, biomethanisation plants process organic waste through anaerobic digestion, during which methane is captured and later burned to produce electricity (Ward et al., 2008). The digestate can then either be directly applied in agriculture or further composted. After these treatments, use of organic fertilizer both lowers the need for synthetic fertilizers and reduces the risk of degrading environmental quality (Favoino and Hogg, 2008; Fernandez-Mena et al., 2016). Organic waste decomposing in landfills can also leach nutrients into the environment, resulting in eutrophication of aquatic ecosystems and other negative impacts on environmental quality (Kjeldsen et al. 2002).

Whereas the treatment of organic waste in large, centralized operations is preferable to landfilling from a sustainability perspective, this method comes with its own set potential of new problems or tradeoffs. For example, due to the large cumulative transporting distances necessary for waste collection in some urban areas, it has been suggested that organic waste treatment in large-centralized facilities can have a relatively poor environmental performance compared to household-level treatment (Bjorklund et al., 1999; Lundie and Peters 2005). Furthermore, large-scale facilities require heavy machinery, necessary for waste preparation and aeration during composting, which consumes energy and leads to greenhouse gas emissions (Lundie and Peters 2005; Lou and Nair, 2009). Managing organic waste through large-scale, centralized facilities also incorporates environmental impacts associated with plant construction and maintenance, as revealed with life cycle assessment (Di Maria and Micale, 2015). Furthermore, locations for such facilities must be chosen carefully to balance the trade-off between long transport distances and their negative externalities for land-value and human health in urban areas, due to their output of odours, bio-aerosols, and heavy vehicle traffic (Smet et al., 1999; Sironi et al., 2007; Domingo and Nadal, 2009; Giusti, 2009).

In response to such potential tradeoffs, decentralized organic waste valorization has been proposed as a complementary strategy for conventional centralized practices in urban centers. As an alternative to reliance only on large, centralized organic waste treatment facilities, a localized network of small to medium scale, decentralized facilities can provide additional co-benefits (Pai et al. 2019). For example, in their case study of Chicago, Pai and colleagues (2019) demonstrated the viability of complementary, decentralized composting through its benefits for community outreach, landfill diversion, and cost savings. As an alternative to reliance only on large, centralized organic waste treatment facilities, a localized network of small to medium scale, decentralized facilities can provide additional co-benefits (Pai et al. 2019). Locating the recovery and valorization of organic waste close to its origin can help to lower the greenhouse gas emissions associated with organic waste treatment due to short transport distances (De Feo et al., 2016). Furthermore, decentralizing waste treatment also allows for reduced transportation distances from source to treatment, since it cuts the need for waste to be stored in a temporary deposit, which is often the case in centralized practices and leads to higher emissions of methane and odours (Righi et al., 2013). After the waste has been valorized, the end-product still needs to reach the consumer. A decentralized composting facility targeting local markets could cut down substantially on the emissions that would result from transporting the compost to its final destination. Although I was unable to easily find estimates of this in the literature, my initial hypothesis in this research is that the impact of transportation on overall greenhouse gas emissions from a decentralized operation will likely be negligible compared to emissions related to waste processing and its lifecycle.

Smaller facilities involved in decentralized treatment may have additional co-benefits. For example, they can be set up faster and at lower overall expense, as they tend to be less capital-intensive and can be integrated in already existing infrastructure—potentially offering greater flexibility and adaptive capacity to municipalities in their waste management strategies. Since smaller facilities may be associated with less odour generation and vehicle traffic, they may help to increase public acceptability (Righi et al., 2013). Such comparatively ‘low-tech’ operations for waste treatment also provide employment opportunities for lower-skilled workers in cities that may be more vulnerable to unemployment (Pai et al., 2019). As such, rather than replacing conventional practices on a city-wide scale, decentralized facilities could be focused on areas of high output of organic waste not being targeted by existing municipal organic waste separation (in high-income cities[1]). If such facilities can be co-located with consumers of organic fertilizers, such as urban agriculture operations or plant nurseries, the recovered nutrients could be both valorized and recycled locally while also minimizing transportation distances and helping to offset life cycle energy demands (Mohareb et al., 2017; Grard et al., 2018).

2.2.1. Vermicomposting

Vermicomposting may be particularly well suited for decentralized organic waste valorization, due to its compact size, high volume reduction potential, and high value of its end-product. Vermicomposting employs earthworms, such as the intensively feeding and fast reproducing *Eisenia fetida* (Rosik-Dulewska et al., 2014), alongside mesophilic microorganisms to break down and stabilize organic waste (Adi and Noor, 2009). Over the last decade there has been growing interest in vermicomposting amongst homesteaders and scientists alike. A search of the term “vermicompost*” on the scholarly database, Scopus, yields 4,889 results, over 70% of which have been published in the last 10 years (search conducted on January 20, 2022). Vermicomposting employs earthworms, such as the intensively feeding and fast reproducing *Eisenia fetida* (Rosik-Dulewska et al., 2014), alongside mesophilic microorganisms to break down and stabilize organic waste (Adi and Noor, 2009). Vermicomposting has been studied from several perspectives,

[1] I do not discuss the case of cities in the Global South here, given my focus on a case study of Montreal, but decentralized waste management could be a promising solution in low-income cities with limited existing waste management infrastructure (e.g., Singh, 2020).

including its potential for treating sewage sludge (Boruszko, 2016; Roy, 2017; Świątek et al., 2019) and fertilizing crops with nutrient-rich worm castings (Hernandez et al., 2015; Kostecka et al., 2018). Worm castings, the end-product of vermicomposting, are more compact and of better quality than regular compost due to a higher nutrient availability for plants, owing to the effects of enzymes and humic substances in the digestive organs of the worms (Suthar, 2009; Hernandez et al., 2015; Vodounnou et al., 2016). Worm castings also contain diverse communities of beneficial microbes that increase nutrient processing, stimulate root growth (Pii et al., 2015) and can help prevent the spread of pathogens (Scheuerell & Mahaffee, 2002).

There are a variety of different vermicomposting systems, ranging from simple windrow or wedge beds to more technical systems, such as the continuous flow-through (CFT) reactor (Edwards et al., 2011). CFT reactors require no turning or additional aeration of the compost and are fully automated, minimizing the amount of labour necessary for operation. Furthermore, these systems are amongst the most efficient vermicomposters in terms of processing rate (Edwards et al., 2011). Due to these benefits, I decided to implement this practice as the focus of my study. A CFT system consists of a 4 ft wide (1.2 m) and 3 ft deep (0.9 m), raised, rectangular bin with a metal frame and plastic walls, which serves as the composting bed. At the bottom of the bed is a metal grid on which a motorized breaker bar periodically runs along the length of the bin, loosening up cured worm castings, which drop below the bed and are then ready to be collected (Edwards et al., 2011). Figure 2.1 depicts a diagram of the basic components of a CFT reactor system by Edwards (2011). The benefit of such a system is that it is largely automated and hence requires only minimal labour to be operated, while at the same time being relatively easy to assemble and maintain. With an estimated average output of about 0.75 lb/sq ft (3.66 kg/m^2) per day (personal communication, Dan Lonowski, Michigan Soilworks), CFT systems are much more efficient than conventional windrow vermicompost systems and use less space (allowing them to be operated indoors) and prevent leaching of nutrients and other contaminants into groundwater. While it is possible to directly add unprocessed organic waste to a CFT system, this may cause the temperature in the compost to rise too high, which can be lethal for the worm population. Hence it is recommended to first pre-treat the feedstock in a separate thermophilic composting system before adding it to the

CFT system (personal communication, Dan Lonowski, Michigan Soilworks). This also ensures that seeds and pathogens are sterilized and won't contaminate the end-product.

A 2011 book, *Vermiculture Technology: Earthworms, Organic Wastes, and Environmental Management*, edited by Clive Edwards and colleagues, offers an in-depth overview of vermicomposting and potential applications across a range of contexts. One chapter in that book by Jensen et al. (2011) examines the commercial potential of vermicomposting in the United States, serving as an inspiration for my systems modelling analysis in this thesis.

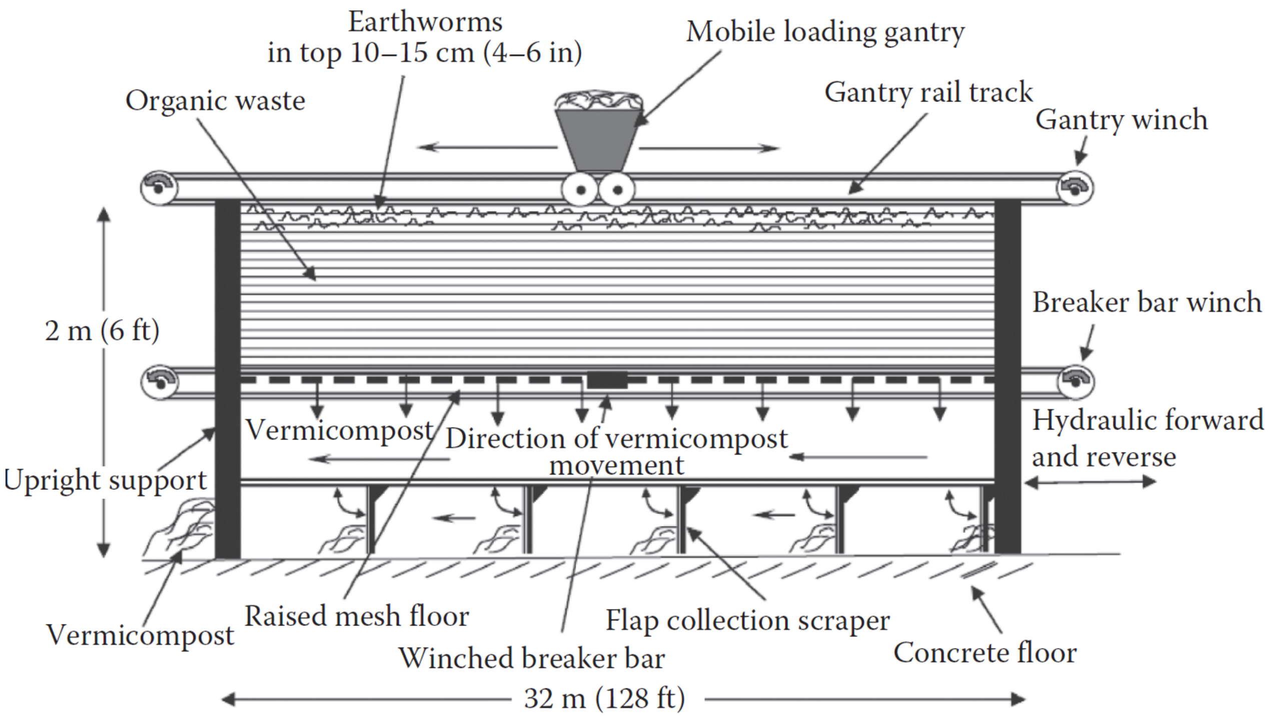

Figure 2.1: Schematic of a CFT vermicomposting reactor (Source: Edwards, 2011, chapter 8, pg. 95, in Edwards, C. A., Arancon, N. Q., & Sherman, R. L. (Eds.). 2011. Vermiculture Technology: Earthworms, Organic Wastes, and Environmental Management. *CRC Press*, Boca Raton, FL.).

2.3. Organic waste management in Montreal

Since my research uses Montreal as a case study, I briefly review the city's organic waste management situation in this section. Montreal is the largest city in the Canadian province of Quebec (with 24% of the province's population) and the second largest city in Canada. As of 2020 when I began this study, the City of Montreal reported that it recycled about 30% of the 390,876 tonnes of organic waste produced on the Island, with the rest being landfilled as part of the MSW (City of Montreal, 2020). Currently, organic waste in Montreal is mostly collected from residential buildings with eight or fewer dwellings. Larger residential buildings, businesses and institutions predominantly do not separate their OW, meaning that organic waste from these sources is ultimately being landfilled (Malmir et al., 2020). In 2012, the consulting firm Solinov conducted a study for the City of Montreal focused mainly on quantifying city-wide ICI food waste based on literature values and surveys of various companies and organizations. They estimated that food waste (and a small amount of green waste) generated by Montreal's ICI sectors amounted to a total of 228,000 tonnes (Solinov, 2012).

As part of its sustainability commitments, the City of Montreal municipality plans to divert 60% of its organic waste from landfills by 2025 (City of Montreal, 2020). To this end, several large treatment plants are being constructed across the Island of Montreal. A composting centre and a biomethanation plant are expected to become operational later in 2022 (Henriques, 2019). Additionally, the city plans to construct another biomethanation plant in the LaSalle borough by 2026 and a pre-treatment centre in Montreal East by the end of 2027. Another composting plant was originally planned as a fifth management centre, but due to construction delays and surging costs, the city has postponed the construction of this facility indefinitely (Gyulai, 2020).

Such large, centralized facilities clearly come at high financial costs. The first composting plant is projected to cost the city $175 million dollars, or triple its initial estimate (CBC News, 2021a). The construction of the plant has also sparked protests among residents worried about potential odours, increased traffic and the environmental impact of the plant (CBC News, 2018). As part of these plans, the City of Montreal also announced in early 2021 a goal to collect organic waste from dwellings in buildings of nine or more units as well as from the ICI sectors, both of which were previously overlooked in the organic waste collection. The City of Montreal is therefore aiming to collect organic waste from 350,000 additional dwellings alongside 30,000 businesses and institutions by 2025 (CBC News, 2021b).

2.4. Research Questions and Hypotheses

In the face of growing waste generation and associated methane emissions from landfilling, urban organic waste management is a major sustainability challenge that requires innovative solutions. Conventional approaches to urban organic waste treatment that involves building large-scale facilities may be an effective option in high-income cities, but comes with potential tradeoffs, such as high construction expenses, considerable transportation distances and collection distances. Relatively little research has been done on the potential of mitigating these impacts by complementing large-scale facilities with decentralized, relatively low-tech organic waste management (but see, e.g., Righi et al., 2013 and Pai et al., 2019). Due to its efficiency and capacity for waste valorization, vermicomposting could be a well-suited method of decentralized organic waste management.

With the City of Montreal scaling back the number of new organic waste treatment facilities to be constructed in coming years while simultaneously planning to dramatically increase the serviced sectors and populations for organic waste collection, consideration of alternative, lower cost and more flexible organic waste treatment systems may be particularly insightful in this context. In this thesis, I therefore focus on a decentralized approach to food waste valorization by using smaller-scale and strategically located treatment facilities, such as in locations with high food waste generation and in areas far away from existing large facilities. I aim to examine how such an alternative approach with vermicomposting could complement and reinforce the centralized facilities that are planned to become operational in 2022. Collectively, this contributes insight to the broader understanding of creating a circular economy in urban areas. Vermicomposting is well-suited waste valorization practice, as it is relatively low-tech, fast to construct, odorless, and has a high potential for reduction of feedstock volume.

To investigate the feasibility of such an approach to organic waste management in urban neighborhoods, using Montreal as a model city, my research addresses the following questions:

> What is the magnitude and spatial distribution of presently unrecovered (landfilled) food waste from key sources (i.e., large residential buildings, food businesses, and institutions) across the Island of Montreal?
>
> What is the relationship between the available feedstock and urban land value/rental rates, and how might this affect the profitability of decentralized organic waste management in cities?
>
> Given potential feedstock availability, the estimated revenues/costs of decentralized urban vermicomposting, and the potential greenhouse gas emissions, what is the efficacy of this approach to organic waste management relative to reliance on centralized facilities only?

Through these questions, I therefore examine the relationship between key parameters involved in organic waste management, such as the potential magnitude of recyclable waste feedstock (and thus end-product available for valorization), fixed costs, capital investments, revenues, and emission rates of decentralized vermicomposting facilities.

My hypothesis at the onset of this research was that setting up a few small- to medium-scale vermicomposting operations in strategic locations on the Island of Montreal could allow for the diversion of a sizeable portion of currently unrecovered food waste (i.e., large residential and ICI sources likely to have been landfilled as of 2020-2021) and that such facilities can be both profitable and have a relatively positive environmental impact by reducing the output of greenhouse gases from food waste that would otherwise be landfilled. To test this hypothesis, my study has two distinct components: (1) mapping the currently unrecovered food waste to identify potential strategic locations for vermicomposting; and (2) systems modelling of a hypothetical facility to assess economic feasibility. Specifically, I use a unique approach to estimate the distribution of food waste generation from discrete sources across the Island of Montreal that don't presently receive organic waste pickup services by the city (i.e., institutions, businesses, and large residential buildings) by 'spatially disaggregating' existing city-wide scale food waste estimates.

I then apply these results to identify potential candidate sites for decentralized treatment facilities across the Island. Next, my systems model uses the locally available feedstock to assess the economic feasibility as well as relative greenhouse gas emissions impact of food waste recovery and treatment by decentralized vermicomposting in comparison to landfilling. This model includes the valorized end-product, revenues, fixed costs, capital investments and CO_2-equivalent emissions. Finally, I investigate how the profitability of hypothetical facilities in areas representative of different land value are affected by varying rental rates.

The findings of my research suggest that food waste generation from selected sources is heavily concentrated in 'hot spots' around the city centre as well as around large supermarkets on the Island of Montreal. My systems model suggests that decentralized vermicomposting facilities can be profitable and reduce carbon emissions but that site location is crucial and should be chosen within hot spots of high-density organic waste generation. Furthermore, given the moderate correlation between land value and food waste generation, there may be trade-offs between availability of organic waste feedstock and rental rates; therefore, sites with relatively low rental rates but high food waste availability should be considered when choosing a facility location as they may represent 'sweet spots'.

Chapter 3: Methods

3.1. Study area and context

The study area for my research is the Island of Montreal, located on the St. Lawrence River in southwestern Quebec, Canada. The Island contains the City of Montreal with its 19 boroughs as well as 14 smaller independent municipalities that include both suburban and denser urban neighborhoods (Figure 3.1). As a single municipality, the City of Montreal had a population of 1.7 million in 2016 (land area of 366 km^2), while all the municipalities on the Island of Montreal totaled to just over 2 million (Statistics Canada, 2016). The Greater Montreal Census metropolitan region comprises 4,604 km^2 to the north, south, and east of the Island of Montreal and includes a population of about 4 million (Statistics Canada, 2016). Montreal is the second most densely populated city in Canada, with population densities in different boroughs ranging from nearly 13,000 people per square kilometer in Le Plateau Mont Royal to just 2,000 people per square kilometer in Saint-Laurent (Statistics Canada, 2016). To substantially decrease the amount of organic waste that is currently being landfilled on the Island, the City of Montreal is planning to construct several waste management facilities, the locations of three of these are shown in Figure 3.1, alongside the Lachenaie landfill, which is the closest to the Island.

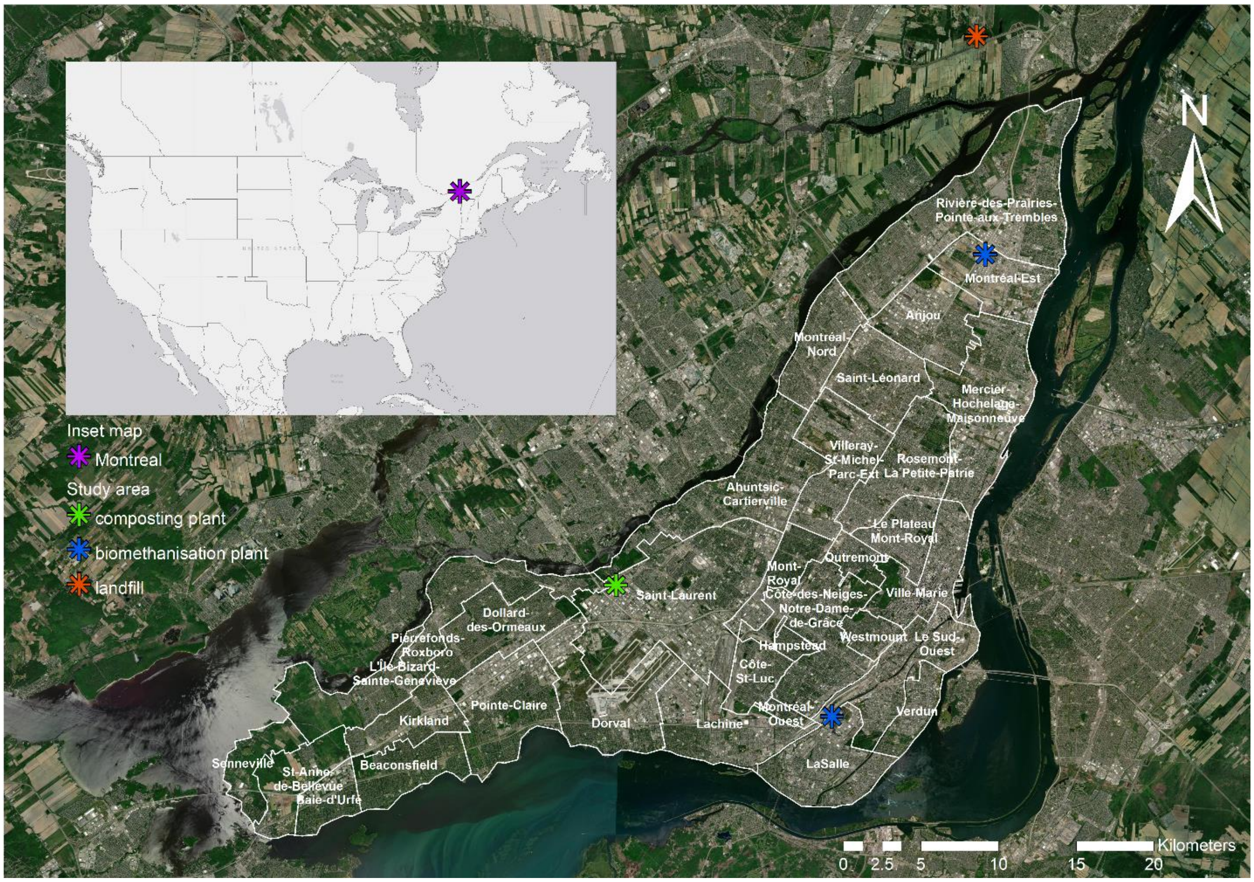

Figure 3.1: Map of my study area, the Island of Montreal. The purple marker on the inset map of North America marks the location of Montreal. Marked locations on the Island of Montreal represent the locations of 3 (out of the 5 originally planned) organic waste treatment centres (blue and green markers; the composting plant is shown in green, the two biomethanation plants are shown in blue), as well as and the Lachenaie landfill located off the Island in the northeast corner of the map (red marker). Note that the downtown/city centre is located in the 'Ville-Marie' borough. At the time of finalizing this thesis, no definitive sites could be confirmed for the remaining two planned treatment centres. Satellite image source: ESRI, DigitalGlobe.

My study consists of two main components (visualized in the flowchart in Figure 3.2): (1) an analysis of the spatial distribution and magnitude of food waste generation conducted with a geographic information system (GIS) and (2) a systems model of a hypothetical small- to medium-scale vermicomposting facility to examine operational costs, revenues, and direct greenhouse gas emissions. Given that my study was conducted in 2020-2021, before the planned opening of Montreal's first two large-scale organic waste management facilities, it focuses on the food waste collection and treatment context of that period. As the aim of my research is to understand vermicomposting as a complementary alternative treatment option for cities, I deliberately exclude sources and locations that are already well serviced by the organic waste collection that began in 2015 (personal communication, Martin Héroux, City of Montreal). My analysis of unrecovered food waste is therefore focused on six main source categories that were underrepresented or ‘gaps’ in organic waste collection, including larger residential buildings and industrial, commercial and institutional (ICI) locations (personal communication, Martin Héroux, City of Montreal). Organic waste from all other sources is therefore excluded, including those from the industrial sector, as I assumed that the generation of organic waste varies substantially depending on the type and size of industrial operation and little data were available to quantify this. The timeframe of my study ranges over the period from 2012 to 2021 and thus represents a general overview of the longer-term food waste situation rather than a precise snapshot for a specific point in time. Total city-wide waste data has mostly been sourced from a 2012 study (Solinov, 2012) with key sources from between 2006 and 2012, population estimates are from 2016 (Statistics Canada, 2016), and geographic points of interest are from 2021 data (Open Street Maps, 2021; City of Montreal, 2021).

In the following sections, I first outline the steps I took in my spatial analysis of food waste distribution (section 2.1). After I estimate the total unrecovered food waste by discrete source locations and types, I then summarize these into a single gridded raster of food waste generation. I use this unrecovered food waste raster with data on land value to identify ideal candidate sites for vermicomposting facilities and determine the overall amount of food waste within the collection areas around each facility. In section 2.2, I then break down the structure and parameters of my systems model which simulates the operation of a vermicomposting facility. Spatial analysis was conducted in ArcGIS v10.7.1 (ESRI, Redlands) and QGIS v3.4.1 (QGIS Association); systems modelling was conducted in STELLA Architect v1.9.5 (isee Systems).

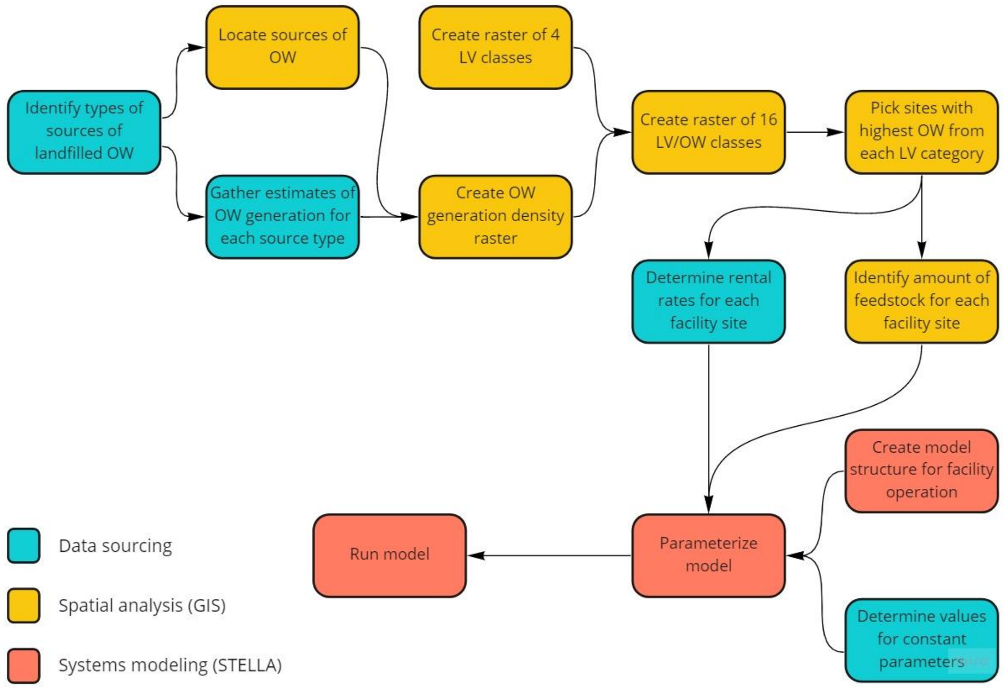

Figure 3.2: Flowchart illustrating the methods and links between the spatial analysis and systems model analysis. The boxes represent key steps in my study, colour-coded into stages of data sourcing (blue), spatial analysis (yellow) and systems modelling (red). 'OW' refers to organic waste, which in my study, is almost exclusively food waste.

3.2. Spatial analysis of 'unrecovered' food waste generation

3.2.1. Estimates of total food waste by source type

To identify high density areas of currently landfilled food waste on the Island of Montreal, I first estimated the annually generated food waste from the following six source categories: (1) residential buildings with nine or more dwellings, (2) primary and secondary schools, (3) universities, (4) hotels, (4) restaurants, (5) grocery stores and (6) hospitals. The selection of these specific food waste source categories was based on three criteria: First, that the source did not receive pickup services of separated organic waste from their municipality; second, that the source's operation was expected to result in a continuous output of food waste; and third, that the amount of generated food waste could be reliably estimated at a discrete geographic location (e.g., building) based on publicly available data. Buildings from the industrial sector were not included in this study, as the generation of food waste varies substantially depending on the type and size of industrial building and little data being openly available, making reliable estimation difficult. Table 3.1 outlines the general approach used to estimate the food waste amounts and spatial distribution for each source category.

Table 3.1: Breakdown of the methods and data sources for my spatial analysis of food waste generation by category.

Source type	**Spatial standardization method**	**Spatial data source**	**Food waste data source**
Residential buildings (≥9 dwellings)	Average household value allocated by number of households per building and location	Property assessment units from City of Montreal (2021)	Average household data from von Massow et al. (2019)
Universities	Discrete data from each institution allocated by location	Points of interest / building footprints from Open Street Maps (2021)	Institution-specific data
Hotels	Average food waste per establishment allocated by location		Aggregate ICI sector estimates from Solinov (2012)
Restaurants			
Schools and colleges*	Spatial disaggregation of category-specific total food waste by building footprint areas and locations		
Grocery stores			
Hospitals			

*Surveys for schools include 4% green waste (Solinov, 2012), which I retained given my focus on vermicomposting (see section 5.2 for discussion).

For residential buildings, I estimated food waste generation by multiplying the number of households in each building with the amount of food waste produced by the average Canadian household (von Massow et al., 2019). To determine the number and spatial distribution of residential buildings on the Island of Montreal, I used the geographical extract of property assessment units (City of Montreal, 2021). From this dataset, I extracted buildings with nine or more dwellings and multiplied this by household food waste generation (229.32 kg household/yr). For universities, I sourced values for the generated food waste of the seven major post-secondary educational campuses in Montreal directly from the reported values of the individual universities (Personal communications, Agathe Moreau, Office of Sustainability, McGill University; Université de Montréal, n.d.; Champagne, 2018; Décoste, 2019; Concordia Compost, 2020), as they vary substantially in their number of students and the extent of their culinary services. The university data only represents the food waste that is currently being separated, not including the amount that ends up in the municipal solid waste at this time, as data on the latter was not available.

For the four remaining source categories, I derived the values for the total amount of food waste generated on the Island of Montreal from a report from 2012 by the environmental consulting firm, Solinov (2012). They estimated the amount of organic materials from industrial, commercial and institutional (ICI) sectors that could potentially be recovered in treatment centers, representing waste from 20,382 establishments. Their estimates are based mainly on literature values (key sources are from the 2006-2012 period, but some estimates are older), which they validated through surveys of different companies and organizations in Montreal (Solinov, 2012). Given the variability in sizes of schools, grocery stores and hospitals, I used a 'spatial disaggregation' approach rather than an average to account for their potential magnitude of contribution to food waste generation. I first extracted each individual building footprint area and compared this to the total building footprints across the study area for each respective category; I then distributed the total food waste values from Solinov (2012) with a scaling approach, as a proportion of each building types' contribution to the total footprint of its respective category. Finally, while restaurants and hotels also vary in size and characteristics, I assume that they are a relatively homogenous, in part due to data limitations including the ability of building footprints to adequately reflect establishment size. I therefore estimated the distribution of food waste generated from individual restaurants and hotels by equally distributing an average share of the total generated food waste from Solinov (2012) to each building location among all the establishments on the Island of Montreal, located through Open Street Maps (Open Street Maps, 2021). Although restaurants vary in size, I observed that they are so numerous and broadly distributed across the Island that the implications of this assumption should be minimal in terms of identifying hot spots of food waste generation.

3.2.2. Combined raster grid of total annual food waste

After estimating the spatial patterns and geographic distribution of currently unrecovered food waste by source sector across the Island of Montreal, I summarized these in a gridded raster format in a geographic information system (GIS). I combined all individual sources into a single raster with a 100 m resolution (cell size of 10,000 m^2), which approximates the size of a typical city block in dense urban neighborhoods of central Montreal. Each grid cell in this raster therefore represents the total amount of unrecovered food waste, revealing hot spots with concentrated potential feedstock for composting within neighborhoods. The food waste generated by large buildings or institutions with footprints that span across multiple cells were assigned to the cell that contained the corresponding boundary's centroid. To assess feedstock available from nearby grid cells and to smooth out the high variation across individual grid cells (e.g., a grid cell with a supermarket may have a very high value while an adjacent grid cell has a very low value), I applied a radius of 400 meters that summed the food waste availability from all surrounding grid cells by using a focal statistics operation (with a 4 x 4 search radius). This yielded a food waste density 'heat map' that allowed for easy visualization of hot spots of unrecovered OW, which I classified into four categories from lowest to highest, based on quartiles.

3.3. Site selection: land value and network analyses of local waste sourcing

Next, to identify suitable candidate sites for decentralized waste processing across different representative types of neighborhood contexts, I overlayed information on land values with the total food waste raster. To my knowledge, no seamless, publicly available dataset exists for rental costs across Montreal. Therefore, I used land values as a proxy for rental cost and associated site characteristics. Specifically, I created a raster with equal cell size (100 m resolution) of land value by converting and aggregating a detailed vector-format land use dataset for 2020 that includes land values from cadastral records and data from the Quebec Ministry of Municipal Affairs and Housing (CMM, 2020). I classified the land values into four categories of land value based on quartiles (Figure 3.3). By intersecting the four land value categories and the four food waste value categories, I generated a map with 16 categories that represent a gradient in food waste and land values. From this map, I identified the areas with the highest amount of food waste being produced within the four categories of land value and, to capture the variation within the neighborhood types, I then visually selected four sites within each category that could be suitable locations for decentralized vermicomposting facilities and represent different urban contexts in Montreal. My overall goal in this approach was to investigate how the profitability of facilities would be affected by each location, which would differ in both rental rates and availability of feedstock. Since the aim of my study was not to simulate a city-wide application of this practice, but instead to examine its potential in strategic locations with favorable conditions, I only focused on those areas of each land value category that had the highest rates of food waste generation.

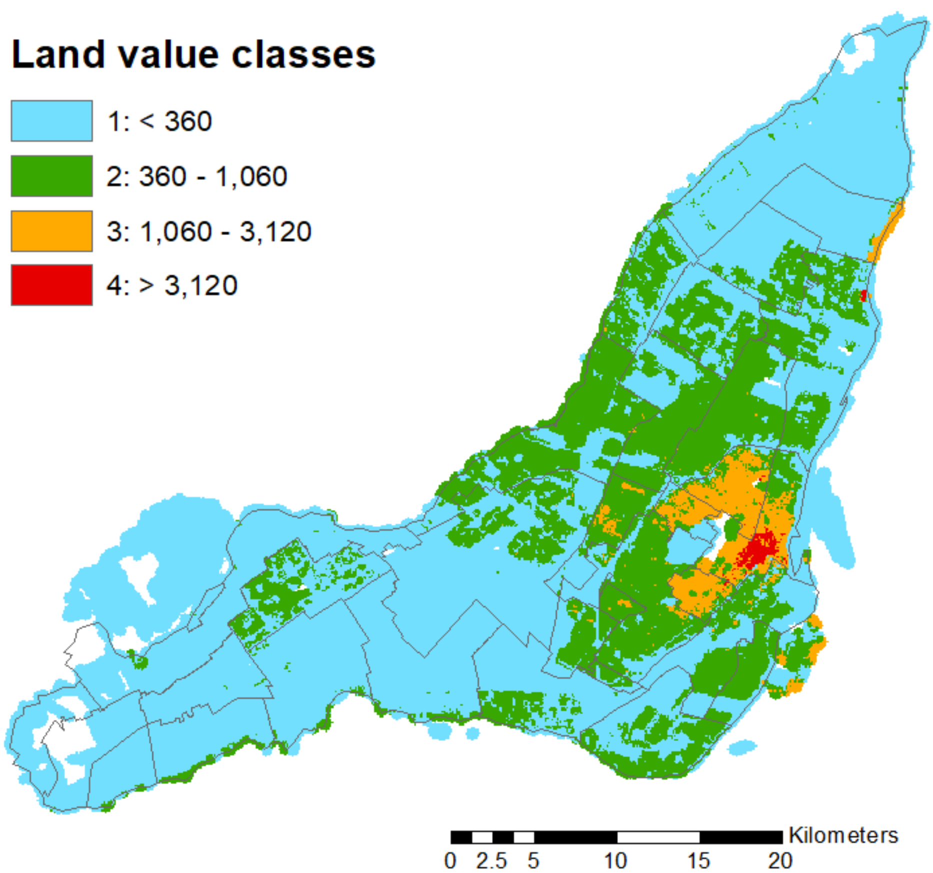

Figure 3.3: Classification of land value in Montreal into 4 categories based on cadastral data, ascending from lowest (1) to highest (4) value, based on quartiles. The legend shows the land values in $CAD per square meter for each quartile (averaged to the grid cell level). This map was intersected with the 4 categories in the final food waste generation raster to arrive at 16 categories (see Figure 4.2 in the *Results*).

In addition to the focal statistics operation to identify food waste hotspots based on a radius of surrounding grid cells (section 3.2.2.), I further accounted for the need for organic waste transport from source locations to the final candidate sites for vermicomposting within the same neighborhood. By using the Network Analyst tool in ArcGIS, I estimated a collection area around each of the chosen locations that could be reached within a 400-metre distance along the road/lane network (City of Montreal, 2020). I chose a distance threshold of 400 metres to represent a readily 'walkable' distance in urban neighborhoods (Olson, 2010; Manaugh and El-Geneidy, 2011; Pai et al., 2019), which could allow businesses to drop off their own waste and save on pickup fees. However, depending on the location of the businesses, the amount of food waste generated and the time of year (Montreal has harsh winters with low temperatures and heavy precipitation), dropping off their waste on foot may be unfeasible in some cases. This network approach effectively simulates a decentralized pickup area for each composting facility that would reduce vehicular transport distances while accounting for major obstacles in the built environment, such as highways or canals, that could impede easy collection of organic waste within neighborhoods. I then compiled the total amount of food waste from all the identified sources within each of the site collection areas and used these values to parameterize my vermicomposting model.

3.4. Vermicomposting systems models for selected sites

Based on the representative candidate sites for decentralized organic waste treatment facilities across Montreal from my spatial analysis (section 3.1), I next simulate hypothetical vermicomposting operations in a systems model. Specifically, I hold the collection area constant for each facility (at 400 m around the facility) with food waste availability depending on the geographic location of the site; thus, the facility location becomes the major driver of the systems model. The purpose of my model is to investigate the economic feasibility of such an operation by tracking potential revenues from worm casting sales and the offsetting of waste pickup fees, alongside operational expenses and capital investments over time. Furthermore, my model aims to calculate the amount of GHG emissions that would be offset by recovering and treating the available food waste locally instead of dumping it at a landfill. The STELLA Architect (isee

Systems) software used in my model development employs quantitative stock-flow modelling and visualizes the various interconnected factors comprising a system into functional, numerical parameters: *Stocks*, which accumulate or discharge entities through inflows and outflows and *Converters*, which invoke weighted influences on stocks, flows and other converters (Ford, 1999).

My model consists of three main components, each calculated on a weekly timestep:

1) A series of stocks and flows representing the conversion of food waste feedstock to vermicompost. This encompasses revenue streams of the operation, including sales of the valorized product, since these are dependent on the vermicompost production.
2) Various capital investments and operating costs representing the overall expenses of the facility. Besides labour and utilities, rent for the facility space is the major operational cost accounted for, which relates to facility location (i.e., effects of land value).
3) The direct CO_2-equivalent greenhouse gas emissions associated with the operation compared to the emissions produced through landfilling of the same amount of food waste. The direct emissions considered are the food waste treatment or landfilling, and the transportation of waste; other life-cycle emissions and indirect emissions are omitted.

After setting the structure of my model following these three components, I assigned each stock, flow and converter with values sourced from the results of my spatial analysis, literature sources, commercial databases or from personal communications with experts from the industry (Table 3.2). In particular, each component of the model receives input from a converter representing the total available feedstock in the collection area surrounding the facility location (described in section 3.3), as the amount of food waste processed determines the size and hence the revenues, costs and emissions of the operation. All monetary values are in Canadian Dollars ($).

Once I added all consistent parameters to my model, I entered the remaining varying parameters depending on what location I wanted to simulate. These are namely the amount of available feedstock in the collection area, the average commercial rental rate of the area and the distance of the location from the landfill. I first ran the model with average values from all 16 sites to assess the general economic feasibility of the practice. To investigate how the economics would differ between each land value class I then ran the model four times, each having assigned the average values from the four representative sites within each land value category.

Table 3.2: List of parameters from the model with corresponding values and units. Values marked with * are sourced from the spatial analysis and thus vary based on the facility's location. Additional details on the data sources are provided in the text. SD: standard deviation of low/medium/high values from literature.

Parameter	Value	Unit	Source
Available feedstock	*	kg	Spatial analysis
Composting reduction	0.5	-	Michigan Soilworks
Vermicomposting reduction	0.775	-	Michigan Soilworks
Fraction of compost unsold	0.15, random	-	Initial estimate (author), with a random multiplier of 0-5.
Worm castings price	6.46	$/kg	Estimated average market rate
Offset organic waste tipping fee	0.215	$/kg	Compost Montreal
Facility size multiplier	2.3	-	Initial estimate (author)
Facility rental rate	*	$\$/m^2$/year	Average from Centris database (commercial buildings)
Utilities	28.42	$\$/m^2$/year	Average for industry in Canada from Iota Communications (2021)
Labor hours per CFT size	1.51	hr/week/m^2	The Urban Worm Company
Hourly wage	13.5	$/hr	Quebec minimum wage in 2021
Price of worms per CFT size	363.29	$\$/m^2$	Estimated average market rate
CFT system cost	1,905.27	$\$/m^2$	Michigan Soilworks
Vessel price per feedstock	38.5	$/kg	Greenmountain Technologies
Miscellaneous investments	123,500	$	The Urban Worm Company
Composting emissions (low, average, high)	0.067, 0.119, 0.150 (SD: 0.045)	kg CO_2-eq/kg	Colón et al., 2011; Mu et al., 2017; Thomas et al., 2020
Landfill emissions (low, average, high)	0.606, 0.922, 1.287 (SD: 0.343)	kg CO_2-eq/kg	Lou and Nair, 2009; Dorward, 2012; Bernstad Saraiva Schott et al., 2016
Truck loading capacity	13,000	kg	Estimated industry average
Distance to landfill	*	km	Derived from Google Maps
Truck emissions per t-km (low, average, high)	0.076, 0.127, 0.178	kg CO_2-eq/t-km	Sims et al., 2014
Carbon offset value	16.6	$/t CO_2-eq	Win et al., 2017

3.4.1. Simulating vermicomposting production and sales

In the first component of the model, the available feedstock generated each week within the 400-m collection area of the selected facility location provides the input to two flows that feed into individual conveyor stocks, each representing a staggered in-vessel batch composting system. In STELLA, 'conveyer' stocks retain their inputs for a set transit time, after which their outflows receive the original amount of the input. I use these stocks to simulate a batch composting system, which, unlike continuous flow systems, are loaded once at the beginning of the composting process and only harvested once the process is complete. Therefore, in the case of my model, the conveyor stocks representing the batch composting systems, are emptied only once the thermophilic phase has been completed, which is represented by their transit time. In my model, pre-composting of the food waste is conducted for 4 weeks before adding it to the CFT unit to ensure that potential pathogens from the original feedstock have been destroyed and that temperatures in the vermicompost don't rise high enough to endanger the worm population (personal communication, Dan Lonowski, Michigan Soilworks, 2021). I therefore set the transit time for each pre-composting conveyor stock to four weeks. For simplicity, I included only two conveyors, each with a capacity twice the amount of the available feedstock, therefore representing two batch composting systems loaded on two consecutive weeks. To simulate a situation with staggered loading of these systems, I apply an initial delay of 2 weeks for the inflow of one of the conveyor stocks.

The outflows from each pre-composting stock (receiving an inflow multiplier of 0.5) represent the weight reduction during composting (Michigan Soilworks, 2021) and feed into another conveyor stock that represents the continuous flow-through (CFT) worm composter. I set the transit time of this conveyor to eight weeks to reflect the time it takes for pre-composted feedstock to be completely digested and turned into worm castings (Michigan Soilworks, 2021). As the system can be continuously fed, its size is dependent on the magnitude of the available feedstock and therefore its capacity is equal to the amount of pre-composted feedstock available. The outflow of the vermicomposter (receiving a multiplier of 0.775) represents the weight reduction during the digestion process (Michigan Soilworks, 2021), which feeds into a stock that holds the finished worm castings product. To simulate the sales of the product and calculate weekly revenues, the product stock receives an outflow into the revenue stock, which is multiplied by the average market price of worm castings per kilogram. This value is based on several online retail suppliers from North America that I located through online searches in July 2021. My model therefore assumes that all final generated worm castings (valorized compost product) can be immediately sold, which represents an idealized situation, since local demand for compost may be limited and could fluctuate seasonally. To account for this, a converter is applied to the sales flow that represents unsold product (initially set at 15%, but adjusted with a random component, see below, section 3.4.2). As an additional source of revenue, I estimated potential waste pickup service revenues, which can also be thought of as the offset cost savings from businesses no longer needing to pay organic waste tipping fees. Compost Montreal, a private composting business in Montreal, charges an average of $0.215 per kg of organic waste (Compost Montreal, 2021). I used this value to calculate the inputs of a flow representing weekly earnings from food waste pickup fees for sources within the collection area.

3.4.2. Operational expenses and investment costs

The second component of the model estimates the expected main capital investments alongside all fixed costs required to start up and operate a vermicomposting facility of the size necessary to treat and valorize the available food waste in the collection area. Cumulative profits of the operation over time are calculated as the difference between total revenues and total expenses.

First, the required CFT system size is calculated by dividing the weekly input from the collection area into the CFT conveyor stock (estimated at half the weekly available feedstock), by the feeding rate per square foot. A CFT system produced by Michigan Soilworks can be fed about 1.841 kg/sq ft of pre-composted feedstock each week (personal communication, Dan Lonowski, Michigan SoilWorks).

Next, to incorporate the weekly rental of the facility space, I estimated the total area required for the composting units, CFT systems, packaging stations as well as small offices and other utilities. To calculate the weekly rent of the operation, the total required area was multiplied by the rental rate per square foot of commercial space for each facility location, which I identified by averaging commercial rents from 3 to 5 buildings around each candidate location from an online real estate database in October 2021 (Centris, 2021). To enable loading of machinery around the CFT systems, I set the vermicomposting area at twice the area required for the CFT system itself (personal communication, Dan Lonowski, Michigan SoilWorks). The container vessels produced by Green Mountain Technologies measure 192 sq ft and have a capacity of 2.295 t/week (Green Mountain Technologies, 2021), so I divide the weekly available feedstock by 0.007 and then doubled this space to account for loading and operation of pre-composting vessels. Finally, I added one third of the size of the CFT units to the facility size calculation to account for storage space and an additional 200 sq ft to include space for packaging, a small office and other utilities.

Ongoing expenses in the model include utilities and labour. Utility costs are incorporated by using the annual average of utility expenses per unit area for industry in Canada (Iota Communications, 2020), multiplied by the total required facility area. To calculate the labour costs, I multiplied the size of the CFT unit with the estimated work hours per unit area required to run such an operation (0.07 hrs/sq ft, personal communication, Steve Churchill, Urban Worm Company) with the provincial hourly wage of $13.50 (CNESST, 2021). To factor probable labour required for the pickup of waste, I doubled this value in the model. The combined ongoing expenses for rent, utilities and labour are then combined into a flow which feeds the expenses stock with weekly fixed costs.

To account for major upfront capital costs, an initial flow is added to the expenses stock as the sum of the costs for the pre-composting and vermi-composting systems, as well as a number of miscellaneous costs. The cost for the CFT system is calculated by multiplying the area of the system by a value of $177 per sq ft, which is the commercial pricing of a larger unit (Michigan Soilworks). To this I added $33.75 per sq ft to account for the initial purchase of worms. Pre-composting vessel costs are calculated by multiplying the available feedstock by the cost of a single vessel and dividing it by its weekly processing rate (Green Mountain Technologies, 2021). Finally, I included the purchase of a truck, skid steer, trommel harvester and a bagging system (one-time, estimated cost of $123,500).

One of the most uncertain factors in my model is the ‘unsold fraction’ for the valorized worm compost production. To simulate more realistic market demand, including the impact of fluctuating demand temporally on operations from different land value categories, I added a random component to the final model. Specifically, a converter is used to multiply the fraction of unsold product by a random value between 0 and 5. As a result, the percentage of generated worm castings sold each week ranges from 25% to 100%. I generated several runs with this change implemented and documented the profits from an average operation from each land value category.

3.4.3. Greenhouse gas emissions

In the final component of my model, I estimate the direct greenhouse gas (GHG) emissions on a carbon dioxide equivalent basis (CO_2-eq) that could be avoided (offset) by composting rather than landfilling with municipal solid waste. The Lachenaie landfill, located in Terrebonne, Quebec (roughly 34 km from Montreal's city center; shown in Figure 3.1), is where the bulk of Montreal's waste is currently shipped. I make a simplifying assumption that the only differences in CO_2-eq between the two scenarios is the GHG production from food waste decomposition in the landfill compared to the GHG production from pre-composting in my model, as well as the difference in transportation distance. For my decentralized food waste management scenarios, I assume transport distance is negligible in the collection area; with landfilling, I assume sanitation trucks travel from the collection area to the landfill and back to dispose of the OW. Of course, additional emissions can be considered in a full life cycle analysis, for instance, emissions from the production of input materials and from heating/electricity for the facility. I considered life-cycle emissions from raw material manufacturing to beyond the scope and system boundary of my model, while electricity-related emissions should be minor given that >98% of electricity in Quebec is derived from hydroelectricity (Statistics Canada, 2021). To include the possibility of generating revenue from the offset carbon, I added an additional converter tracking profits made from carbon trading at \$16.6 per offset ton of CO_2-eq (Win et al., 2017).

The emissions differential between the landfilling and decentralized composting scenarios is calculated in the model by subtracting the CO_2-eq released during composting from the emissions that would be released if the same amount of food waste is landfilled. I was unable to locate peer reviewed information quantifying GHG emissions from the decomposition of food waste through combined in-vessel composting and vermicomposting. To calculate the emissions released during the combined pre-composting and vermicomposting of a simulated operation, I therefore parameterized my model with a calculated average of emissions released from in-vessel composting of food waste from the literature of 119 kg CO_2-eq/t (Colón et al., 2011; Mu et al., 2017; Thomas et al., 2020). However, several studies found that vermicomposting has marginally lower CO_2-eq emissions rates than conventional composting (Chan et al., 2011; Wang et al., 2014; Nigussie et al., 2016). My results for the CO_2-eq released during combined composting and vermicomposting should thus be considered a conservative estimate. I reviewed studies on the greenhouse gas emissions of decomposing food waste in landfills employing methane gas collection, from which I derived an average value of 921.7 kg CO_2-eq/t (Lou and Nair, 2009; Dorward, 2012; Bernstad Saraiva Schott et al., 2016). Finally, an additional flow is added to the emissions stock that represents emissions by sanitation trucks traveling from the collection area to the landfill site. To calculate the total distance travelled to haul this waste, I divided the amount of weekly generated food waste by the carrying capacity of a truck (which I derived from the average value of garbage trucks from various manufacturers located in an online search), then multiplied it by the distance from the collection area to the landfill (calculated using Google Maps, n.d.); this value is then doubled to account for roundtrips. The trucks are assumed to travel to the landfill at full capacity and travel back empty, which results in an average payload weight of 6.5 tonnes. An emission factor of 0.127 kg CO_2-eq/t-km is applied to this travel distance and averaged payload, assuming average emission rates of diesel, medium haul, heavy duty vehicles (Sims et al., 2014). Again, I did not account for transportation emissions generated locally in the collection area for gathering waste, in part because these should be roughly equivalent under both scenarios (decentralized composting and landfilling). As emission estimates for transportation and decomposition of food waste can vary substantially, aside from averages, I also included high and low estimates from the literature in my analysis.

3.4.4 Alternative model runs

I ran my model in three distinct configurations: To investigate the general economic feasibility of a vermicomposting operation, I first ran my model with average values assigned for all variable parameters (available feedstock, rental rate and distance from landfill) from across all representative sites in my study (shown in Table 4.2). Next, I conducted a comparative run of four models, each representing an average facility from one of the four land value categories to investigate the impact of location on the profitability of the operation. Finally, I introduced random fluctuations to the unsold fraction of product sales (see section 3.4.2) and ran the four models several times to test whether profitability would be impacted differently in the various locations, when simulating more realistic market conditions.

Chapter 4: Results

4.1. Spatial distribution of unrecovered food waste

I identified a total of 10,882 sites on the Island of Montreal as sources of potentially unrecovered (landfilled) food waste, including larger residential buildings, educational institutions, hotels, restaurants, grocery stores and hospitals. Table 4.1 summarizes the number of sites within each of these categories and their cumulative annual mass of generated food waste across the study area. Collectively, these sources generate a total of 141,351 tonnes of food waste annually. Residential complexes are by far the largest overall contributor to food waste generation (45%), whereas grocery stores have the highest output of waste per facility (approximately 55 tonnes per store annually).

Table 4.1: Number of sites and their estimated cumulative annual food waste generation by source category. Sources are sorted by amount of annual food waste generated, from largest to smallest.

Type	Number of sites	Annual food waste [t/year]
Residential buildings	7,892	63,476
Grocery stores	659	35,949
Restaurants	1,567	22,507
Hotels (including food service)	157	11,865
Schools and colleges*	535	4,543
Hospitals	65	2,471
Universities	7	540
Total	10,882	141,351

*includes 4% green waste

Spatial patterns of food waste generation show a highly uneven distribution across the Island, with 'hot spots' of unrecovered waste in locations with either large residential complexes, grocery stores, or large institutions (Figure 4.1). The highest overall rates of food waste generation are located in the downtown area of Montreal, with rates of up to 2,300 tonnes produced annually within the 400-meter radius considered in my analysis. Other areas with relatively high rates of waste generation in central Montreal are mainly peripheral to the downtown core, including the Plateau Mont-Royal borough (to the north-east of downtown), which has a high population density in addition to a high concentration of restaurants. Similar patterns exist in sections of the Côte-Des-Neiges-Notre-Dame-de-Grâce borough (to the west and south of downtown), which also has a concentration of apartment buildings, restaurants, and retail businesses. These locations of concentrated food waste (>580 t cumulatively per grid cell per year) are visualized in Figure 4.1 in a bright green to bright red colour ramp. Other areas on the Island with such concentration of food waste typically reflect locations with either a grocery store or a group of residential buildings.

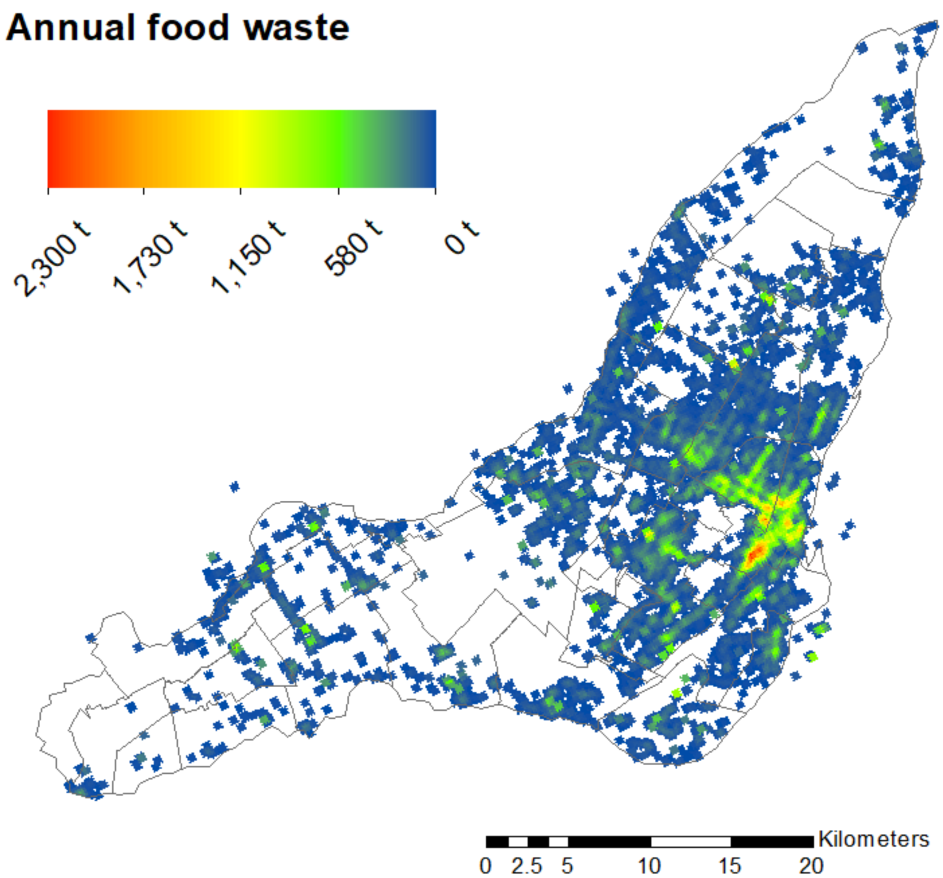

Figure 4.1: Raster map showing the magnitude of unrecovered food waste generated by the identified sources across the Island of Montreal. Values from the original 100-m grid cells are summed based on a focal search radius of 400-meters (i.e., each grid cell shows the cumulated food waste from the surrounding 4 grid cells). Grid cells in blue have non-zero values but have comparatively small food waste generation.

4.2. Facility site selection and neighborhood collection areas

To identify potentially suitable locations for decentralized organic waste management, I classified the food waste density map into four categories and combined them with the classified map of land value categories as from Figure 3.3. This shows distinct clusters or ‘zones’ across the Island with similar gradients of food waste and land values (Figure 4.2), from which I selected sites from the highest category of food waste density within each category of land value. The final selected candidate locations within each category are shown in Figure 4.3a, which I subsequently used as inputs from the spatial analysis for systems modelling.

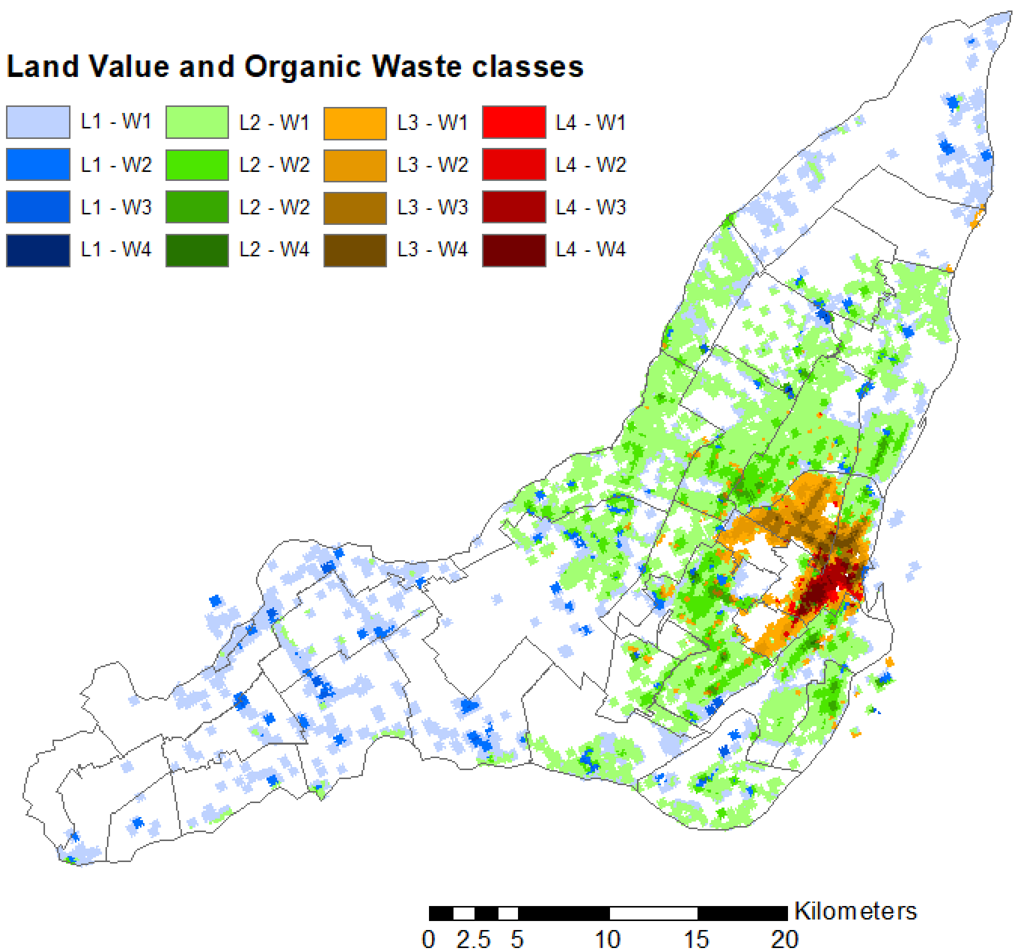

Figure 4.2: Relationship between food waste distribution and land value used to determine site selection for representative areas. Combined rasters of land value (L) and food waste (W) into 16 classes from lowest (L1 –W1) to highest land value and food waste (L4 - W4).

Next, I assigned a collection area to each facility site and isolated all the food waste sources within each area. Figure 4.3 shows the selected facility locations and one representative network collection area example from each of the four land value categories. The total annually generated food waste within each collection area is on average lower in locations that have lower average rents for commercial buildings in the surrounding area (Table 4.2). Facilities in areas of higher land value have a higher number of pickup locations available on average and therefore a higher amount of generated food waste. Cumulatively, the food waste available across the sources in the collection areas around the 16 chosen sites amount to 16,296 t/year which comprises about 12% of the total food waste generated by all identified sources on the Island of Montreal.

Table 4.2: Total number of potential sources of food waste, total annual amount of food waste and average rental rates of commercial buildings within each facility's collection area. Averages (means) for land value categories are shown in bold, which area the final values used in the modelling in section 3.3.

Site ID	Number of sources	Available food waste [t/year]	Rental rates [$/sqft*year]
1.1	18	448	15.0
1.2	6	1,396	18.6
1.3	5	890	21.0
1.4	5	144	20.0
1 (mean)	**8.5**	**719**	**18.7**
2.1	45	1,324	19.3
2.2	46	836	24.2
2.3	41	426	23.6
2.4	56	643	24.6
2 (mean)	**47**	**807**	**22.9**
3.1	57	1,015	25.4
3.2	50	1,118	28.6
3.3	61	682	26.7
3.4	60	522	24.9
3 (mean)	**57**	**834**	**26.4**
4.1	49	1,305	35.5
4.2	130	2,187	28.9
4.3	72	1,321	37.5
4.4	90	2,040	34.6
4 (mean)	**85**	**1,713**	**34.1**

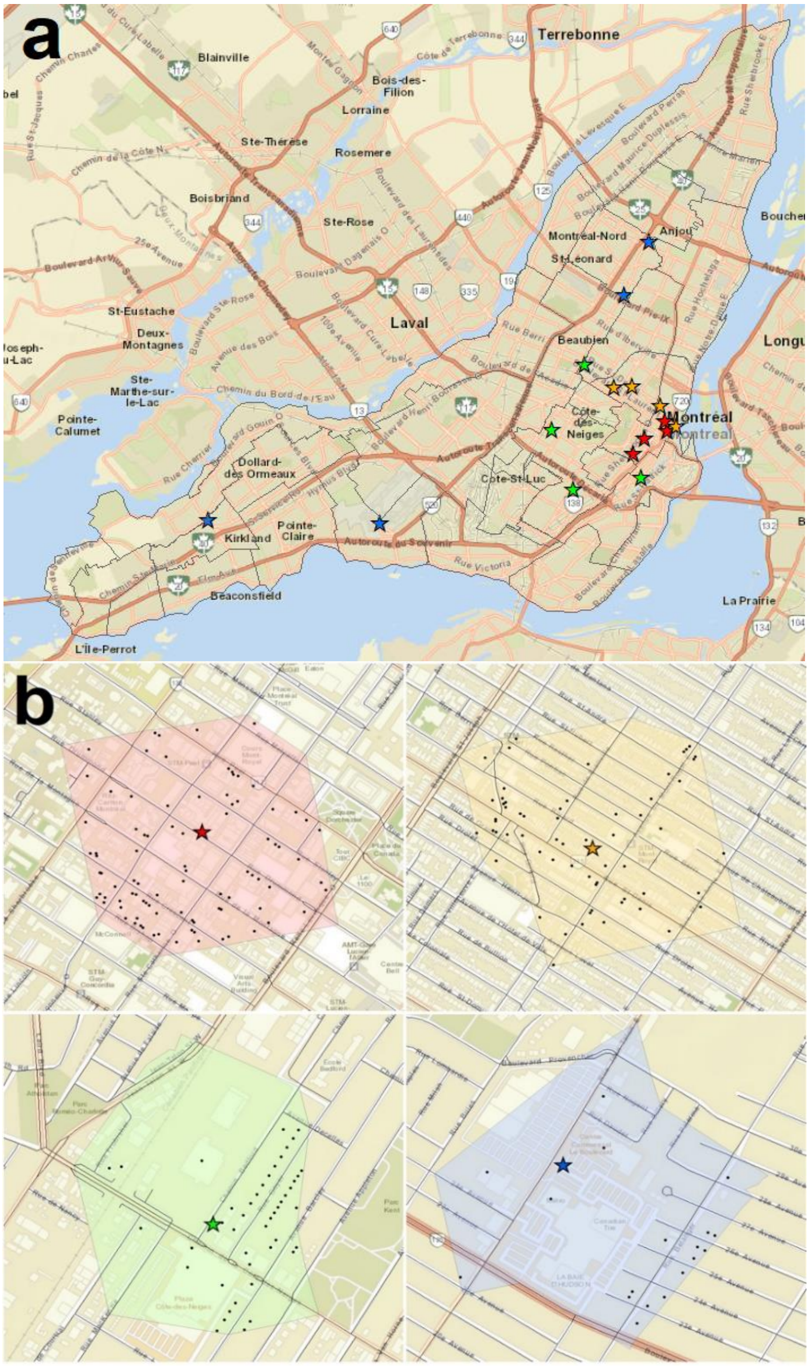

Figure 4.3: Locations of modeled facility sites and collection areas of four representative areas. (a): The 16 selected representative facility sites used for modelling, selected based on the areas identified from the combined raster with highest amount of food waste within each of the land value categories. (b): Representative facilities (stars) from each land value class with their collection areas, which extend 400 meters along the road network, and the contained sources (dots) of generated food waste within each area. Road map image source: ESRI, DigitalGlobe. Road network data: City of Montreal (2020).

4.3. Systems model of a vermicomposting facility

My final model simulates the technical, economic and emission related factors of a decentralized vermicomposting facility (Figure 4.4). The model consists of the process of waste valorization and associated revenue streams (green), investment costs and ongoing expenses from the operation (red) and the main, direct greenhouse gas emissions associated with processing and transportation (yellow). The converter representing the available feedstock within each collection area is the main input for my model and affects each of its components, such as the weekly amount of processed food waste, the size of the composting unit and in turn the associated expenses. In turn, the direct GHG emissions are also determined by the available feedstock. Since the model contains no feedback loops through which outputs regulate the inputs, the results are linear in nature.

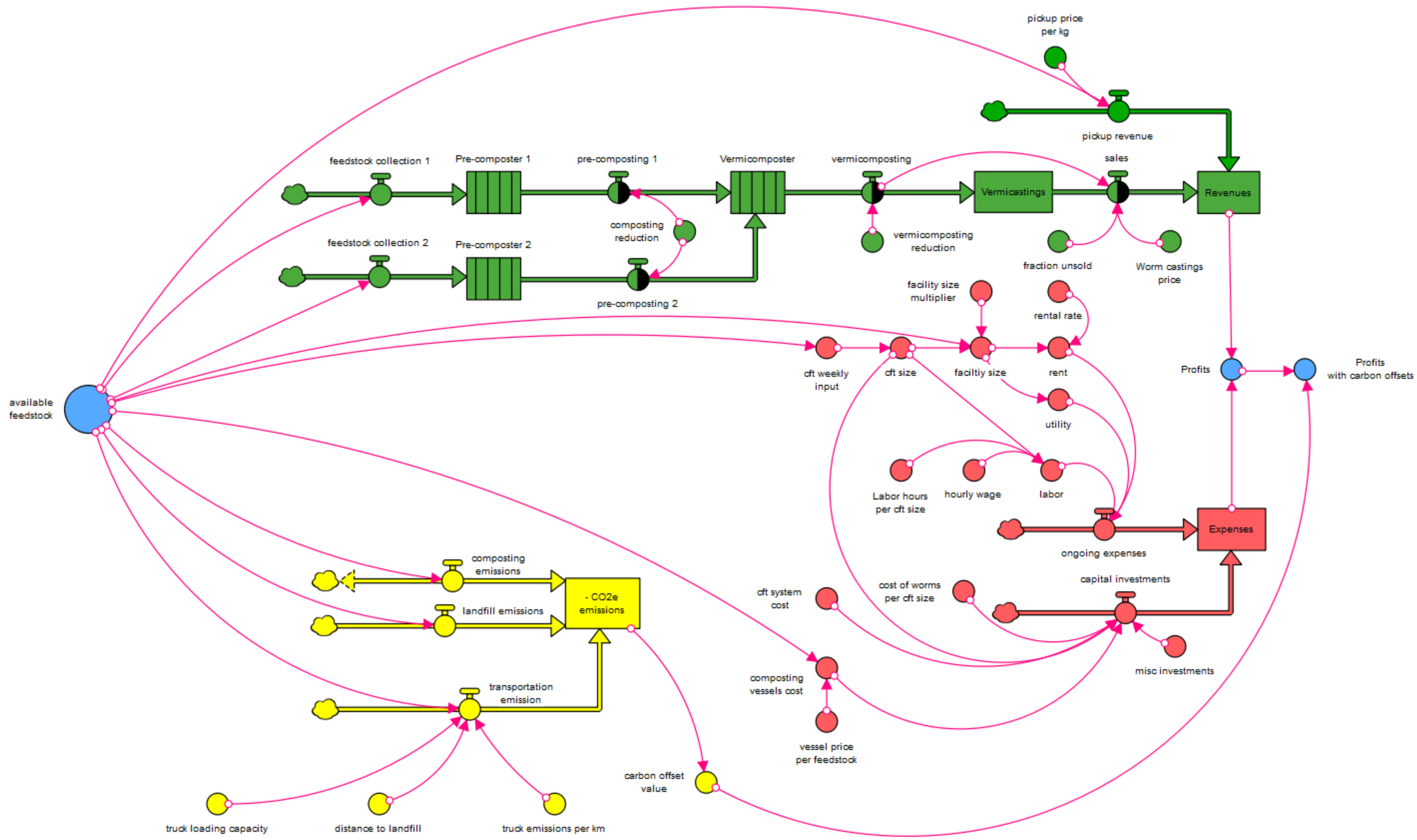

Figure 4.4: Systems model of a vermicomposting operation. Production and revenues in green, expenses in red and emissions in yellow.

4.3.1. Financial accounting of an ‘average’ facility

I first calibrated the model with average values for available feedstock and rental rates to assess general trends in the financial accounting. Of the ongoing expenses (Figure 4.5), labor and rent contribute 57% and 39% of the overall costs, respectively. Utility costs make up about 4% of the annual budget. In terms of capital investment, the majority of the costs are attributed to setting up the vermicomposting system itself, with 47% going towards the machinery and 9% towards the purchase of earthworms. The pre-composting vessels make up 38% of the capital expenses and the remaining 6% go towards various smaller purchases.

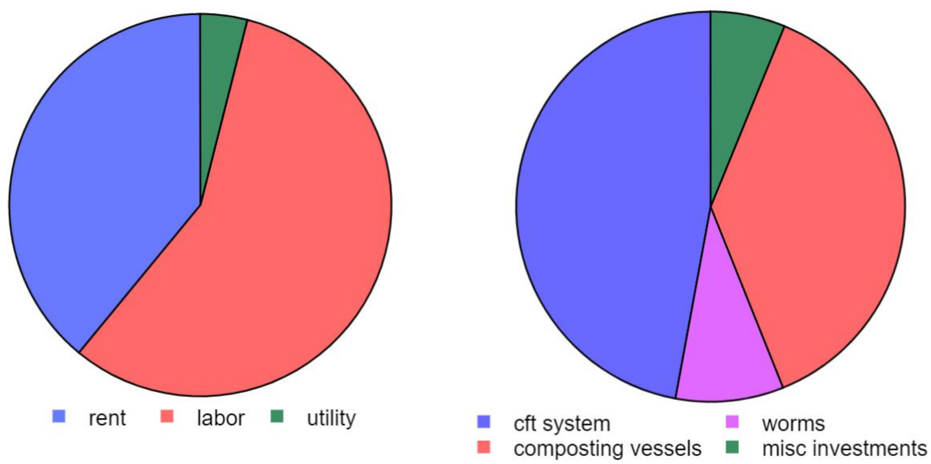

Figure 4.5: Breakdown of ongoing expenses (left) and capital investments (right) required for the setup and operation of a vermicomposting facility. Average values from all chosen sites are assigned to rental rates and available feedstock converters.

The expenses, revenues, and profits of a simulated facility with average values for available feedstock and rental rates show that such an operation can theoretically be profitable over the first 100 weeks of operation (Figure 4.6). There is an uptick of expenses in the first week representing the necessary capital investments of about $1.7 million, after which they stabilize at about $17,500 per week (the combined cost of labor, rent and utilities). The revenues remain low during the first 14 weeks due to the time it takes to generate worm castings from the feedstock, at $4,200 per week, which represents the fees from waste pickup. Once worm castings are being sold, they rise to $52,000 per week. The breakeven point is at about week 90, where the cumulative revenues rise above the cumulative expenses and the operation has a return on its investments. After 150 weeks, profits have reached $1.7 million.

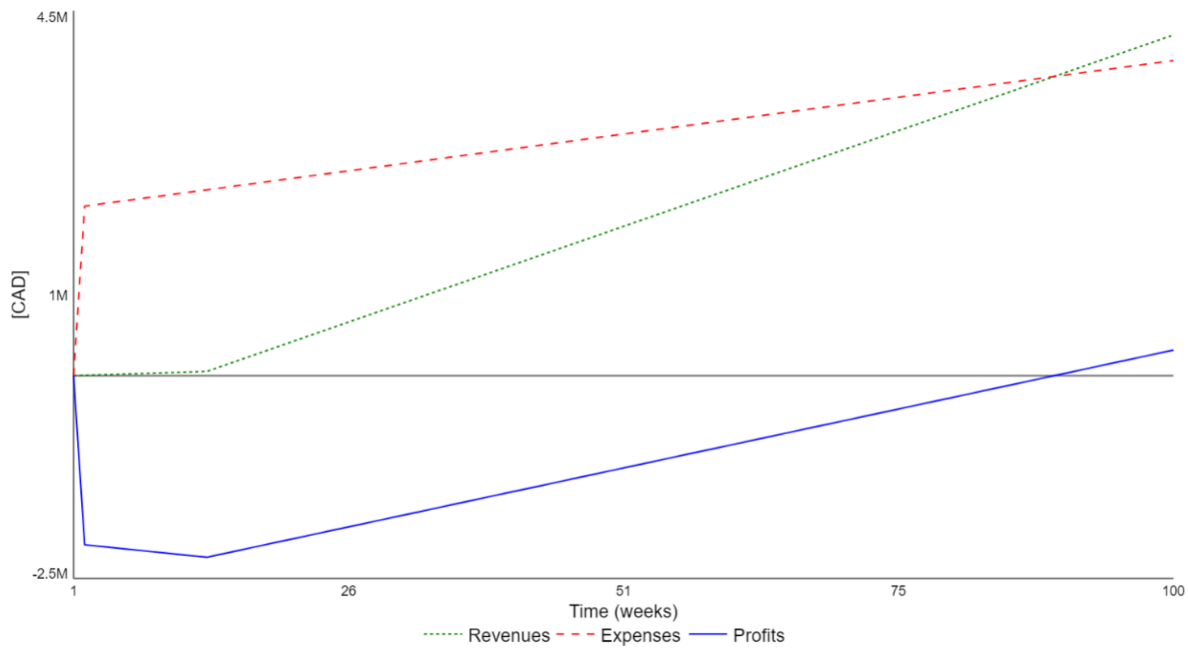

Figure 4.6: Revenues, expenses and profits of an 'average' modeled vermicomposting facility. Average values are assigned for available feedstock, rental rates and distance from landfill. The model was run for the first 100 weeks of operation. CAD: Canadian dollars ($).

4.3.2. Comparative accounting of facilities across the four representative neighborhood types

Alternative model runs simulating average facilities from each land value categories (Figure 3.3) show the higher initial costs as well as the higher profits of larger facilities processing a larger volume of food waste (Figure 4.7). Facilities in the downtown core area (LV4) have by far the highest capital expenses; however, the greater output from the facility also results in higher revenues, due to increased output of valorized organic waste. Due to lower rental rates, facilities located further away from the city centre start getting returns on their investments earlier than facilities downtown, despite lower revenues, which is owed to the lower relative ongoing rental expenses (Figure 4.8). My model simulations suggest that locations within each land value class are potentially profitable, however, there is a clear tradeoff between higher revenues from sites with relatively more available feedstock and lower rental rates in areas with relatively less feedstock. Locating facilities in the downtown area (LV4) may therefore be considered as an option with both 'higher risks and higher rewards', whereas sites in less densely populated areas (e.g., LV1) come with lower risk but also lower potential for food waste recovery. (Further discussion of the quantitative results around this point are given in section 5.1.3.)

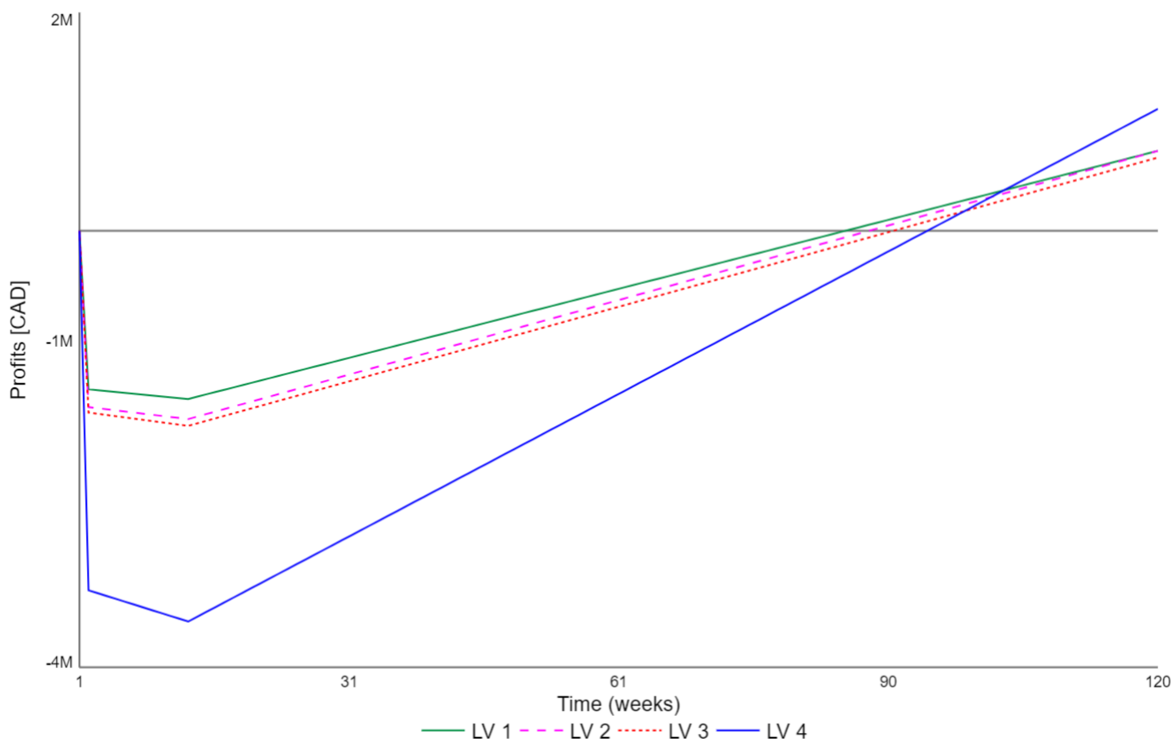

Figure 4.7: Profits generated by facilities located in each of the four sectors of land value. Average values from the respective land value categories are assigned for available feedstock, rental rates and distance from landfill for each model run. The model was run for the first 120 weeks of operation. CAD: Canadian dollars ($).

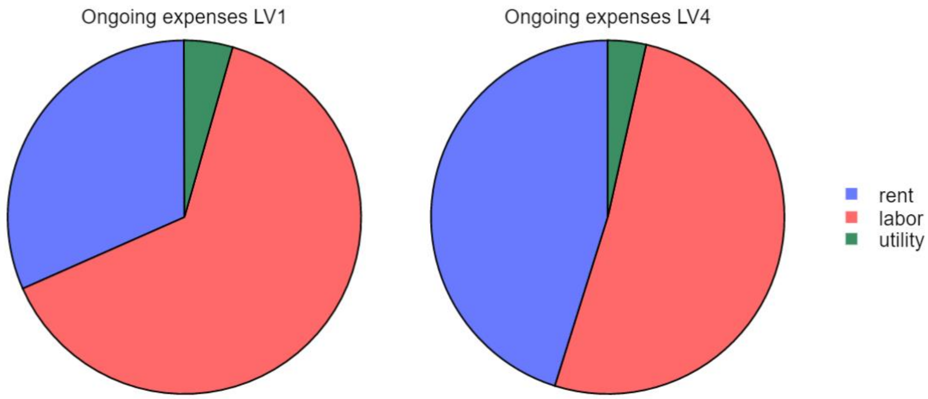

Figure 4.8: Breakdown of ongoing expenses for operations in the lowest (LV1, left) compared to the highest (LV4, right) cost category of rental rates.

4.3.3. Product demand fluctuations affect downtown operations' profitability most severely

Adding random fluctuations of product demand to simulate more realistic market conditions, negatively affected the profitability of averaged operations from all areas of differing land values (Figure 3.3). This reduction in overall profitability occurred due to the increase of the fraction of unsold product which increased to 37.5% on average. The two simulation runs depicted in Figure 4.9 demonstrate that larger operations with higher fixed costs, such as the downtown facilities, are impacted to a higher degree by unfavorable fluctuations in market demand for worm castings. Operations with higher total expenses demonstrate a greater reduction in profits with reduced revenue, which is shown in an increase in time before the operation has made a return on its investment compared to smaller operations located in areas of lower land value.

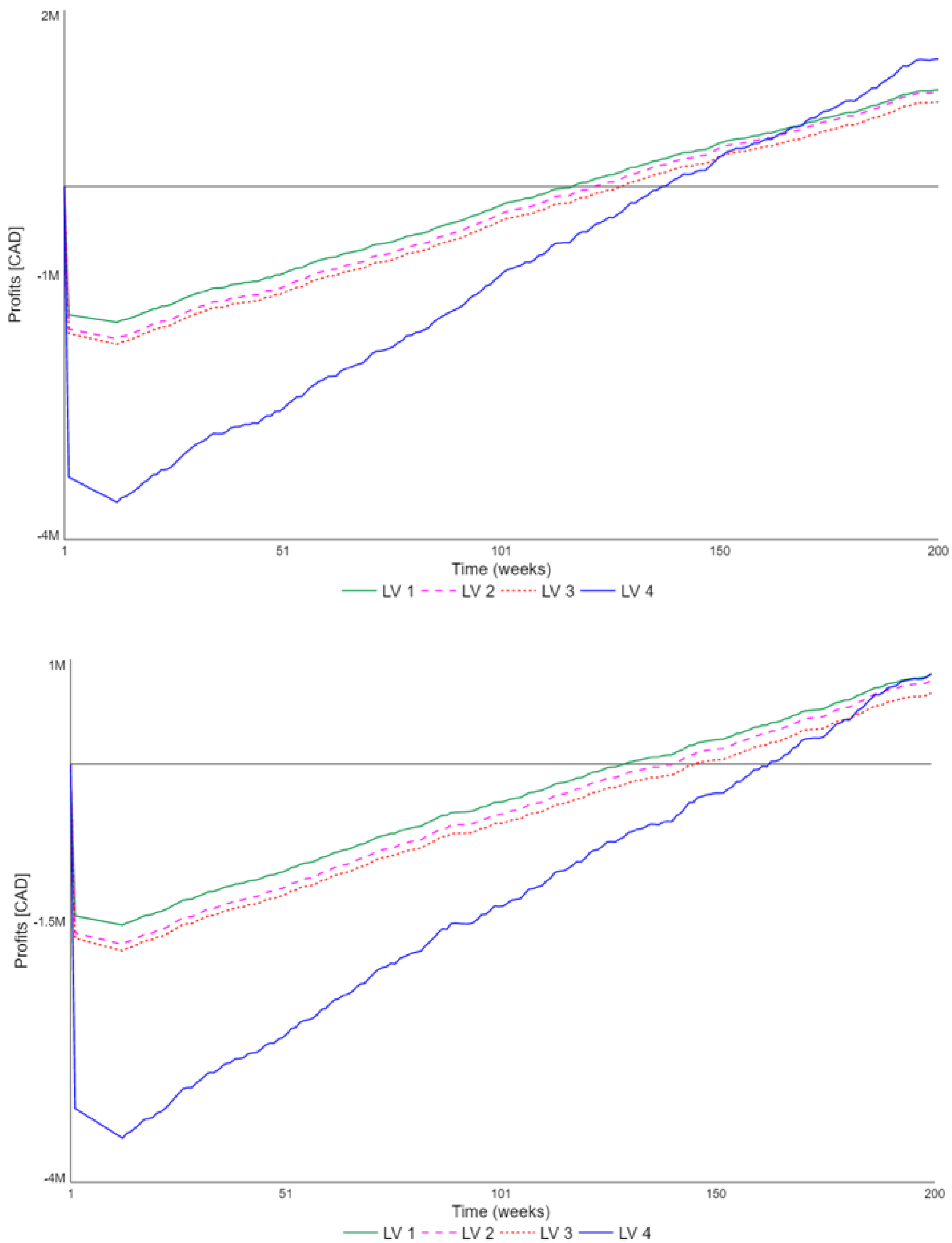

Figure 4.9: Two example simulation runs of generated profits by facilities located in each of the four sectors of land value with random market fluctuations. The fraction of unsold product randomly fluctuates between 0 and 75%, which influences the break-even point, particularly for the LV4 location (downtown area). The model was run for the first 200 weeks of operation. CAD: Canadian dollars ($).

4.3.4. Relative GHG emissions from vermicomposting versus landfilling

The processing of feedstock by an average facility substantially decreases the amount of GHG emissions when compared to landfilling of the same amount of food waste (Figure 4.10). At 2.32 t of CO_2-eq per week, the vermicomposting of the additional diverted feedstock generates about 13% of the GHG emissions that would be generated by landfilling (18 tonnes of CO_2-eq per week). Emissions generated from the transport of the waste from the collection area to the landfill are negligible in comparison (average of 0.08 t of CO_2-eq per week). Therefore, the processing of food waste through decentralized vermicomposting would avoid (offset) about 15.8 t of CO_2-eq each week in direct emissions for an average facility, without accounting for indirect or lifecycle emissions. Considering all the combinations of composting, landfilling and transportation estimates, the avoided emissions range from 9 to 24 t CO_2-eq each week. Using the 'average' estimates in Figure 4.10, this amounts to 810 kg of avoided CO_2-eq for every tonne of food waste treated (and ranges from 460 to 1,226 kg CO_2-eq with assumptions about 'low' and 'high' avoided emissions estimates, respectively).

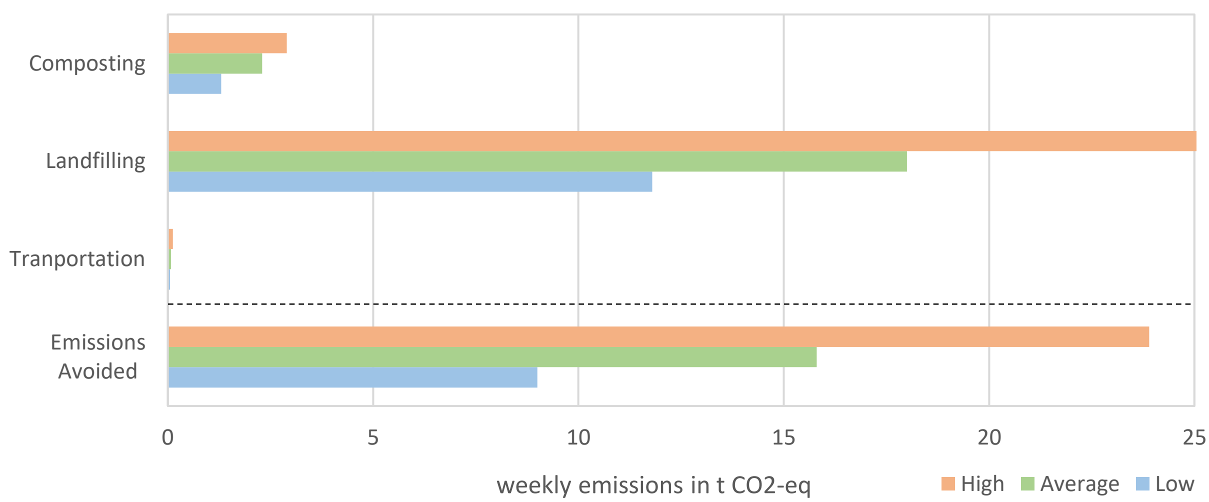

Figure 4.10: Emission outputs and differential from composting and landfilling. Bars represent from top to bottom: emissions from composting, from landfilling, from transportation of food waste from the collection area to the landfill and the potential reduction in carbon emissions from diverting waste to a local vermicomposting facility instead of landfilling (emissions avoided). The three values for each category represent high (red), average (green) and low (blue) estimates for generated emissions. These estimates were used to calculate the avoided emissions, yielding the highest and lowest possible results, as well as the average. The outputs are derived from the model representing an 'average' facility (section 4.3.1).

Chapter 5: Discussion

5.1. Reflecting on the efficacy of vermicomposting at the neighborhood scale

One of the goals of my research was to estimate the approximate spatial distribution of currently unrecovered food waste across the Island of Montreal, which revealed clear ‘hot spots’ of food waste generation in some neighborhoods. These areas could be strategic locations for alternative waste management, such as vermicomposting. I used the results of my spatial analysis on potential feedstock availability to simulate the economics and emission implications of decentralized vermicomposting facilities, demonstrating that such operations can potentially be profitable. However, I find that neighborhoods with a high density of food waste generation could benefit more from local treatment, as greater feedstock availability is needed to yield relatively higher potential revenues. My findings serve as a proof of concept, demonstrating that managing food waste at the neighborhood scale through vermicomposting can be potentially profitable while substantially reducing carbon emissions through the diversion of food waste from landfills. Such neighborhood vermicomposting operations could be operated with relatively quick start-up and at relatively low cost, making them potentially well suited to complement large-scale waste management facilities in areas of high food waste generation not adequately serviced by the centralized system. In general, my approach of combining estimates of waste generation from specific sources with their spatial distribution using publicly available data (that is readily accessible for most high-income cities) is also a promising approach towards understanding spatial patterns of organic waste in any urban context, which could help municipalities to make informed decisions towards finding priority areas for alternative waste management practices.

Complementing conventional, centralized food waste management facilities with alternative practices, such as decentralized vermicomposting, could close certain gaps in urban food waste recovery, as identified in my spatial analysis, as well as provide more cost-effective options for municipalities. To enable processing large quantities of organic waste on the island, the city of Montreal has contracted the construction of a large composting facility in the St. Laurent borough, which is expected to be operational in 2022. The facility has a capacity of 50,000 tonnes per year and will cost the city $18 million for land expropriation and $146 million for construction and decontamination (Gyulai, 2019). This amounts to a total capital investment of $164 million, which means the price per tonne for annual capacity is $3,280. Compared to a price per tonne annual capacity of $1,960 for an average vermicomposting operation in my study, the capital investment of a decentralized vermicomposting facility amounts to about 60% that of a large-scale composting facility. Furthermore, the modular setup of a decentralized facility could be deployed within weeks rather than years. Smaller facilities may also avoid potential negative externalities, such as depreciation of land value in the surrounding neighborhood. However, even small facilities may cause issues within the surrounding neighborhood, due to increased traffic and potential odors. Therefore, when choosing a site for a vermicomposting facility, further consideration should be given to potential disruptions to nearby residents and businesses. Also, since chosen sites may be more likely to be located in lower-income neighborhoods (given the consideration of property values for site selection in my study), important questions of environmental justice arise, as it may lead to the depreciation of land values or other negative impacts on marginalized communities.

5.1.1. Spatial disaggregation of food waste as a tool for strategic waste management

Numerous studies have called for the need to identify spatial concentrations of food waste in cities (e.g., Warshawsky, 2015; Cerciello et al., 2019; Fattibene et al., 2020). My approach to spatially disaggregate unrecovered food waste from identified sources is a simple but effective tool to map out hotspots of food waste generation and therefore pinpoint areas in which would benefit the most from implementing additional measures towards food waste recovery. It is conceptually similar but much less technically complex and data-intensive than studies of high-resolution urban waste for New York City, United States, by Kontokostaa and colleagues (2018, using machine learning and building-level data) and for Sydney, Australia, by Madden and colleagues (2021, using a probabilistic spatial modelling approach with census and property data). While my results are likely to be considerably less accurate in terms of exact amount of organic waste generated at any given location (subsequent research would be needed to validate my results, for example, with questionnaires for key sources, such as supermarkets), they are also easier to implement and help to reveal broader spatial patterns across the urban region in a moderate resolution that is useful for planning at the neighborhood scale.

In my spatial analysis, I limited this to key sources of food waste generation known to be gaps in Montreal's existing centralized organic waste treatment, which encompasses residential, institutional, and certain commercial sources (i.e., larger housing complexes, schools, universities, hotels, restaurants, grocery stores and hospitals). For comparison, the combined estimate of unrecovered food waste from these sources in my study is about 18.6% larger than the total amount of organic waste that was being recovered by the City of Montreal in 2020[2]. Due to the large variability, uncertainty, and lack of available data on food waste from the industrial sector, I did not include this as a source in my study. However, industry likely represents a considerable opportunity for alternative waste treatment in cities. Solinov (2012) estimated that the annual unrecovered organic waste generated by the food and beverage manufacturing industry on the Island of Montreal was 84,480 tonnes, which is about 38% of the 223,200 tonnes of total organic waste generated by the 'industry' sector overall. Most of the organic waste that is recovered originates from large companies, which either re-use it (e.g., as animal feed) or independently send it to composting facilities (Solinov, 2012).

Small- to medium-sized businesses are less likely to recover their organic waste and hence should be the focus of further research regarding industrial food waste management. While in some cases, I was able to locate reported values of waste generation directly from individual sources (e.g., universities), several others relied on distributing of the best available city-wide estimates with more spatially detailed 'proxy' data. Given the geographic scope of my analysis, the use of average waste generation coefficients across diverse locations within certain source categories (e.g., restaurants) and the uncertainties within the initial Solinov (2012) waste inventory, the results of my spatial analysis are intended to represent an approximation of waste distribution rather than a precise quantification of actual food waste generation. As mentioned above, such spatial estimates of relative food waste magnitudes can therefore help identify and guide efforts to valorize food waste within the city. An example of this is that my results clearly identify supermarkets as

[2] Note that the organic waste collection by the city circa 2020 originated almost exclusively from residential buildings with 8 or fewer dwellings (personal communication, Martin Héroux; and City of Montreal, 2020).

disproportionate ‘hot spots’ of unrecovered food waste on the Island of Montreal, making them strategic locations to focus alternative waste management efforts.

5.1.2. A proof of concept of decentralized vermicomposting

My systems model of vermicomposting operations helps to assess whether such a practice would be operationally feasible in multiple ways, including: the capital, space and labour requirements; whether it could be theoretically profitable in the short- to medium-term; and the potential to offset carbon emissions by valorizing the waste locally rather than sending it to a landfill. My model is a simplified representation of an actual operation, focused on the key processes and components, and therefore intended as an initial feasibility assessment rather than a business model blueprint. Important aspects such as market demand or a comprehensive life cycle analysis could not be included due to the limited scope of my research. For example, Righi and collegues (2013) conducted a life cycle assessment for the decentralized anaerobic digestion of organic waste and identified the practice, due to the reduction of travel distances and the energy saving associated with the process, as a sustainable option of organic waste management. Nonetheless, my research is a crucial first step in developing an alternative urban organic waste management paradigm, through decentralized vermicomposting, by providing proof of concept that showcases the potential profitability and reduction in carbon emissions.

My findings generally corroborate the claim by Jensen and colleagues (2011), who originally developed the CFT vermicomposter, that such a facility could indeed be profitable. However, in their accounting of costs and revenues for the commercial application of an indoor continuous-flow reactor facility (with projected annual profits of about $2.5 million CAD), they modeled a much larger facility: their estimates were for processing 90.7 tonnes of organic waste a day and selling worm castings at only $40 per tonne (however, they note that worm castings are commonly sold between $230 and $1150 CAD per tonne). This is a much more conservative price point estimate for selling worm castings than the one used in my model (my sale price is about $6,460 per tonne). If I use the more conservative value from Jensen and colleagues to parameterize my model, the operation would no longer be profitable, as my simulated operation relies on margins closer to those of retail sales, rather than bulk wholesaling. My rationale for parametrizing the model this way is based on the much smaller scale that my facilities operate at, with far lower throughput of feedstock (about 2.8 tonnes per day). Furthermore, higher rents in urban areas, more conservative estimates of the necessary labour hours, as well as the addition of in-vessel pre-composting to my model also add to this discrepancy. My model was in part parameterized by values derived from personal communications with experts from the industry, given the very limited empirical data on vermicomposting in the literature, which introduced challenges and uncertainties to my study. However, my research helps to inform this gap in the literature, yielding insights that can help to better understand the feasibility, scalability and limitations of decentralized urban vermicomposting.

5.1.3. Tradeoffs between rental rates and available feedstock: Location affects profitability

My findings show that the profitability of a vermicomposting facility is higher in areas of relatively lower land value, however, due to higher amounts of feedstock available, overall revenues are highest in the downtown area of Montreal. To valorize all the available food waste within the collection area of a facility located in the downtown area, its spatial footprint would be roughly 2,000 m^2; based on my spatial analysis, this is close to the average footprint of supermarkets in Montreal (2,038 m^2). Having such a large facility operating in the downtown area would be a difficult undertaking that would come with certain challenges. Noise and odor generation would have to be carefully managed, which may be unfeasible at such a large scale. Furthermore, traffic and odor from trucks delivering food waste to the facility may prove to be a nuisance to the surrounding area. Moreover, as rent contributes 45% of the overall ongoing expenses for a modelled facility in the downtown area, a steady demand for the composting end-product would be crucial to finance the operation. Locating a vermicomposting facility downtown would therefore come at a higher risk, while also potentially yielding greater reward (given greater feedstock availability). In areas of lowest land value on the Island, rent constitutes less to the overall fixed costs (32%), reducing the overall operational costs, but with a tradeoff in that there is less feedstock available.

To explore this tradeoff further, I find that food waste density is moderately positively correlated with the corresponding rental rate for the different sites (Figure 5.1), with typically higher amounts of feedstock available in areas with higher rental rates. (This pattern may be unsurprising, as food waste generation is inherently related to population density, which could also be expected for land values.) Sites with relatively high magnitudes of available feedstock within their collection area in relation to their rental rates could therefore be prioritized when selecting facility locations, as their lower rental costs will make the operation more profitable. These ‘sweet spots’ for potential facility sites are found where this tradeoff between the generation of unrecovered food waste and rental rates is less pronounced, in favour of profitability. Such locations are typically found in close proximity to large residential buildings, grocery stores and institutions with high amounts of generated food waste. When choosing locations for localized food waste treatment facilities, municipalities should first identify such sites, as they offer the best cost-benefit options. In addition, facilities located nearby to such large generators of food waste have the benefit of being able to source considerable amounts of feedstock from a relatively small number of sources. This simplifies logistics and lowers costs associated with transportation of food waste.

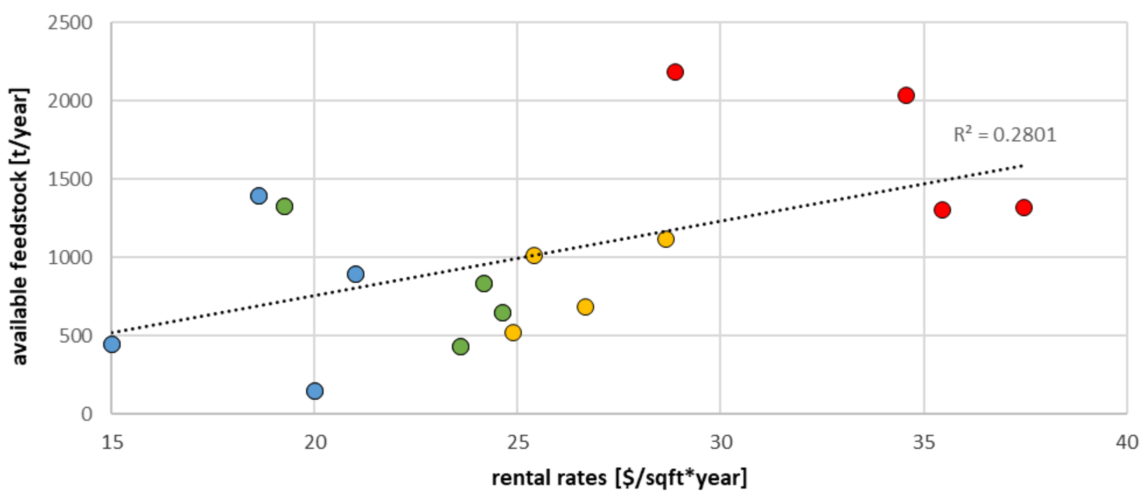

Figure 5.1: Relationship between rental rates and available food waste for each of the selected facility sites. Colour-coding represents the different land value categories from Figure 3.3: 1 (lowest) – blue, 2 – green, 3 – yellow and 4 (highest) – red. The R^2 value corresponds to the linear regression line (dotted line).

My models for different neighborhood types clearly demonstrate these dynamics. While the highest density of food waste generation is located in downtown Montreal, due to a high concentration of large apartment complexes, restaurants and grocery stores, this is likely not the ideal location for a vermicomposting facility. This is because available space is limited and rents are high. I identified hotspots of food waste outside the downtown area that could serve as better locations, which are either situated near conglomerations of large residential buildings or restaurants or have just a few large single source buildings, such as a hospital or supermarket, which contribute the bulk amount of feedstock. The latter scenario has the additional benefit of requiring minimal transportation from feedstock source to processing facility, especially if a facility can be co-located with one of its major sources of food waste.

To further lower the cost of rent, operations could also be located off-island, optimally close to organic farms to be co-located with end consumers of the worm castings. This could, however, dramatically increase transportation distances. Given the relatively low contribution of transportation to the overall GHG emissions, this would likely not have a large environmental impact if feedstock is picked up once a week. However, since many generators of organic waste would likely require more frequent pickup of organic waste, hauling waste off the island on a daily basis, would have a far greater financial and environmental impact, which is unlikely to be offset by the operation’s close proximity to an end-consumer, such as an organic farm.

5.1.4 Potential markets for compost product: neighborhood to regional scales

The extent to which co-location of food waste treatment with beneficial re-use by end-consumers could be achieved in an urban context is a key additional factor to consider when deciding on the feasibility and location of a vermicomposting facility. In their review of reducing food systems energy demand in high-income urban contexts, Mohareb and colleagues (2017) highlighted the role of co-location of urban agriculture operations with waste streams, including the potential to increase crop yields and offset life cycle energy demands. Decentralization of waste treatment can dramatically reduce the cumulative transportation distances necessary to recover food waste (e.g., Pleissner, 2016; Taşkın and Demir, 2020), thus offering a clear benefit over conventional, centralized waste management. However, once the feedstock has been valorized, the product still needs to reach a consumer for beneficial re-use. A key assumption in my model is that this consumer demand is unlimited. To understand the potential of local nutrient recycling through decentralized food waste management, the extent the market for worm castings within the city or at other scales thus needs to be investigated. Identifying potential local consumers of worm castings and their requirements is therefore another factor needed before deciding on a vermicomposting facility's location.

Valorizing food waste from local sources and using the end-product as an organic fertilizer for urban food producing operations would help achieve a 'hyper-localization' of urban nutrient cycles while also minimizing transport distances and GHG emissions from the transportation of unprocessed food waste (Saer et al., 2013; De Feo, 2016). However, given the high concentration of recyclable nutrients relative to nutrient requirements for urban food production, a diversity of potential end-users may need to be involved to beneficially reuse nutrients recovered in food waste. For example, Metson and Bennett (2015) found that urban agriculture on the Island of Montreal requires only 2.6% of the phosphorous imported for food consumption, and an urban agriculture area nearly four times larger than the Island would be needed to beneficially recycle all phosphorus in food and yard waste. Hence, a variety of potential markets for worm casting would need to be considered, such as urban farms, hobby gardeners, community gardens, parks, plant nurseries, landscaping companies, ornamental plant businesses, and retail stores. Which type of consumers would be targeted specifically would depend on the location of the facility and the geographic scale of the markets considered.

Targeted consumer types, depending on market scale, would impact both potential revenues and emissions, creating a trade-off between these two factors (as shown in Table 5.1). To implement this dynamic in my model, potential demand and price margins for worm castings on different market scales would have to be assessed and emissions and costs associated with packaging and shipping necessary to reach those markets would have to be investigated. Comparative runs of model scenarios targeting different markets, each parameterized with the abovementioned respective values, would allow for a direct assessment of the trade-off between profitability and environmental impact when considering different markets. While targeting markets on regional or even national scales would substantially increase the transportation distances associated with the recycling of food waste, decentralized food waste processing may still be beneficial due to the reduction in weight by 60% that occurs during vermicomposting (personal communications, Dan

Lonowski, Michigan Soilworks), which would decrease the costs and emissions from the transportation of food waste.

Prices of worm castings would depend on the type of consumer. When sold in small quantities directly to private individuals either in person or online, the end-product could be priced relatively higher (for example, Jensen et al. 2011 assumed that bagged worm castings could sell for 5-10 times more than bulk product), but there would be no guarantee of continued sales. Garden centres and plant businesses would likely have a longer-term (though seasonally fluctuating) demand for the generated product and would purchase them in large quantities, but at lower prices. Having a diverse pool of consumers, would therefore provide a good balance between consistent sales and high profit margins. To support local communities, surplus compost could also be donated to community gardens and other not-for-profit ventures. This could especially benefit lower-income neighborhoods around urban agriculture development and could gather additional support for a decentralized vermicomposting operation from both the local community and the city at large. As demand is likely the bottleneck limiting profits, donating a small fraction of end-products to local initiatives would not have a substantial effect on the profitability of a vermicomposting facility.

Given the northern climate context of this study, pronounced seasonal fluctuations in market demand would likely have to be considered. Aside from greenhouse growing operations, most consumer demand would likely be limited to the growing seasons from spring to fall. As the shelf life of worm castings is quite high before its quality is diminished, organic waste could still be valorized throughout the cold months and stored until market demand increases.

Table 5.1: Overview of a hypothetical market analysis, including potential end-users and target market scales for the vermicompost product given the geographic context of the metropolitan region of Montreal. The potential magnitude of the impacts on revenues and emissions of the waste management operations presented in my systems model are indicated.

Market scale	**Potential consumer base (Montreal metropolitan context)**	**Potential impact on profitability and likelihood of full use of compost resource**	**Potential impact on emissions**
Neighborhood (e.g., 400-m collection area, several blocks)	Highly variable by neighborhood context (e.g., backyard/hobby gardeners, community gardens), parks and plant businesses in the area.	Low, due to small market demand, but highly dependent on available consumers. Small market reach necessitates higher prices.	Negligible impact given direct sales with limited transport requirements.
City (e.g., borough or municipality)	Institutional and community gardens, large parks and other municipal properties, commercial farms and plant businesses, retail stores within city.	Medium, due to limited market reach, but highly dependent on available consumers.	Low impact from short transport distances.
Regional (e.g., metropolitan area, nearby rural agriculture)	Peri-urban organic farms, horticulture and nurseries (including greenhouses), landscaping companies, larger retail stores, etc.	High, due to large number of potential consumers.	Medium impact from increased transport distances (may be similar to landfilling scenario).
Online sales (e.g., nationwide)	Direct retail sales to private individuals and businesses.	High due to retail pricing and large market reach.	High impact from packaging and shipping.

5.1.5. Expanding product line for additional revenue streams

To diversify the end-product and hence the potential consumer base, a facility could reduce the amount of space dedicated to vermicomposting and instead cure a portion of its pre-composted material further in some of its in-vessel composters. Compost has a lower nutrient density than worm castings (Soobhany et al., 2015) and would be a less expensive end-product, which could be more attractive for urban farmers that are in need for higher volumes of organic material. This would also cut down on overall facility size, as the pre-composting vessels are more space efficient than the CFT units.

Another potential source of revenue is the sale of earth worms themselves (Jensen et al. 2011). With continued operation, the worm population in the CFT units will grow until they have reached a stable equilibrium which is limited by space and available food. Worms could be periodically harvested, without taking too many out at once to negatively impact the digestion of organic waste. Once harvested, the worms could be sold as fish bait, for starting home composters or to enrich the soil of urban growing spaces. Selling worms in addition to their castings would, however, add additional workload and logistics to the operation, which may not be worth the added revenue, considering that potential market demand is likely very limited, at least in the context of Montreal.

5.2. Limitations and uncertainties

The purpose of my facilities model is to broadly assess potential revenues and major expenses from decentralized organic waste valorization operations, as a first step to investigate the feasibility of such an approach on a larger scale. Given the aim and limited scope of my research, the model represents a simplified and ‘idealized’ operation. This involved various simplifying assumptions, uncertainties, and potential omissions. It is therefore not meant to serve as a comprehensive business model, a full accounting of operational balance sheets, or a life cycle analysis of greenhouse gas emissions.

A key assumption related to the composting process is that the collected feedstock has an appropriate carbon-nitrogen ratio (C:N), with no additional bulking agents required throughout the decomposition process. In practice, to optimize pH, temperature, moisture content and C:N ratio during vermicomposting, bulking agents, such as spent brewers' grain, shredded paper, leaves, wood chips. wheat straw or cow dung should be added to nitrogen-heavy feedstock such as food waste (Suthar, 2009; Ravindran and Mnkeni, 2016; Piñero et al., 2020). Maintaining the optimal C:N ratio in a vermicompost through the addition of bulking agents has been shown to reduce GHG emissions (Lv et al., 2018) and to benefit the growth and reproduction of earthworms (Biruntha et al., 2020). Bulking agents are waste products themselves, which are generated continuously by industrial, commercial and institutional sources, and can therefore be easily and reliably obtained. Before setting up a vermicomposting operation, nearby generators of bulking material should first be identified as possible collaborators (for example, Madden et al. 2021 examine the spatial distribution of suburban yard and garden waste).

My spatial disaggregation method of the food waste produced by hotels and restaurants assumes that establishments within each category generate the same amount of waste. As hotels and restaurants can vary a great deal in size, a higher-resolution estimate to better capture the heterogeneity in waste distribution by these generators may have resulted in slightly different patterns in my raster map of food waste density. While I consider that sensitivity analysis beyond the scope of my study, it could be addressed through, for example, surveys of restaurants on their waste generation for refinement and validation, or through randomization of the input rasters to assess uncertainty.

I also assume that each facility picks up all the food waste generated within the collection area, which remains at a consistent level without any seasonal fluctuations. Each facility therefore continuously runs at full capacity, with a consistent output of end-products. Furthermore, pickups only occur on a weekly basis, which would likely be insufficient for many businesses, considering their large output of organic waste. However, more frequent pickups wouldn't largely impact the model, as several batch composters are required for the average volume processed by the facilities and could always be scaled down if necessary. The small transportation distance from the waste generators to each facility also ensures that labour and other costs wouldn't be significantly affected by more frequent pickups. Organic waste arriving in each facility is assumed to be ready to be introduced to the pre-composting vessels without any sorting or pre-treatment, which otherwise may lead to additional expenses.

In my model, ongoing expenses and investments scale linearly with operation size. In practice, however, as an operation increases in size, processes can be made more efficient which reduces labor costs and certain supplies, and machinery could be purchased discounted prices as their volume increases. This relationship between operational size and reduction in expenses, known as economies of scale, is a well-defined area of research in economics. However, calculating how expenses scale with operation size would require insight into the workload dynamics and the cost reduction of specific supplies when purchased in larger quantities. As the economics of vermicomposting is an area with little representation in the literature, this information could not be integrated into my study and any attempt of estimating these relationships would have introduced arbitrary dynamics into my model. I therefore assume labour hours and equipment purchase to scale linearly with the size of a facility and do not account for economies of scale. Only the miscellaneous investments in my model are relatively cheaper for larger operations, as these are assumed to be purchases necessary for each operation, independent of scale. Further simplifications in my calculations of expenses include that no maintenance costs for equipment are required, that the average expenses for utilities per unit area in the Canadian industry is representative of the costs associated with such an operation and that there are no potential regulatory hurdles to be considered, such as the purchase of permits or the adherence for quality or food safety standards.

My model simulations of GHG emissions should not be mistaken with a life cycle analysis of a vermicomposting facility, as I only accounted for the direct greenhouse gas outputs of landfilled and composted food waste as well as transport emissions to the landfill site. Emissions resulting from manufacturing of equipment, packaging material and shipping of the end-product as well as from energy consumption of each facility are therefore not included in the model (however as most electricity in Montreal is generated through hydroelectric power, the latter are likely to be negligible). With some of the potential non-local markets in Table 5.1, these could be substantial sources of emissions. Finally, my model doesn’t track emission of greenhouse gases over time, but instead assumes that all waste instantly releases its emission potential, whereas in reality, especially when landfilling food waste, GHGs are emitted over a long period of time (Cruz and Barlaz, 2010). To account for the abovementioned emissions factors, future research should involve a full life cycle analysis of environmental impacts, including life-cycle emissions, such as done by Saer and colleagues (2013) for food waste processing through windrow composting in the United States. A full emissions accounting with infrastructure requirements included might increase emissions in lower-density neighborhoods since the contribution to building composting facilities would increase.

Chapter 6: Summary and Concluding Remarks

Urban organic waste management is a problem facing many cities. Food waste that is landfilled represents a wasted resource that also contributes to climate change. Innovative and cost-efficient solutions can be adapted to the complex dynamics of the modern urban landscape. Small- to medium-sized vermicomposting operations, located in areas of high food waste output, have the potential to complement conventional, centralized waste management facilities by targeting sources of organic waste that may be difficult to manage through the conventional approach, namely the institutional, commercial, and industrial sector. Addressing such blind spots of organic waste management on the neighborhood level could carry multiple potential co-benefits, such as to: minimize transportation distances, increase resource use efficiency, reduce methane emissions, and create local business and employment opportunities. At the same time, while my model shows that this could be technically possible in the case of neighborhood vermicomposting, several logistical challenges and uncertainties remain, particularly for the potential beneficial re-use of the compost resources.

The first step in establishing a local organic waste management operation is finding an optimal site for a facility, which should take the availability of unrecovered organic waste as well as land value into account, to maximize the profitability of the operation. To this end, I created a relatively simple methodology for spatially disaggregating and identifying spatial patterns of organic waste in cities, based largely on publicly available and easily accessible data. My approach yields a visual representation of the relative magnitudes of generated (and unrecovered) food waste within a set of collection areas around discrete source locations within the city, highlighting the disproportionate contribution of some sources (e.g., supermarkets). Such maps could help municipalities to quickly identify strategic areas within the city that would benefit the most from localized organic waste recovery. Furthermore, my approach to comparing the distribution of unrecovered food waste with land value across the Island of Montreal offers a guide for decision-makers to easily locate sites that offer relatively high amounts of feedstock at relatively low rental rates, helping to maximize their profitability. To further contribute to this spatial prioritization of candidate sites for decentralized food waste management, future studies could focus on combining this information with the distribution of potential consumers of worm castings in Montreal, helping to ensure localized markets for vermicomposting operation. Such efforts would also be critical to creating a truly ‘circular economy’, for example, by co-locating urban vermicomposting with urban food production.

Through a systems model simulating decentralized vermicomposting operations, I demonstrated their economic feasibility and their carbon offset potential. My research is a first step in assessing the potential of such an approach, providing a proof of concept that may inspire further research in this area. More insight is required on the benefits and drawbacks of this approach to food waste management, to allow for a thorough assessment of whether a low-tech, decentralized system could in certain contexts be better suited than a highly efficient, centralized operation. Future work should dive deeper into the economics of decentralized vermicomposting operations, by investigating potential markets on different scales and suggesting a strategy towards developing local and regional markets for worm castings. Furthermore, such research could pave the way for future business ventures by developing a roll-out plan for a pilot facility, including a financing strategy that would identify potential start-up grants, government subsidies, and the potential for collaboration among key stakeholders. To provide deeper insight into the potential environmental benefits of a decentralized vermicomposting operation, a comprehensive life cycle analysis would have to be conducted, which would for instance include the emissions related to the production of equipment and the energy required to set up and operate such a facility. This data could then be compared to life cycle analyses conducted on large scale facilities, to allow for a comparative view between the two approaches.

My study investigated the potential of decentralized vermicomposting in the context of a high-income city in a northern climate. However, the relatively low cost and expertise required to set up and run such an operation may ultimately mean that this approach to organic waste management is even more relevant for urban environments in the Global South. As many cities in the Global South lack adequate organic waste management strategies, further studies should investigate the potential of decentralized vermicomposting in diverse lower-income urban contexts. Although several questions remain about the potential for vermicomposting and decentralized organic waste management in practice, my study suggests that these could be feasible as alternative approaches to organic waste management, particularly in contexts where there are ‘gaps’ in conventional approaches to organic waste management (such as in the case of Montreal) or barriers to capital-intensive centralized facilities.

References

Adi, A. J., & Noor, Z. M. (2009). Waste recycling: Utilization of coffee grounds and kitchen waste in vermicomposting. *Bioresource Technology*, 100(2), 1027-1030. AIM Environmental Group (2017). Calgary Organics Composting Facility. https://aimgroup.ca/calgary-organics-composting-facility/

Andrews, D. (2015). The circular economy, design thinking and education for sustainability. *Local Economy*, 30(3), 305-315.

Bernstad Saraiva Schott, A., Wenzel, H., & la Cour Jansen, J. (2016). Identification of decisive factors for greenhouse gas emissions in comparative life cycle assessments of food waste management – an analytical review. *Journal of Cleaner Production*, 119, 13-24. doi:10.1016/j.jclepro.2016.01.079

Biruntha, M., Karmegam, N., Archana, J., Selvi, B. K., Paul, J. A. J., Balamuralikrishnan, B., ... & Ravindran, B. (2020). Vermiconversion of biowastes with low-to-high C/N ratio into value added vermicompost. *Bioresource Technology*, 297, 122398.

Björklund, A., Dalemo, M., & Sonesson, U. (1999). Evaluating a municipal waste management plan using ORWARE. *Journal of Cleaner Production*, 7(4), 271-280.

Boruszko, D. (2016). Determining the Effectiveness in Vermicomposting of Sewage Sludges and the Attempt to Increase the Effectiveness by Applying Bacterial Microorganisms. *Journal of Ecological Engineering*, 17(3), 53-59. doi:10.12911/22998993/63482

Bruce, N., Asha, A. Z., & Ng, K. T. W. (2016). Analysis of solid waste management systems in Alberta and British Columbia using provincial comparison. *Canadian Journal of Civil Engineering*, 43(4), 351-360.

CBC News (2018, September 29). Ville Saint-Laurent residents raise a stink over composting centre project. *CBC News*. https://www.cbc.ca/news/canada/montreal/compost-centre-1.4844406

CBC News (2021, June 17). 5 composting plants promised in Montreal still not built more than a decade later as costs soar. *CBC News.* https://www.cbc.ca/news/canada/montreal/5-composting-plants-promised-in-montreal-not-built-1.6067973

CBC News (2021, March 24). Montreal expands reach of compost collection in effort to divert waste from landfills. *CBC News*. https://www.cbc.ca/news/canada/montreal/compost-collection-montreal-expansion-1.5962785

Centris (2021) https://www.centris.ca/en/commercial-properties~for-sale~montreal-island?view=Map

Cerciello, M., Agovino, M., & Garofalo, A. (2019). Estimating urban food waste at the local level: are good practices in food consumption persistent?. *Economia Politica*, 36(3), 863-886.

Champagne, J-M. (2018) HEC Montreal OP-19: Waste Minimization and Diversion. *AASHE*. Retrieved April 5, 2021 from stars.aashe.org

City of Montreal (2020). Bilan 2020 de la gestion des matières résiduelles de l'agglomération de Montréal.

City of Montreal (2021). Unités d'évaluation foncière. https://donnees.montreal.ca/ville-de-montreal/unites-evaluation-fonciere

CNESST (2021). Minimum wage. https://www.cnesst.gouv.qc.ca/en/working-conditions/wage-and-pay/wages/minimum-wage

Colón, J., Cadena, E., Pognani, M., Barrena, R., Sánchez, A., Font, X., & Artola, A. (2012). Determination of the energy and environmental burdens associated with the biological treatment of source-separated Municipal Solid Wastes. *Energy & Environmental Science*, 5(2), 5731-5741. doi:10.1039/C2EE01085B

Commission for Environmental Cooperation. Characterization and Management of Organic Waste in North America: Foundational Report. (2017). Retrieved from: http://www.cec.org/files/documents/publications/11771-characterization-and-management-organic-waste-in-north-america-foundational-en.pdf (accessed January 1, 2022).

Concordia Compost (2020). Concordia University waste data, compiled by Waste Not, Want Not. http://www.concordiacompost.ca/data/

Crippa, M., Solazzo, E., Guizzardi, D., Monforti-Ferrario, F., Tubiello, F. N., & Leip, A. J. N. F. (2021). Food systems are responsible for a third of global anthropogenic GHG emissions. *Nature Food*, 2(3), 198-209.

Cruz, F. B. D. L., & Barlaz, M. A. (2010). Estimation of waste component-specific landfill decay rates using laboratory-scale decomposition data. *Environmental Science & Technology*, 44(12), 4722-4728.

De Feo, G., Ferrara, C., Iuliano, C., & Grosso, A. (2016). LCA of the Collection, Transportation, Treatment and Disposal of Source Separated Municipal Waste: A Southern Italy Case Study. *Sustainability*, 8(11). doi:10.3390/su8111084

Décoste, M. (2019) Polytechnique Montreal OP-19: Waste Minimization and Diversion. AASHE. Retrieved April 5, 2021 from stars.aashe.org

Di Maria, F., & Micale, C. (2015). Life cycle analysis of incineration compared to anaerobic digestion followed by composting for managing organic waste: the influence of system components for an Italian district. *The International Journal of Life Cycle Assessment*, 20(3), 377-388.

Domingo, J. L., & Nadal, M. (2009). Domestic waste composting facilities: a review of human health risks. *Environment International*, 35(2), 382-389.

Dorward, L. J. (2012). Where are the best opportunities for reducing greenhouse gas emissions in the food system (including the food chain)? A comment. *Food Policy*, 37(4), 463-466. doi:10.1016/j.foodpol.2012.04.006

Edwards, C. A., Arancon, N. Q., & Sherman, R. L. (Eds.). (2011). Vermiculture technology: earthworms, organic wastes, and environmental management. *CRC Press*, Boca Raton, Fl. 623 pp.

Environment Canada. (2014). https://www.ec.gc.ca/gdd-mw/default.asp?lang=En&n=6F92E701-1

European Commission (EC). (2015) Communication from the Commission to the European Parliament, the council, the European economic and social committee and the committee of the regions. Com/2015/0614 final. Closing the loop - an EU action plan for the circular economy.

FAO, Assessing the Contribution of Bioeconomy to Countries' Economy (2018) www.fao.org/publications

Fattibene, D., Recanati, F., Dembska, K., & Antonelli, M. (2020). Urban Food Waste: A Framework to Analyse Policies and Initiatives. *Resources*, 9(9), 99.

Favoino, E., & Hogg, D. (2008). The potential role of compost in reducing greenhouse gases. *Waste Management & Research*, 26(1), 61-69.

Fernandez-Mena, H., Nesme, T., & Pellerin, S. (2016). Towards an Agro-Industrial Ecology: A review of nutrient flow modelling and assessment tools in agro-food systems at the local scale. *Science of the Total Environment*, 543, 467-479.

Ford, A. (1999). Modeling the environment: an introduction to system dynamics models of environmental systems. *Island press*. Washington DC.

Giusti, L. (2009). A review of waste management practices and their impact on human health. *Waste Management*, 29(8), 2227-2239.

Gooch M, Bucknell D, LaPlain D, Dent B, Whitehead P, Felfel, A, et al. The Avoidable Crisis of Food Waste: Technical Report; Value Chain Management International and Second Harvest. (2019). Retrieved from: https://www.secondharvest.ca/getmedia/58c2527f-928a-4b6f-843a-c0a6b4d09692/The-Avoidable-Crisis-of-Food-Waste-Technical-Report.pdf (accessed May 13, 2020).

Grard, B. J. P., Chenu, C., Manouchehri, N., Houot, S., Frascaria-Lacoste, N., & Aubry, C. (2018). Rooftop farming on urban waste provides many ecosystem services. *Agronomy for sustainable development*, 38(1), 1-12.

Green Mountain Technologies. (2021). Custom Stainless Steel CCS. Green Mountain Technologies. https://www.compostingtechnology.com/in-vessel-composting-systems/containerized-compost-systems/custom-stainless-containerized-compost-system/

Gyulai, L. (February 19, 2019). Contractors will keep revenue from $175M St-Laurent composting plant. *Montreal Gazette.* https://montrealgazette.com/news/local-news/st-laurent-composting-plant-cost-soars-again-contractors-will-keep-revenue-from-citys-organic-waste

Gyulai, L. (November 25, 2020). Pandemic delaying organic waste-treatment centres in Montreal. *Montreal Gazette*. https://montrealgazette.com/news/local-news/organic-waste-treatment-centres-in-montreal-delayed

Henriques, B. (August 15, 2019). Montreal unveils new organic waste treatment centre in bid to fight climate change. *Global News.* https://globalnews.ca/news/5771329/montreal-biomenthanization-composting-plant/

Hernandez, O. L., Calderín, A., Huelva, R., Martínez-Balmori, D., Guridi, F., Aguiar, N. O., ... & Canellas, L. P. (2015). Humic substances from vermicompost enhance urban lettuce production. *Agronomy for sustainable development*, 35(1), 225-232.

Intergovernmental Panel on Climate Change (IPCC), 2007. Climate Change 2007 – The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the IPCC. New York, Cambridge. <http://ipcc-wg1.ucar.edu/wg1/wg1-report.html> (retrieved 07.10.08).

Iota Communications. (2020, July 23). What Is The Average Utility Cost Per Square Foot Of Commercial Property? *IotaComm* https://www.iotacommunications.com/blog/average-utility-cost-per-square-foot-commercial-property/

isee Systems. (2018). STELLA–Systems Thinking for Education and Research.

Jensen, J., Christie, B., & Edwards, C.A. (2011). The commercial potential and economics of vermicomposting. In Edwards, C.A., Arancon, N.Q., & Sherman R. (Eds.), Vermiculture Technology: Earthworms, Organic wastes, and Environmental management (pp. 303–322), Boca Raton, FL: *CRC Press, Taylor & Francis Group*.

Kaza, S., Yao, L. C., Bhada-Tata, P., Van Woerden, F., (2018). What a Waste 2.0 : A Global Snapshot of Solid Waste Management to 2050. *Urban Development*;. Washington, DC: World Bank. https://openknowledge.worldbank.org/handle/10986/30317 License: CC BY 3.0 IGO.

Kjeldsen, P., Barlaz, M. A., Rooker, A. P., Baun, A., Ledin, A., & Christensen, T. H. (2002). Present and long-term composition of MSW landfill leachate: a review. *Critical Reviews in Environmental Science and Technology*, 32(4), 297-336.

Kontokosta, C. E., Hong, B., Johnson, N. E., & Starobin, D. (2018). Using machine learning and small area estimation to predict building-level municipal solid waste generation in cities. *Computers, Environment and Urban Systems*, 70, 151-162.

Kostecka, J., Garczyńska, M., Podolak, A., Pączka, G., & Kaniuczak, J. (2018). Kitchen Organic Waste as Material for Vermiculture and Source of Nutrients for Vermicompost Plants. *Journal of Ecological Engineering*, 19(6), 267-274. doi:10.12911/22998993/99691

Kummu, M., De Moel, H., Porkka, M., Siebert, S., Varis, O., & Ward, P. J. (2012). Lost food, wasted resources: Global food supply chain losses and their impacts on freshwater, cropland, and fertiliser use. *Science of the Total Environment*, 438, 477-489.

Leão, S., Bishop, I., & Evans, D. (2004). Spatial–temporal model for demand and allocation of waste landfills in growing urban regions. Computers, *Environment and Urban Systems*, 28(4), 353-385. doi:10.1016/s0198-9715(03)00043-7

Lou, X. F., & Nair, J. (2009). The impact of landfilling and composting on greenhouse gas emissions–a review. *Bioresource Technology,* 100(16), 3792-3798.

Lundie, S., & Peters, G. M. (2005). Life cycle assessment of food waste management options. *Journal of Cleaner Production*, 13(3), 275-286.

Lv, B., Zhang, D., Cui, Y., & Yin, F. (2018). Effects of C/N ratio and earthworms on greenhouse gas emissions during vermicomposting of sewage sludge. *Bioresource Technology*, 268, 408-414.

Madden, B., Florin, N., Mohr, S., & Giurco, D. (2021). Spatial modelling of municipal waste generation: Deriving property lot estimates with limited data. *Resources, Conservation and Recycling*, 168, 105442.

Malmir, T., Ranjbar, S., & Eicker, U. (2020). Improving Municipal Solid Waste Management Strategies of Montréal (Canada) Using Life Cycle Assessment and Optimization of Technology Options. *Energies*, 13(21), 5701.

Manaugh, K., & El-Geneidy, A. (2011). Validating walkability indices: How do different households respond to the walkability of their neighborhood?. *Transportation Research part D: Transport and Environment*, 16(4), 309-315.

Masullo, A. (2017). Organic wastes management in a circular economy approach: Rebuilding the link between urban and rural areas. *Ecological Engineering*, 101, 84-90.

Metson, G. S., & Bennett, E. M. (2015). Phosphorus cycling in Montreal's food and urban agriculture systems. *PLoS One*, 10(3), e0120726.

Mohareb, E., Heller, M., Novak, P., Goldstein, B., Fonoll, X., & Raskin, L. (2017). Considerations for reducing food system energy demand while scaling up urban agriculture. *Environmental Research Letters*, 12(12), 125004.

Morseletto, P. (2020). Targets for a circular economy. *Resources, Conservation and Recycling*, 153, 104553.

Mu, D., Horowitz, N., Casey, M., & Jones, K. (2017). Environmental and economic analysis of an in-vessel food waste composting system at Kean University in the US. *Waste management*, 59, 476-486.

Olson. J (2010). The neighbourhood unit: How does concept apply to modern day planning. *Texas : EVstudio Colorado & Texas Architects & Engineers*.

OpenStreetMap contributors. (2020) Planet dump 2020. Retrieved from https://planet.openstreetmap.org

Pai, S., Ai, N., & Zheng, J. (2019). Decentralized community composting feasibility analysis for residential food waste: A Chicago case study. *Sustainable Cities and Society*, 50. doi:10.1016/j.scs.2019.101683

Papargyropoulou, E., Lozano, R., Steinberger, J. K., Wright, N., & bin Ujang, Z. (2014). The food waste hierarchy as a framework for the management of food surplus and food waste. *Journal of Cleaner Production*, 76, 106-115.

Parsaeifard, N., Sattler, M., Nasirian, B., & Chen, V. C. (2020). Enhancing anaerobic oxidation of methane in municipal solid waste landfill cover soil. *Waste Management*, 106, 44-54.

Payworks. (2021, December 30). Payroll Legislation - Minimum Wage. *Payworks*. https://www.payworks.ca/payroll-legislation/MinimumWage.asp

Pii, Y., Mimmo, T., Tomasi, N., Terzano, R., Cesco, S., & Crecchio, C. (2015). Microbial interactions in the rhizosphere: beneficial influences of plant growth-promoting rhizobacteria on nutrient acquisition process. A review. *Biology and Fertility of Soils*, 51(4), 403-415. doi:10.1007/s00374-015-0996-1

Piñero, J. C., Shivers, T., Byers, P. L., & Johnson, H. Y. (2020). Insect-based compost and vermicompost production, quality and performance. *Renewable Agriculture and Food Systems*, 35(1), 102-108.

Prieto-Sandoval, V., Jaca, C., & Ormazabal, M. (2018). Towards a consensus on the circular economy. *Journal of Cleaner Production*, 179, 605-615.

Ravindran, B., & Mnkeni, P. N. S. (2016). Bio-optimization of the carbon-to-nitrogen ratio for efficient vermicomposting of chicken manure and waste paper using Eisenia fetida. *Environmental Science and Pollution Research*, 23(17), 16965-16976.

Righi, S., Oliviero, L., Pedrini, M., Buscaroli, A., & Della Casa, C. (2013). Life cycle assessment of management systems for sewage sludge and food waste: centralized and decentralized approaches. *Journal of Cleaner Production*, 44, 8-17.

Rosik-Dulewska, C., Ciesielczuk, T., Karwaczyńska, U., & Gabriel, H. (2014). The influence of red worms (E. Foetida) on compost's fertilizing properties. *Journal of Ecological Engineering*, 15(2).

Roy, E. D. (2017). Phosphorus recovery and recycling with ecological engineering: A review. *Ecological Engineering*, 98, 213-227.

Saer, A., Lansing, S., Davitt, N. H., & Graves, R. E. (2013). Life cycle assessment of a food waste composting system: environmental impact hotspots. *Journal of Cleaner Production*, 52, 234-244.

Scheuerell, S., & Mahaffee, W. (2002). Compost tea: principles and prospects for plant disease control. *Compost Science & Utilization*, 10(4), 313-338.

Sims R., Schaeffer R., Creutzig F., Cruz-Núñez X., D'Agosto M., Dimitriu D., Figueroa Meza M.J., Fulton L., Kobayashi S., Lah O., McKinnon A., Newman P., Ouyang M., Schauer J.J., Sperling D., and Tiwari G., (2014). Transport. In: Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Edenhofer, O., R. Pichs-Madruga, Y. Sokona, E. Farahani, S. Kadner, K. Seyboth, A. Adler, I. Baum, S. Brunner, P. Eickemeier, B. Kriemann, J. Savolainen, S. Schlömer, C. von Stechow, T. Zwickel and J.C. Minx (eds.)].

Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Singh, S. (2020). Decentralized solid waste management in India: A perspective on technological options. *New Delhi: National Institute of Urban Affairs*, 290-304.

Sironi, S., Capelli, L., Centola, P., Del Rosso, R., & Grande, M. I. (2007). Continuous monitoring of odours from a composting plant using electronic noses. *Waste Management*, 27(3), 389-397.

Slorach, P. C., Jeswani, H. K., Cuéllar-Franca, R., & Azapagic, A. (2020). Assessing the economic and environmental sustainability of household food waste management in the UK: Current situation and future scenarios. *Science of The Total Environment*, 710, 135580.

Smet, E., Van Langenhove, H., & De Bo, I. (1999). The emission of volatile compounds during the aerobic and the combined anaerobic/aerobic composting of biowaste. *Atmospheric Environment*, 33(8), 1295-1303.

Solinov (2012). Étude du potentiel des matières organiques en provenance des secteurs industriel, commercial et institutionnel (ICI) à être valorisées dans les centres de traitement de l'agglomération de Montréal.

Soobhany, N., Mohee, R., & Garg, V. K. (2015). Recovery of nutrient from Municipal Solid Waste by composting and vermicomposting using earthworm Eudrilus eugeniae. *Journal of Environmental Chemical Engineering*, 3(4), 2931-2942.

Statistics Canada. (2016). Census Profile, 2016 Census. https://www12.statcan.gc.ca/census-recensement/2016/dp-pd/prof/index.cfm?Lang=E

Statistics Canada. (2018). Disposal of waste, by source. https://www150.statcan.gc.ca/t1/tbl1/en/tv.action?pid=3810003201.

Statistics Canada. (2021). Electric power, annual generation by class of producer. https://www150.statcan.gc.ca/t1/tbl1/en/tv.action?pid=2510002001&pickMembers%5B0%5D=1.6&pickMembers%5B1%5D=3.2&cubeTimeFrame.startYear=2016&cubeTimeFrame.endYear=2020&referencePeriods=20160101%2C20200101

Suthar, S. (2009). Vermicomposting of vegetable-market solid waste using Eisenia fetida: Impact of bulking material on earthworm growth and decomposition rate. *Ecological Engineering*, 35(5), 914-920. doi:10.1016/j.ecoleng.2008.12.019

Świątek, J., Spitzer, T., Grobelak, A., & Kacprzak, M. (2019). Effects of Biochar Addition on Vermicomposting of Food Industry Sewage Sludge. *Journal of Ecological Engineering*, 20(3), 36-45. doi:10.12911/22998993/97242

Taşkın, A., & Demir, N. (2020). Life cycle environmental and energy impact assessment of sustainable urban municipal solid waste collection and transportation strategies. *Sustainable Cities and Society*, 61, 102339.

Pleissner, D. (2016). Decentralized utilization of wasted organic material in urban areas: a case study in Hong Kong. *Ecological Engineering*, 86, 120-125.

Thomas, A. R., Arulraj, P. R., Kranert, M., & Philip, L. (2020). Investigation on greenhouse gas emissions and compost dynamics during in-vessel co-composting of septage and mixed organic wastes.

International Journal of Environmental Science and Technology, 17(3), 1675-1690. doi:10.1007/s13762-019-02450-z

Tominac, P., Aguirre-Villegas, H., Sanford, J., Larson, R., & Zavala, V. (2020). Evaluating landfill diversion strategies for municipal organic waste management using environmental and economic factors. *ACS Sustainable Chemistry & Engineering*, 9(1), 489-498.

UN, G. A. (2015). General Assembly Resolution 70/1: Transforming our world: the 2030 Agenda for Sustainable Development.

United Nations Environment Programme (UNEP). (2021). Food Waste Index Report 2021. Nairobi.

U.S. Environmental Protection Agency OLEM. (2017). Food recovery hierarchy. Accessed April 11, 2022 from https://www.epa.gov/reducefoodwaste/food-recovery-hierarchy

Université de Montréal (n.d.). Compostage. Université de Montréal. Retrieved April 5, 2021 from durable.umontreal.ca

van der Werf, P., Larsen, K., Seabrook, J. A., & Gilliland, J. (2020). How neighbourhood food environments and a pay-as-you-throw (payt) waste program impact household food waste disposal in the city of Toronto. *Sustainability*, 12(17), 7016.

Vodounnou, D. S. J. V., Kpogue, D. N. S., Tossavi, C. E., Mennsah, G. A., & Fiogbe, E. D. (2016). Effect of animal waste and vegetable compost on production and growth of earthworm (Eisenia fetida) during vermiculture. *International Journal of Recycling of Organic Waste in Agriculture*, 5(1), 87-92. doi:10.1007/s40093-016-0119-5

Von Massow, M., Parizeau, K., Gallant, M., Wickson, M., Haines, J., Ma, D. W., ... & Duncan, A. M. (2019). Valuing the multiple impacts of household food waste. Frontiers in nutrition, 6, 143. Ward, A. J., Hobbs, P. J., Holliman, P. J., & Jones, D. L. (2008). Optimisation of the anaerobic digestion of agricultural resources. *Bioresource Technology*, 99(17), 7928-7940.

Warshawsky, D. N. (2015). The devolution of urban food waste governance: Case study of food rescue in Los Angeles. *Cities*, 49, 26-34.

Wilson, D. C., Rodic, L., Scheinberg, A., Velis, C. A., & Alabaster, G. (2012). Comparative analysis of solid waste management in 20 cities. *Waste Management & Research*, 30(3), 237-254.

Win, S. S., Hegde, S., Chen, R. B., & Trabold, T. A. (2017, June). Feasibility assessment of low-volume anaerobic digestion systems for institutional food waste producers. In *Energy Sustainability* (Vol. 57595, p. V001T02A003). American Society of Mechanical Engineers.

World Bank. (December 16, 2021). Canada: Degree of urbanization from 2010 to 2020 [Graph]. In Statista. Retrieved January 11, 2022, from https://www.statista.com/statistics/271208/urbanization-in-canada/

Xue, L., Liu, G., Parfitt, J., Liu, X., Van Herpen, E., Stenmarck, Å., ... & Cheng, S. (2017). Missing food, missing data? A critical review of global food losses and food waste data. *Environmental Science & Technology*, 51(12), 6618-6633.

Yilmaz, M., Tinjum, J. M., Acker, C., & Marten, B. (2021). Transport mechanisms and emission of landfill gas through various cover soil configurations in an MSW landfill using a static flux chamber technique. *Journal of Environmental Management*, 280, 111677.

Zeller, V., Towa, E., Degrez, M., & Achten, W. M. (2019). Urban waste flows and their potential for a circular economy model at city-region level. *Waste Management*, 83, 83-94.