Transforming trash: reuse as a waste management and climate change mitigation strategy

By

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A dissertation submitted in partial satisfaction of the
requirements for the degree of
Doctor of Philosophy
in
Energy and Resources
in the
Graduate Division
of the
University of California, Berkeley

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Fall 2011

Abstract

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Waste reflects the culture that produces it and affects the health of the people and environment surrounding it. As urbanization and waste production increase on a global scale, cities are faced with the challenge of how to manage their waste effectively to minimize its negative impacts on public and environmental health. Using waste as a resource can offer a variety of environmental benefits, including climate change mitigation, though these benefits are variable and uncertain. My work begins with an overview of the relationship between solid waste and the environment, focusing on two trends over time and space: regionalization and formalization of waste management. Recognizing that appropriate waste management must be determined locally, I then focus on two places, one in the Global North, and one in the Global South, whose waste production and management differ tremendously, and quantify the climate benefits from reuse strategies at different scales using life-cycle assessment (LCA). In California, USA, where waste production and access to technology are abundant, I ask: how can the state minimize the greenhouse gas (GHG) emissions from its municipal waste management? I conclude that source reduction and anaerobic digestion are the methods by which CA could most greatly and robustly reduce its waste emissions. I also find that waste LCA results are very sensitive to model assumptions, about system boundary, landfill behavior, and electricity generation, though the emissions from source reduction are robust to these inputs. In Bogotá, Colombia, where the municipal government is in the process of modernizing their recycling system, I ask: what are the GHG emission implications of this modernization? I find that the unregulated recycling system is more financially sustainable, more socially inclusive, and abates more greenhouse gas emissions than does the municipal system. The municipal system, on the other hand, conforms to aesthetic visions of a modern city, and provides workers with steady employment and benefits. A hybrid model could combine the incentives and efficiency of the informal system with the working conditions of the municipal one. In Bogotá and in California, modes of reuse – technologies or behaviors that use waste as a resource – offer waste management, environmental and climate benefits.

To my family.

To my father, for your tireless work to protect our planet, for encouraging my pursuit of interesting questions, and for believing I could do anything;
To my brother, for being a positive, brilliant force in the world, for your life-long friendship, and your curiosity;
To my mother, my inspiration and my best friend, for your commitment to love, truth, and justice.

Acknowledgements.

I feel very fortunate to have so many people to thank.

First of all, I want to thank my family, for a wonderful life filled with love and support. Thank you to Martha and Tony, my second set of parents, for always leading by example and working towards a better world. Thank you, Pepe, for your love, for the beautiful yesterdays and the tomorrows to come. And Mariana, thanks for helping to make these years in Berkeley so lovely and so magical. And to all my friends, family, and colleagues: thank you for making this world more beautiful and more interesting.

I want to thank the Energy and Resources Group, students and faculty, for this unparalleled intellectual community. What a tremendous gift and opportunity it has been to be among you for 6 years. Special thanks go to:

- Stacy Jackson, for our weekly swims and the beautiful friendship that arose from them. You are an inspiration!
- Malini Ranganathan, Anne Short, and Ashley Murray, for being model citizens, scholars, and women.
- Isha Ray, for your guidance, generosity, and wit.
- Alex Farrell, for encouraging my love of garbage, and for instilling in me principles of honest and effective scholarship.
- Derek Lemoine, for broadening my academic horizons and always challenging me.
- Josh, for the pranting (!), adventures, and friendship, and the Aptes, for sharing with me their cabin in the woods, where I prepared for my oral exams and wrote the final chapter of this dissertation.
- Kevin and Andy for our writing group.
- Niels, Pants, and Christian, for great friendships, backpacking trips, and conversations.

I'd like to thank my committee – Kara Nelson, Arpad Horvath, Mike O'Hare, George Tchobanoglous – for your feedback, encouragement, and guidance.

I also received wonderful research support from collaborators in Denmark and in Colombia. Special thanks to Anders Damgaard, Daniel Gomez, Marco Tulio Espinosa, Asociación de Recicladores de Bogotá, Silvio Ruiz Grisales, and many workers in the recycling chain who shared their time and stories with me.

I am also grateful for generous funding from the National Science Foundation Graduate Research Fellowship, the Institute for International Studies (Simpson Fellowship), the US Student Fulbright Fellowship, the University of California Berkeley's Chancellor's Fellowship, Partners of the Americas Climate Change Fellowship, and the Fernström Fellowship.

"The consumption of soap and paper, the quantity of letters exchanged, the extension of public libraries and the use made of them etc are often taken as a measure of the actual degree of civilization of a nation. An extensive and refined use made of the waste materials of industry and housekeeping might be considered with equal right as the measure of the degree of industrial development and capability."

- Regnier Ferdinand von Habsburg, 1876 (As quoted in Desrochers, 2002)

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Introduction.

Waste, a symbol of wealth and modernity, reflects the culture that produces it and affects the health of the people and environment surrounding it. As urbanization and waste production increase on a global scale (UNH 2010; Cohen 2004), cities are faced with the challenge of how to manage their waste effectively to minimize its negative impacts on public and environmental health. Cities may manage waste by containing it, and thereby minimize its impact on the surroundings, or they may seek to maximize its benefits by reusing waste, through material recycling, energy production, composting, or direct reuse. Using waste as a resource offers a variety of environmental benefits, including climate mitigation, though these have not been well quantified (Bogner et al. 2007). This dissertation aims to explore opportunities for reuse-centered waste management, and quantify the benefits of doing so.

Though the environmental and social impacts of waste production and consumption are far-reaching, this work focuses on the relationship between waste management and climate change for three reasons. First, the need to avert disastrous climate change is urgent (IPCC 2007) and requires greenhouse gas (GHG) emission reductions from all sectors of the global economy. Second, carbon flows can be an indicator of environmental performance. Well-managed waste management systems are likely to emit fewer greenhouse gases than are poorly-managed ones, and they may even act as a GHG sink. Reduction of GHGs from waste systems is correlated with reduced energy production, reduced uncontrolled dumping and burning, and increased beneficial use of waste. Finally, carbon is a widely used metric to classify the environmental impact of systems, and this facilitates their comparison.

Though there are global trends in waste production, managing waste is a locally-specific challenge; appropriate methods to handle waste depend on the context of a place. As such, this work begins with a large-scale view of waste, and then zooms in on two locales, differing in scale, culture, wealth and technological context, and analyzes opportunities for effective waste management and climate mitigation. In the first chapter, I provide a global overview of the environmental impact of waste production and management, highlighting cross-cutting trends in waste generation – increasing quantities and complexities – and management – increasing formalization and regionalization. The second chapter focuses on California. Illustrative of many high waste-producing regions, the state manages waste in a highly technological way, and at a regional scale. Further, the public is willing to take bold action on the environment, so it is a place where it is feasible to implement innovative waste solutions. In this representative region of the Global North, I ask: *How can California mitigate the GHG emissions from its waste sector?* The third and fourth chapters are devoted to the recycling system in Bogotá, Colombia. This capital city is emblematic of many developing cities, in its growing population and consumption, its municipal management of waste, and its attempts to formalize its very active unregulated recycling sector. I explore the implications of Bogotá's plan to 'modernize' its recycling system. Specifically, these chapters ask the following: *what are the environmental and* *social trade-offs of replacing unregulated recycling with a municipal recycling system? What are the greenhouse gas benefits of municipal versus unregulated recycling in Bogotá?*

Throughout this work, I home in on policy and methodological gaps in the literature. The second chapter aims to help guide solid waste management policy in California by analyzing waste treatment scenarios for their climate mitigation potential, and to explore uncertainties in solid waste life-cycle assessment (LCA) methodology used to analyze alternative management strategies. The third and fourth chapters address a dearth of quantitative research on the environmental services provided by the informal sector in the Global South (Gutberlet 2008). In seeking to understand the functioning of the unregulated recycling sector in Bogotá, I provide a set of methods with which others can perform similar analyses, and also provide data to cities that are increasingly choosing to formalize their waste management systems.

Chapter 1. Municipal Solid Waste and the environment: a global perspective

1. Introduction

The production of solid waste is an inevitable consequence of human activity, and its management directly impacts the health of the people and environment surrounding it. Though widely understood as a concept, waste – garbage, rubbish, discards, junk – eludes definition, varying by who is defining it. Engineers define Municipal Solid Waste (MSW) as materials that are discarded from residential and commercial sources (Williams 2005; Tchobanoglous and Kreith 2002), or as materials that have ceased to have value to the holder (McDougall, 2001). Anthropologists hold that garbage is factual evidence of a culture, that "what people have owned – and thrown away – can speak more eloquently, informatively, and truthfully about the lives they lead than they themselves ever may" (Rathje 1994, p. 54). Ecologists claim that there is no waste in nature (McDonough 2002), and Supreme Court Justice Sutherland proclaimed, presaging Industrial Ecological views, in 1926 that waste "may be merely a right thing in a wrong place, like a pig in the parlor instead of the barnyard" (Desrochers, 2002). How waste is treated reflects its definition; refuse workers in hauling waste to a landfill treat it as valueless, and waste pickers who recover materials from refuse treat it as ore (Assaad 1996). Whichever conception of waste one subscribes to, the world's waste generation rate has dramatically increased since the Industrial Revolution, and is now faced with the challenge of managing it.

Post-consumer waste, through its production and management, affects air quality, water quality, public health, and is an emerging contributor to climate change. Improperly managed waste can affect the environment at different scales. Open dumping of wastes directly contaminates nearby water bodies with toxic chemicals and heavy metals, and poses a threat to public health by attracting disease vectors and exposing people living near the waste to the harmful products within. Incineration of waste in the absence of air pollution control technologies emit a variety of pollutants, including dioxins and furans, persistent organic pollutants that mix globally, and negatively affect human and ecological health. Waste management also emits a variety of greenhouse gases – most notably methane from decomposing organic waste – that contribute to global climate change. Current estimates hold that waste management emits 5% of global GHG emissions, but this estimate is uncertain, and apt to change, as waste management can act as either a contributor of GHGs or a sink (Bogner et al. 2007). Because waste poses a threat to people and the environment, provision of waste management services has often fallen to cities, which are charged with providing public goods to their citizens. Global trends in waste production – the increasing quantity and complexity of Municipal Solid Waste – compound the challenge, making waste management "one of the biggest challenges of the urban world" (Chaturvedi, UNH 2010, 1).

Demographic changes are concentrating waste in cities. Increases in waste production are associated with a growth in wealth, urbanization, and population (Tchobanoglous and Kreith, 2002; Johnstone and Labonne 2004; Bogner et al. 2007). While the global population is on the rise, the distribution of the population is changing more dramatically. The world is urbanizing at a rapid and unprecedented scale, and most of this urbanization is occurring in small and medium sized cities within low-income nations (Cohen 2004). The same areas that are seeing the greatest urbanization trends are home to a billion "new consumers" – people from 20 developing and transition nations whose combined spending capacity equals that of the US (Myers and Kent 2003). This newly-affluent population is rapidly increasing their consumption of meat, cars – the cars owned in the Global South grew 89% from 1990 to 2000, with China's fleet increasing 445% and Colombia's 217% – electricity, and other consumer goods (Myers and Kent 2003). Along with an increase in consumption come an increase in use of natural resources to produce those goods, and an increase in the waste that must be managed at their end-of-life.

Cities and their citizens use a number of technologies, policies and behaviors to control the negative impacts of their waste, and to find beneficial reuses for it. This combination of methods comprises waste management, which can be broken down into six functional elements: waste generation, waste handling at the source, collection, transport, processing and transformation, and disposal (Tchobanoglous and Kreith 2002). These elements describe the path that waste takes, from creation to disposal. Though the particular activities take different forms in different parts of the world, the elements are universal. Following waste generation, waste is handled by the source. This may be comprised of placing the waste in a receptacle, or separating waste into like components. The waste may then be a collected, by a formal or informal actor, and transported to another site, where it may be processed and transformed into new products. Transformation can take many forms. For example, organic waste can be converted to energy via anaerobic digestion, to a liquid fuel via biochemical pathways, to humus via composting, or it can be used directly as feed for animals or applied to agricultural fields. Any waste remaining, or that is not processed into another product, is then disposed, in a controlled or uncontrolled manner.

Since the early 1990s, the "waste hierarchy" has guided waste management policy by defining which waste management technologies should be used preferentially. From most to least environmentally friendly, the hierarchy lists: waste reduction, reuse, recycling & composting, energy recovery (within which combined heat and power is the most preferable, followed by incineration, then landfill gas combustion), and landfilling (Williams 2005). More recently, this hierarchy has been critiqued because of the lack of scientific basis of the ordering, and its failure to address differing costs of the technologies. Additionally, the hierarchy is difficult to implement, as most waste management plans use a combination of technologies. The most resounding critique is that it is intended as a universal guideline, and does not account for specific local situations, which are likely to affect which technologies are appropriate and preferable (McDougall 2001).

In a very different approach to guiding waste management decisions, Integrated Waste Management (IWM) has emerged as a set of principles by which to handle waste in an environmentally and economically sustainable, socially acceptable manner (McDougall 2001). It is "integrated" because it advocates a holistic view of waste that includes all waste flows in society, and aims to control all attending solid, liquid and gaseous emissions. An IWM system is not uniform; it is characterized by flexibility, and specificity to local conditions. Because of this, IWM does not prescribe solutions; rather, it holds principles and characteristics that allow different locales to develop their own systems in response to their contexts. The establishment of Integrated Waste Management systems is a goal for most cities (McDougall 2001).

2. Solid Waste: Composition, Quantities, and Variability

2.1. Quantities and Composition

Two billion tonnes of Municipal Solid Waste were discarded worldwide in 2006, and forecasts predict a 36% increase by 2011 (UNH 2010). Though a number of studies cite alarmist numbers about the rise of solid waste production, few recognize that these numbers are highly uncertain. The production of waste varies in space and with time. The quantity and composition of what people throw away varies with income, climate, demographics, culture, and technology. As people gain wealth, they tend to throw more away, and what they throw away contains materials that are more complex (Bogner et al. 2007, Johnstone and Labonne 2004; Kinnaman 2009, Zhen-Shen 2009, Gomez 2009). For these reasons, waste characteristics vary greatly between cities, with industrialized cities tending to throw away greater quantities of waste, which tends to contain more recyclable goods and electronics (Dangi 2011), and industrializing cities discarding less, and with high biodegradable fractions in their waste (UNH 2010). Local climatic conditions also affect the nature of waste. In Bamako, Mali, for example, almost 50% of municipal waste is dirt and sand, because of its proximity to the desert. MSW generation rates for a selection of the world's cities are illustrated in Figure 1, and Figure 2 shows waste composition for those cities. Figure 1 is a plot of waste production versus the Human Development Index (HDI), which is a comparative measure of well-being for nations and cities, calculated by the United Nations Development Program. This indicator uses measures like literacy and life expectancy to give an overall assessment of a place's "development." These data were taken from a single source, for which a consistent definition of MSW was applied: it includes all commercial and household waste, excludes wastewater, industrial and construction waste (UNH 2010).

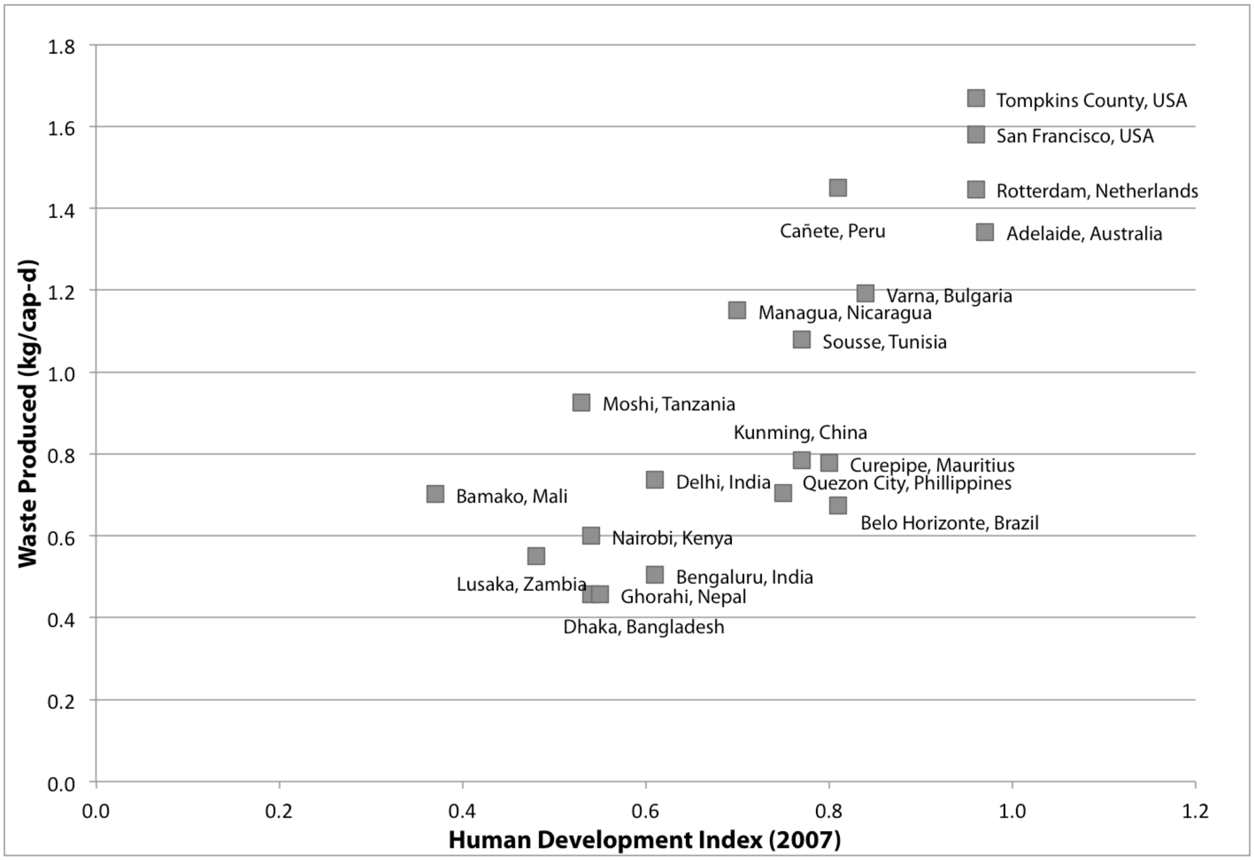

Figure 1: Per capita waste generation rates versus Human Development Index for 20 selected cities. Data from UNH (2010).

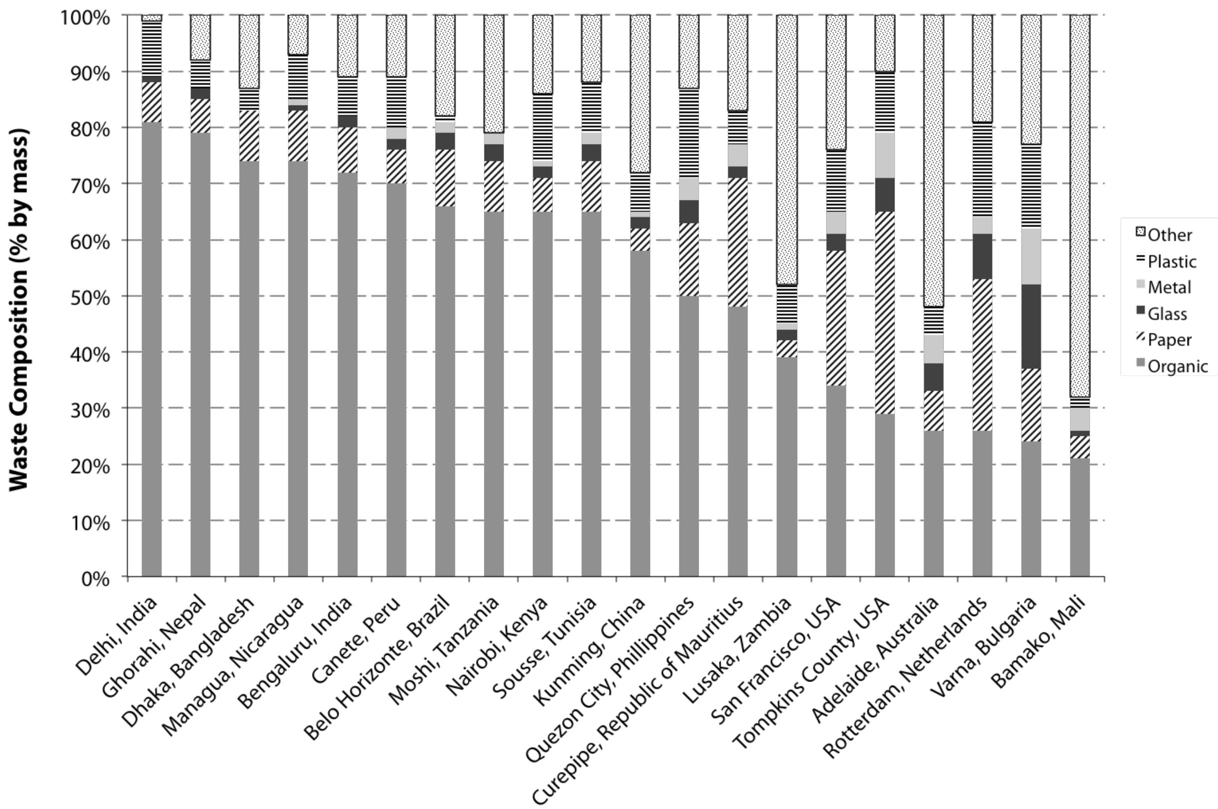

Figure 2: Waste composition for 20 selected cities. Data from UNH (2010).

Some general trends between cities and their waste characteristics are evident in Figures 1 and 2. The more wealthy and "developed" a city is, the more waste it produces. Poorer nations tend to have higher organic fractions in their waste, and richer cities tend to have more complex waste compositions. The World Bank's forthcoming report "What a waste" provides a broad overview of waste production, and characterizes waste production by region. Though these estimates are likely uncertain, given the variability in waste composition and generation, and the large areas over which these estimates are given, they provide a first-order estimate of regional differences in waste production.

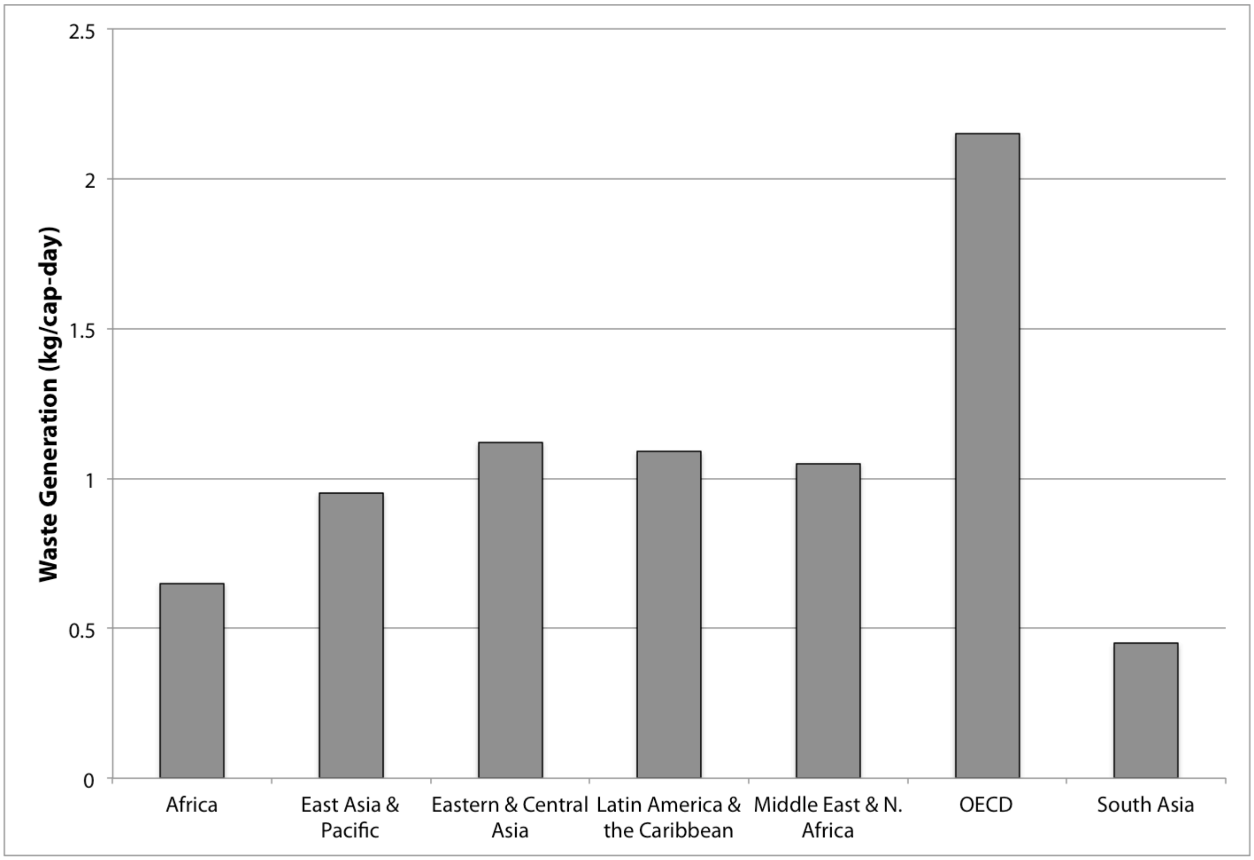

Figure 3: Waste generation per-capita by regions of the world show great differences. Data from World Bank (2011).

In Figure 3, we can observe that the wealthiest nations – the OECD – produce far more waste than do other regions, creating four times more waste than African and South Asian consumers, and about twice as much waste as the rest of the world.

2.2. Variability

Not only does waste vary between cities, it varies within a city over time. Over a short time scale, waste characteristics tend to vary seasonally, with quantity and composition changing over the course of the year (see Gomez et al. 2009). Over a longer time frame, waste discarded by citizens reflects technological and cultural trends. In a unique study, Walsh (2002) examined changes in waste composition in New York City over a century, and is able to identify telling trends. Until 1950, ash was the most abundant material found in Municipal Solid Waste, because most homes burned coal for heating and cooking. Glass entered the waste stream after the 1960s, when non-returnable glass and steel containers took the place of refillable glass bottles. Plastics appeared in the waste stream in 1971 (Walsh 2002).

More recently, global consumers have adopted a great range of electronic products, which has led to a great increase of e-waste (Casanova in UNH 2010). In Nigeria, for example, the proliferation of cell phones has led people to discard their landlines (Nnorom and Osibanjo 2008). In the United States, consumers rapidly adopt technological changes in televisions, computers, and cell phones. Of the 2.25 million tonnes of e-waste produced in 2007, American consumers stored 75% of their 'obsolete' electronics in their home, sent 18% to be recycled, and the rest was disposed in landfills (Wagner 2009). The penetration of electronic goods in Latin America is nearly as high as that of industrialized nations (Silva 2008). Globally, 4000 tonnes of e-waste are discarded per hour, and the majority (80%) is sent to Asia for processing. Ninety percent of the electronic waste sent to Asia goes to China. Though China is the global receiver of e-waste, it is also emerging as a major consumer, with its own e-waste production increasing 14% per year (Ongondo 2011).

2.3. Uncertainty and Data Quality

Comparing waste characteristics between cities is very difficult, due to variability, measurement difficulties, and differing definitions of waste. Waste is dynamic; it varies over time (seasonally and decadally), and between cities (due to cultural, economic, climatic factors; den Boer 2010). But additional to natural variation, the absence of regularly collected data and the lack of a universal standard for the definition and measurement procedures for MSW make our knowledge of waste characteristics highly uncertain. There is no universal definition for MSW; though most include household and commercial waste, some cities include street sweepings and industrial waste in their definition, some measure at the point of disposal, and some measure at the point of generation. Nor do cities follow a standard method for measuring composition, so two identical samples can be analyzed using different methods, and each can receive a different estimate for its composition (Lebersorger and Schneider 2011b). The lack of a global database on waste production, using a harmonized definition of waste, is a key gap in the literature (McDougall 2001; Beede and Bloom 1995).

The solid waste data that do exist are unreliable. Waste data are often outdated, estimated, or inaccessible (UNH 2010). While data quality on solid waste for the world's wealthiest nations is quite good, due to standard definitions and regular bookkeeping from the OECD (OECD 2008), there is no such centralized trove of data for the developing world. UN-Habitat's 2010 book, "Solid waste management in the world's cities," provides an excellent overview of the state of solid waste in the Global South, and collected uniform data and lessons learned from 20 cities. Generally, solid waste data in the developing world, if it exists, comes from each municipality, or an academic study focused on that area. Within the academic community, there is a notable lack of data from Africa, though three recent works aim to fill that gap (Couth and Trois 2010, Couth and Trois 2011, Friedrich 2011), an increased attention on Asia, especially on China and India, and a focus on urban areas. Waste generation is lower and more disperse in rural areas, so it is even harder to track. Finally, informal uses of waste often go unreported, so these 'system losses' are either absent or unexplained in cities' waste databases (UNH 2010).

2.4. Variability in waste management

Concurrent with local variation in waste characteristics, each location employs a variety of waste treatment methods, ranging from low to high technological treatment. Generally, higher income cities have access to and employ more technological methods for waste management – mechanized collection, separation, and treatment – where lower income cities tend to rely on higher labor, lower technology options. Open dumping is a common waste management method in the Global South, and landfilling is the most prevalent waste technology worldwide (World Bank 2011).

The growing complexity of MSW challenges historical waste management methods. In Bamako, Mali, organic waste is applied directly to agricultural fields, closing the cycle from production to consumption with only one step. "Today, increasing amounts of plastics – many related to the practice of packing water in small 'pillows,' which did not exist in 2002 – makes this practice an increasing problem for the environment" (UNH 2010 p. 126). Similarly, many rural homes have historically buried or burned their trash, a treatment that is mostly benign for organic waste, but creates toxins when the waste contains heavy metals or plastics. The household's ability to safely manage its own waste declines as the waste becomes more complex.

3. Evolution of solid waste management

3.1. Drivers in waste management development

Wilson (2007) identifies four imperatives that drive the development of waste management plans: public health, environmental protection, resource recovery, and climate change. Any combination of drivers may be motivating changes in a city's waste management, at any given time, though the dominant driver tends to change over time. Public health tends to be the motivating factor in development of waste policies in places where little waste management infrastructure exists. Waste is commonly dumped in an uncontrolled manner in Haiti, creating a public health hazard, and motivating change (Bras 2009). Health concerns are important drivers in places that have low levels of safe disposal, such as China (Chen 2010). In extreme cases, public health calamities have driven important changes in waste management. The spread of disease in Surat, India, after uncollected waste clogged drains and contributed to flooding, sparked widespread public interest in improving waste management. Similarly, a landslide at the Payatas dump in Quezon City in the Philippines led to improvements in their waste management (UNH 2010).

Environmental protection as a driver of waste management policies emerged in the context of environmental movements across the globe. Though this driver is most prevalent in more industrialized contexts, where there is strong legislation protecting the air, water and land (UNH 2010), it is also important where environmental degradation is highly visible. In Mauritius, an island nation, "the need to protect coral reefs and the surrounding ocean has been instrumental in the construction of high quality wastewater treatment systems and the construction of a state-of-the art containment landfill for the whole island" (UNH 2010 p. 57). On islands, the visibility of waste and its impact can impel adoption of waste management policies to protect the environment. Similarly, environmental protection is an important driver in Rotterdam, Netherlands, where its environmental fragility, namely its high water table, has catalyzed the adoption of policies that minimize landfilling and maximize beneficial reuse of MSW (UNH 2010 p. 76). The need to protect the environment through effective waste management may also be external; Bulgaria's desire to become a member of the European Union required the nation to improve its waste system (UNH 2010).

Though resource recovery also provides environmental benefits, it drives changes in waste management through economic signals. Where resources are scarce, materials are recovered, repaired or reused, rather than disposed. Resource recovery was the dominant mode of 'waste' handling in pre-industrial societies; Strasser (1999) provides a nice history of the trade in waste materials by peddlers in the pre-industrial United States. This driver is especially prevalent in resource-poor cities, such as Bamako, Mali (UNH 2010) and is often the motivating force behind their recycling systems.

Climate change has emerged as a driving force for changes in waste management. The threat of climate change, coupled with the need to control GHG emissions from all sectors of the economy has made emission reduction from waste management a policy goal for many states. Though waste contributes modestly to global greenhouse gas emissions (<5%), waste management has the *potential* to either be a net source or sink of GHGs (Bogner et al. 2007). Because landfills are the largest source of these gases within waste management, and because these emissions are growing in developing nations, many waste projects in the Global South are focused on containing these emissions. Climate change is an important driver for waste management plans in both industrialized and industrializing nations. Where OECD nations may look to reduce the carbon emissions from their waste management in order to meet national emission reduction targets, industrializing nations are increasingly looking to the Clean Development Mechanism as a means of funding improvements in their waste management plans, and so must select GHG-abating waste management projects to qualify.

Another reason cities are choosing to improve their waste management is aesthetic. In developing country contexts, "the importance of recognition, image and municipal pride in keeping streets clear cannot be underestimated" (UNH 2010 p. 98). An essential component of a modern city is cleanliness (Kaika and Swyngedouw 2000; Thieme 2008). Handyani et al. (in UNH 2010) identify "the public image of the city" as being the most important driving force in Delhi's waste management development. As host of the 2010 Commonwealth games, the city's authorities worked hard to "present Delhi as a clean world-class city with advanced technology" (UNH 2010 p. 58). Creating a positive international image also led to modernization of waste management in Kunming, China, as it prepared to host the World Horticultural Exhibition in 1999 (UNH 2010). Tourism rewards clean cities; its economic benefits drive efforts to keep Varna, Bulgaria's streets clean (UNH 2010). Though the concern for appearances may not lead to overall effective waste management, collection coverage "tends to be high in cities where authorities are concerned with public image" (UNH 2010 p. 96). Good collection is the first step in waste management systems.

3.2. Historical development of waste management systems

3.2.1. Shift from local to regional, and informal to formal waste management: A look at the United States

The interplay of the drivers discussed above has led to a broad historical shift from local to municipal to regional management of waste. Louis (2004), Kollikkathara (2009), Melosi (2000) and Strasser (1999) provide nice overviews of the sanitation revolution in the United States. In pre-industrial times, the household was the locus of waste management. The value of materials was high enough that there was a well established repair and reuse industry, centered in the home. Home economics was so efficient that in 1882, a booklet on the subject had to define a waste paper basket: "It is for collecting all the torn and useless pieces of paper, and should be emptied every day, care being taken that nothing of value is thus thrown away" (Strasser 1999 p. 67). Little was thrown out for two reasons. First, women would make, repair and re-purpose clothing (and other household items) until they became rags. Second, when these objects (rags, in this case) were no longer useful, women traded them with ambulant peddlers for pots and wares. These peddlers "became a major institution of the nineteenth century distribution and…[were] at the center of the recycling system" (Strasser 1999 p. 73). Waste management in 19th century United States was centered in the home, with one outlet to industry, for products no longer used by the house, but useful for manufacturing new products. Peddlers provided the collection and transportation that linked home and industry, effectively carrying materials that were 'waste' in one place, to a place where they were instead raw materials.

A number of changes led to the decreased exchange between homes and industry, via peddlers. First, people bought more goods in response to declining prices (post Industrial Revolution) and the appearance of mail-order catalogs. Second, because people could more easily buy new goods, their incentive to accumulate 'waste' to trade with itinerant peddlers declined. As Americans began to throw things away, they also began living in cities, so their waste began to pile up. The household ceased to be the center for waste management; women no longer were occupied with the salvaging, repair and reuse of items, and fewer citizens had animals to consume discarded organic waste. Where homes had been mostly self-sufficient in rural America, they became part of an urban network, which "imported most of their goods and exported their waste" (Louis 2004). By the end of the 19th century, the two-way trade between households and industry, linked by peddlers, "had given way to specialized wholesalers and waste dealers – a separate, highly organized trade built on a foundation of industrial waste, supplemented by scraps collected from scavenging children and the poorest of the poor. For the first time in human history, disposal became separated from production, consumption and use" (Strasser 1999 p. 109). The locus of waste management shifted from the household to the city.

Reuse and recycling habits did not vanish; they dwindled. Companies began selling packaged products, and "middle class people learned to toss things in the trash, attracted by the convenience and repelled by the association of reuse and recycling with a new class of impoverished scavengers. As cities and towns took responsibility for collecting and disposing of household refuse, it became easier to throw things out. Ever-increasing amounts of trash demanded complex systems and huge investments in sophisticated equipment, promoting the notion among citizens that refuse was a technical concern, the province of experts who would take care of whatever problems trash presented" (Strasser 1999 p. 113). Cultural changes – learning to throw things away – and municipal responsibility for discarded items led to increases in the amount of trash produced in cities. These conceptual shifts paved the way for a shift from informal to formal waste management. Waste was re-defined as a technical and municipal concern, not one to which citizens should be concerned.

The movement towards formalized management of garbage required two elements: a weakening of the institutional ties between informal waste workers (e.g., scavengers, peddlers) and citizens and cities embracing "the Progressive position that government – and not free enterprise – was responsible for public health and should exercise that responsibility in the matter of refuse (Strasser 1999 p. 120). These two elements occurred simultaneously. As peddlers were pushed out by an increase ease of shopping and discarding, a new class of scavengers was born in the

US, who picked through garbage in cities (rather than exchanged directly with citizens). These activities, “reuse, recycling, and bricolage, became identified as activities of the poor during a time of rising consumption and of new possibilities for convenient disposal” (ibid p. 136). Its association with poverty made the business of recycling less pleasant. Municipalities also passed laws that intentionally weakened the position of these recyclers, by “[dropping] regulations requiring citizens to separate their trash” (ibid p. 135), and even more directly by prohibiting the informal waste trade. Officials in New York City prohibited households from “[selling] unwanted rags and other wastes to ragmen who appeared at the door… [instead requiring people] to take unwanted things to licensed second hand dealers, ‘men who had fixed places of business.’ With a single stroke, the streets would be free of refuse and of the poor who made their livings spearing debris and pushing it on carts or hauling it around in bags on their backs” (ibid p.140). A combination of cultural habits that encouraged easy disposal, and an earnest effort by municipalities to take responsibility for their city’s waste led to a shift from informal, decentralized management to formal treatment of waste.

Though the accumulation of waste in cities posed a nuisance, municipalities moved to manage solid waste only after tackling the more pressing public health hazard, unmanaged sewage. Urbanization occurred rapidly in the United States, with 5.1% of the population residing in urban areas in 1790, 11% in 1840 and 51% in 1920, and its attendant accumulation of untreated wastewater led to disease outbreaks (Louis 2004). After investing in regional infrastructure for wastewater management, cities did not have the budget to do the same for solid waste, so it was at first managed locally, not regionally (Kollikkathara 2009). As such, cities had two choices: to contract waste services from local scavengers (who were already collecting, sorting, and recovering waste), or to provide waste management services themselves. American cities chose the latter, and mostly followed the municipal management system designed by George Waring in New York City in the late 1890s. He set the standard for American waste management by organizing waste management into unit operations: source separation of waste (into organic, non-putrescibles and ashes), waste collection, resource recovery, and disposal. Though there were important changes in technology, Waring’s waste management paradigm is essentially what still exists in US cities today: organized, technology-focused, and operated by the municipality (Louis 2004).

The technological shift in waste management was profound. Collection in New York was gradually mechanized; initially, people and horses collected waste, then cable cars and trolleys did, and finally trucks. Where urban waste management began as a way to remove waste from cities (and dump it just outside), it evolved to provide different waste treatment services. The first large-scale waste incinerator was built in the US in 1885, and home-incinerators became widespread in the mid-20th century. The first centralized recycling center[1] was established in Chicago in 1904. Sanitary landfilling – controlled disposal of waste to minimize its impact on the surrounding environment – was invented in 1934, and by the 1960s was the most common waste treatment method in the US (Louis 2004).

The regionalization of waste management processes derives from an increasing concern for protecting the environment from our waste, and the resulting passage of legislation on how waste

[1] Of course, decentralized recycling has a much longer history.

should be managed in the US. The Clean Air Act (1970) regulated emissions from MSW incinerators, landfills and composting facilities, and meeting those standards was more difficult for smaller operations. The definitive legislation that altered the scale of waste management activities was the Resource Conservation and Recovery Act (1976), which defined solid and hazardous waste, established strict standards for sanitary landfills, and prohibited the open dumping of wastes. The immediate impact was the closing of open dumps, and the rapid decline in the number of landfills (a 50% decrease from 1976). The broader impact was a movement from municipally operated to regionally operated waste management facilities. Because it was more expensive to keep a landfill (or incinerator) that met environmental guidelines, regions invested in fewer, larger landfills that served multiple municipalities (Louis 2004).

3.2.2. EVOLUTION OF THE INFORMAL SECTOR AS A WASTE SERVICE PROVIDER

3.2.2.1. INFORMAL PUBLIC GOOD PROVISION

Though in the United States (and in many other nations, in the Global North and South), municipalities have provided waste management services to its citizens, mostly through capital-intensive, government-financed infrastructure projects, an alternate model of provision has arisen in developing cities. Here, the evolution of waste management services has been a history of evolving informal actors, small businesses and entrepreneurs taking over sectors ignored by the state, propelled by the economic benefits from providing that service.

The puzzle of why some cities provide more public goods – defined as goods that are non-excludable and non-rival – to their citizens than others has been tackled by a variety of scholars under various contexts. Standard political science models conceptualize two relevant actors in the struggle for service provision: the government, purveyor of goods, and civil society, receiver of goods. Academic studies have focused on the demand side of goods provision, asking which factors allow communities to effectively organize and demand services, as well as on the supply side, examining what makes governments effective in providing public goods. On the demand side, the level of economic development is often hypothesized to increase demand for public goods, because with wealth comes an expectation of high standards of living (Ziblatt 2008). Ethnic heterogeneity is associated with lower public goods provision and scholars have supposed a variety of mechanisms for this association, including that having a diverse set of preferences may obfuscate potential collective action (Tsai 2007; Ostrom 2000; Ziblatt 2008), a higher willingness to bear costs to goods provision when the beneficiaries are co-ethnics, improved effectiveness of collaboration between co-ethnics, and better enforcement mechanisms within ethnicities (Habyarimana et al. 2007). These associations are consistent with the observation that richer, more homogeneous places have higher rates of public good (water, wastewater, waste) service provision.

Studies focused on the supply side of goods provision examine the factors that allow governments to provide people with public goods. Ziblatt's 2008 study on goods provision in 20th century German cities postulates that it is government *capability*, measured by fiscal resources of the city and the professionalism of officials, that explains differing provision of public goods. Chhibber (2004)'s analysis of Indian states associates increased public goods provision with the party system, where public goods are provided by two party systems as an election strategy, and club goods are distributed by parties in multi-party systems, because these parties need to win the favor of a smaller slice of the electorate. Also focusing on the supply side, Tsai (2007) studies rural areas in China where both democracy and formal institutions of accountability are weak, and finds that the characteristics of local solidary groups - specifically, whether they give leaders moral standing – explain differences in the public goods obtained by citizens. Her study flips the standard model of goods provision by conceptualizing civil society as the actor, impelling government officials to work for them, where the previous studies focused on government as the actors providing goods either as a measure of their effectiveness or of their election strategy.

Not all research points towards the government as a benevolent provider. Savedoff and Spiller (1999) paint a more nuanced picture of the government's role in water provision, showing that in the Latin American context, governments have incentives to keep water prices low, thus keeping service coverage and quality low and decreasing public support. This leads to a low-level equilibrium, in which governments' short time horizons preclude the raising of tariffs and the improvement of service. Then it is conceivable that even if a government is capable (according to Ziblatt's measures), and the public demands goods, they still may not be effectively provided through the state. In these cases, there is an additional way (besides Spiller and Savedoff's regulatory suggestions) to improve public good provision: the entry of another player in the goods provision market.

Absent from the public goods literature is a third actor: civil society as a purveyor of goods. Organizations within civil society may fill gaps in public good provision through informal transactions, transactions "not legally recognized by the state" (Assaad 1996, p. 117). Informality is often used to govern transactions by those who are marginalized by the existing economic order, as "a mechanism for adapting to shortcomings in modern…regulated states. Rather than operating in the absence of formal systems, formal and informal modes of exchange thrive in the 'interstices of the formal system'" (Tripp 1997, p. 17). Because these interstices can be quite large in resource-constrained states, informal employment is widespread in developing nations, comprising "half to three quarters of all non-agricultural employment … 48% in North Africa, 51% in Latin America, 65 % in Asia, and 72 % in sub-Saharan Africa" (Delgado 2008). This employment takes hold in areas where the government "lack[s] the resources to meet the demands of urbanization and enforce laws…Rapid urbanization in developing countries has created pressures that have constrained the capacity of cities to provide adequate employment, waste disposal, water supply, food supplies, and housing" (Delgado 2008). It is precisely in these areas that informal transactions thrive.

Many goods are provided informally in developing country contexts: informal housing is prevalent in developing cities, with 20% of Rio de Janeiro's residents inhabiting favelas (Fabricius 2008), 50% of Mumbaikers living in slums, and one in three global urban dwellers residing in informal settlements (Gouverneur and Grauer 2008). Transport services are often met informally; small entrepreneurs control 95% of urban transport in Lima (Ghersi 1997) and Rio's informal van fleet now exceeds the size of the municipally owned bus fleet (Fabricius 2008). Housing, health care, solid waste collection and education are mostly provided informally in Pakistan, where the state has been unable to keep up with a growing demand for services (Hasan, 2002).

Access to water, sanitation and electricity is often obtained informally as well, whether through pirated connections (Fabricius 2008), or through small-scale providers, who are very important sources of water and sanitation services in the developing world. Solo estimates that 25% of water supply in Bamako is provided through shared connections with neighbors, privately owned tanker trucks meet 30% of water needs in Tegucigalpa, privately owned toilets are expanding access to sanitation throughout India, Bangladesh, Peru and China, and 95% of sanitation services in sub-Saharan Africa are supplied by private septic tank cleaners and night soil carriers. What Solo dubs “the other private sector” is indeed a major provider of public goods in urban developing cities; in Latin America, 25% of the population depends on small-scale private providers for water services and 50% of the population relies on non-state actors for sanitation services. In Africa, these numbers are far greater (Solo 1999). Importantly, this widespread “urban informal micro-enterprise should be viewed as a part of a voluntary small firm sector similar to those in advanced countries that, due to the laxity of enforcement of labor and other codes, is able to choose the optimal degree of participation in formal institutions” (Maloney 2004, p. 1173). This sector then represents a flexible and entrepreneurial labor force that is able to adapt quickly and provide goods and services under changing conditions.

3.2.2.2. THE INFORMAL WASTE SECTOR

The informal provision of waste services is ubiquitous in developing nation cities. Two percent of people worldwide depend on waste for their livelihood (Medina 2007; UNH 2010). There are an estimated 2 million “scavengers” in China alone (Chen 2010). But what is the informal sector? The term informal is “used to describe the relationship between workers and the state” (Mitchell 2008, p. 2020) – not their level of organization or even professionalism. The informal sector of waste management is comprised of people who separate, collect, dispose and re-sell waste; the work done is characterized as “small-scale, labor-intensive, largely unregulated and unregistered, [and] low-technology” (Wilson 2006, p. 797). Though “informal,” the sector is often complex, able to recover a high proportion of recyclables, flexible, and able to quickly adapt to changing economic conditions (ibid).

The informal waste workers are ubiquitous, but the niche that they inhabit – and their overall importance in the waste management of a city – is quite variable. They may be the only players providing collection for a city, as in Haiti (Noel 2010) or Delhi, where the informal sector connects households and temporary storage units called *dhalaos* through an innovative collaboration between the formal and informal sectors. The New Delhi Municipal Council subsidizes this system, realizing that it is unable to provide primary collection to its city. From the *dhalaos*, a mix of private companies and the municipality provides secondary collection. In Bamako, Mali, the informal sector is also a key player in waste collection. Providing 57% coverage of the city, over a hundred micro-enterprises comprised of people driving donkey carts collect 300,000 tonnes of waste per year, and deliver it to secondary collection sites, in a private-to-private arrangement between the enterprises and the waste generators. Informal Service Providers (ISP) collect waste from 30% of the city of Lusaka, Zambia (UNH 2010).

Though sometimes involved in waste collection and disposal, as noted above, the informal sector is most commonly involved in the recycling sector, as itinerant waste buyers, street-pickers, dump-pickers, truck-pickers, workers in junk shops, or processors of waste materials (Wilson 2006; UNH 2010). In Cañete, Peru, and Bogotá, Colombia, informal collectors remove materials from bags of waste that would otherwise be sent to landfills; they reroute materials from a path of waste into a recycling chain. In many cities, this work is done farther along on the waste chain. In Nairobi, 1000 waste pickers live on the dump at Dandora, and remove valuable items to resell (UNH 2010). While developed nations prohibited the informal recycling that was prevalent early in their industrialization and have had to build their recycling rates anew, many developing nation cities remain centers of material recovery and reuse through the participation of people who scavenge goods from city waste and resell the materials to manufacturers. Because the money they make comes from the intrinsic value of the materials they recover, the incentive to collect recyclable material is strong. Because their wages come from resale, and not through contracts with the city, informal sector recycling is a "free" service provided to the municipality – essentially, a "a subsidy by the poor to the rest of the city" (UNH 2010 p 138) that provides a livelihood for workers (Gutberlet 2008; Gutberlet 2010). Thus, informal work offers (at least) two types of benefits: it provides employment to the very poor, and it provides an environmental and waste management service to the cities in which it operates.

The recycling rate achieved by informal workers varies by locale. Informal actors in Turkey recycle 10-15% of the waste produced (Turan 2008); 22% of Pune, India, waste is recycled informally (UNH 2010); and most notably, the *Zabbaleen* recycle 66-80% of waste in Cairo, Egypt (Assaad 1996; UNH 2010). There are places where informal recycling outperforms the formal recycling sector in developed nations. Cairo's recycling rate is greater than the United States' (33%) and that of most other developed nations.

The level of organization of informal waste work also varies tremendously, with the widely-studied *Zabbaleen* in Cairo representing an extremely well-organized, highly effective organization (see Assaad 1996; Fahmi and Salah 2005; Fahmi et al. 2006; Fahmi and Sutton 2010), and individual waste picking from dumps representing the lowest level of organization and power (Wilson 2006) and the highest level of personal health risk. Though the integration of this sector into an Integrated Solid Waste Management plan has been recognized as essential for cities in the Global South, "a necessary first step towards integration is to recognize the economic, social and environmental benefits that result from informal recycling" (Wilson 2006, p. 805) and this has not yet been done.

Waste management systems, however, are not either formal or informal; they are both. Waste management systems fall along a "formal-informal continuum, with different categories of actors who interact, overlap and may themselves change category in response to changing circumstances" (UNH 2010 p. 72). It is this flexibility of the informal sector that allows it to endure; it moves to find niches of opportunity within cities. Formal and informal waste management interact fluidly and symbiotically (Tripp 1997, p.17); both may thrive within the same city, and the shape that each takes may be unique. The formal-informal waste combination may be a public-private partnership, as in Delhi, or collection may be provided privately by micro-entrepreneurs, as in Zambia. Collection may be officially municipal, but with widespread informal recycling, as in Bogotá, Colombia, or collection may be provided by of private corporations, as is now common in the United States. Informal collection may exist in highly regulated waste management contexts – though the co-existence of formal and informal waste actors is often neglected by academia – alongside formal collection systems, as in Berkeley California, where scavengers pluck materials from already-sorted recycling bins and garbage. Though quite different in incentive structure from the informal recycling often seen in cities in the Global South, the informal recycling sector in Berkeley involves hundreds of people, and works to collect the deposits on the bottles and cans collected (this is essentially a cash transfer between the municipal recycling system and these informal workers).

Because of the dynamic nature of the informal sector, it is difficult for outsiders (e.g., academics, NGOs) to fully understand its functioning. However, "understanding the activities of informal recyclers is perhaps the key ingredient for successful recycling and organics recovery in low and middle income countries" (UNH 2020 p. 129). Some cities – such as Belo Horizonte, Brazil, and Buenos Aires, Argentina – have made notable efforts in both understanding and integrating the informal sector into their waste management plans. But these cities' active integration of the informal waste sector is atypical; many municipal governments aim instead to forcibly remove their informal workers (Medina 2007) . The scale of the informal waste sector in developing cities and its importance as a form of livelihood for workers, makes the integration of the informal waste sector into waste management plans a central obstacle facing the development of Integrated Waste Management plans in developing nations (McDougall 2001).

3.3. Formalization of waste management in the Global South: A look at Bogotá, Colombia

Many cities are adopting changes in their waste management systems. As a large and fast-growing urban center, Bogotá is representative of a class of growing, developing cities that need to expand urban waste services. Waste there is currently managed by a combination of formal and informal actors. The municipal government manages waste collection and disposal (though these services are operated by private companies), and a large informal sector is the work force behind an unregulated recycling system. Colombia is home to "the most dynamic scavenger cooperative movement in the world" (Medina 2001); and its capital city is home to about 20,000 informal waste workers who recover approximately 1000 tonnes of recyclable material each day. This informal network is comprised of a chain of nodes that receive and process waste. The chain with collectors, who use a variety of collection mechanisms, from burlap sacks to hand-drawn carts, to horse drawn carriages, to gather recyclable material. They sell their goods to *bodegas*, which sort and store materials, and then sell large volumes of materials to industry, which use the materials to create new products. As a part of the city's modernization plans, the municipal government is formalizing its recycling system by giving the rights of collection to four private companies. These companies use trucks to collect recyclables from households and bring them to a pilot recycling facility. These two systems – the long-standing, informal one, and the new formalized one – are currently at odds, each fighting for the right to recycle Bogota's waste. The city has passed a number of laws which limit the informal sector's right to work, including a law that states that public sorting of waste is illegal, and one that prohibits the use of horse-drawn carriages in the city. The implications of formalization are explored in the following chapters.

4. Current status of solid waste management: Technologies and Policies

Just as the governance of waste has evolved over time, towards regionalization and towards formalization, so have the technologies and policies used to minimize the negative environmental and social impacts of waste. The technologies used vary by locale, but cover the functional elements of waste management systems: waste generation, waste handling at the source, collection, transport, processing and transformation, and disposal (Tchobanoglous and Kreith 2002). Waste generation and waste handling are dependent on human behaviors, and municipalities tend to use policies (rather than technologies) to affect changes to these elements. Waste technologies are focused on the remaining elements, collection through disposal.

4.1. Technologies

4.1.1. Waste collection

The ability to manage a complex and massive quantity of waste is dependent on an effective collection system. Collecting waste starts with material rejected from generators (Tchobanoglous and Kreith 2002) and is a necessary precursor to treating it. Collection prevents waste from accumulating in the streets and directly impacting local environmental and public health. The first, and sometimes only, step in the formal waste management of a city, waste collection is generally the most expensive component – cities spend 50-60% of their waste budgets on collection alone (Tchobanoglous and Kreith 2002).

Collection influences the quality of recovered materials. “The way waste materials are collected and sorted determines which waste management options can be used” (McDougall 2001 p. 193). If waste is collected such that materials are separated, then processing of like-components is more feasible and efficient than if materials are co-mingled. For example, if paper is mixed with discarded organic waste, then the soiled paper cannot be recycled. If paper is collected separately from food waste, it can be. The same is true for other material fractions.

The mode of collection also influences user participation. In the Global North, many cities provide separate collection for recyclable products and for waste destined for the landfill. (Separate green waste collection is also becoming more common, as in San Francisco, USA). Herein lies a trade-off between user participation and efficient sorting: asking users to sort their own waste raises the likelihood that waste components can be treated appropriately, but asking users to do too much lowers the probability that they will participate at all (Tchobanoglous and Kreith 2002). In contrast, the personal relationship between the consumer and the collector, as observed in Bogota, Colombia by the author, can lead consumers to regularly separate their recyclables. Because the consumers can see where the waste was going, and because they receive waste and sweeping services in exchange for separating their waste, they are willing to expend the extra effort to do so.

A great variety of collection technologies exist, and fall into two general categories: mechanized and non-mechanized. Industrialized cities rely on trucks to achieve almost 100% collection rates (see Figure 4). Usually operated by two people, these trucks compact the waste they receive and deliver it to a transfer station. Where collection exists in lower-income cities, a combination of mechanized and un-mechanized vehicles collects solid waste. In Bogotá, Colombia, where the informal recycling sector is active, collectors use a variety of methods to carry recyclable materials, from burlap sacks, to wooden planks with wheels, to tricycles, human-drawn and horse-drawn carts, and pick-up trucks. The variety of collection vehicles in Bogotá displays a diversity of capital investments that each collector is able to make, of quantities that each may collect in a day, as well as a flexibility that allows collectors to reach small alleys and neighborhoods that are inaccessible to large trucks.

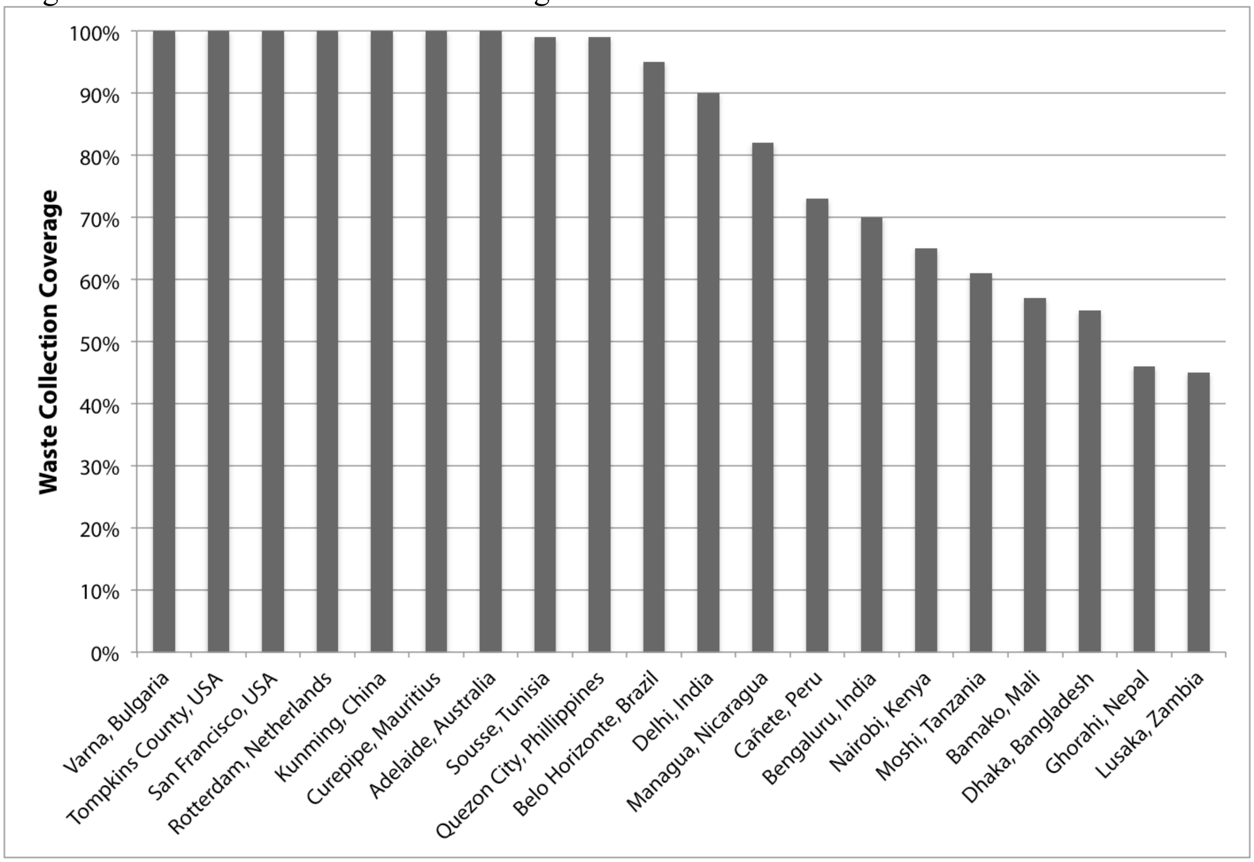

Figure 4: Waste collection coverage for selected global cities. Data from UNH (2010).

A recent trend in waste collection combines formal and informal, mechanized and un-mechanized collection to increase efficiency. In India, and other places, informal workers use un-mechanized vehicles to bring waste from households to small transfer stations, from which municipal trucks collect the waste. This expands collection coverage, "enables micro-privatization of the labor-intensive primary collection," (UNH p.95) and allows the municipality to take over where larger trucks are more efficient. This symbiosis between formal and informal systems allows cities to adapt to their local conditions and maximize collection efficiency.

4.1.2. WASTE PROCESSING AND TRANSFORMATION

After collection, waste may be transformed into useful products through a number of processes. The oldest of these methods use biological systems to convert the oldest of wastes – biogenic[2]

[2] Often called "organic" wastes, biogenic wastes are those that are made of biological matter.

wastes – into energy and compost. Non-biogenic waste processing, incineration and recycling, are methods rooted in more recent history that have evolved significantly in the last century. Finally, we consider two 'technologies' that harness human behavior change as a means to repurpose waste: reuse and waste reduction.

4.1.2.1. ORGANIC (BIOGENIC) WASTE TRANSFORMATION

The degradation of organic waste is a natural process, mediated by microorganisms. Over time, people have learned to commandeer this process with the express purpose of extracting energy and useful materials. These technologies are of particular interest in the Global South, where solid waste is mostly biodegradable.

4.1.2.1.1. COMPOSTING

Composting is the decomposition and stabilization of the organic fraction of municipal solid waste carried out by a microbial community under controlled, aerobic conditions. Though composting has been practiced by people since they first settled in agricultural communities, it is now emerging as a centralized waste management method that both reduces the volume of waste that must be disposed and creates useful products (Diaz 2007). In practice, compost systems may be closed or open, and may occur at the household or municipal scale. Most biogenic matter can be composted, and the resulting product (compost) can be used as a soil conditioner, as fertilizer, as mulch or as a replacement for peat (Tchobanoglous and Kreith and Kreith 2002). Composting offers environmental benefits; by converting organic waste into a useful product, it makes unnecessary further waste management (e.g., transportation, landfilling), and prevents their accompanying environmental burdens. By treating organic waste in an aerobic environment, composting also prevents the creation of methane, a powerful GHG that would otherwise be produced in an anaerobic environment.

Composting fulfills four waste management objectives: to reduce the volume of waste, to stabilize waste, to sterilize waste, and to produce a valuable product from the waste (McDougall 2001; Diaz text). A naturally occurring biological process undertaken by a succession of microbial communities, the aerobic degradation process can be written as:

$$C_aH_bO_cN_d + 0.25\ (4a+b-2c-3d)\ O_2 \rightarrow a\ CO_2 + 0.5(b-3d)\ H_2O + dNH_3$$

The composting process breaks down organic matter in the presence of oxygen, reducing the volume and mass of waste by approximately 50% (on a dry-weight basis); the other 50% of the mass is released as carbon dioxide (CO_2), water (H_2O), and ammonia (NH_3) (Rhyner 1995; Tchobanoglous and Kreith 2002). If the compost is not properly aerated, then methane (CH_4) is also produced. Composting is an exothermic process; it releases heat, and raises the temperature of the substances being degraded. The high temperatures reached in the composting process (upwards of 65° C) destroy most pathogens and weed seeds contained in the organic waste (McDougall 2001).

Though the percentage of MSW that is composted is small for most nations, with values ranging from 1% in the United Kingdom, to about 9% in the United States, to 22% in the Netherlands, composting is growing as a Waste Management strategy in the European Union and in the United States (Tchobanoglous and Kreith 2002). Data on composting in developing nations are lacking, but recent concern about methane release from developing nation landfills (Bogner et al. 2007) may prompt increased interest in composting as a waste management strategy.

The spread of composting as a major waste management technology faces barriers. First, good substrate is hard to come by. MSW is heterogeneous, and composting requires only the biogenic fraction of waste. Thus, its effective separation into biogenic and non-biogenic fractions is necessary for the production of compost. If this separation happens after collection of mixed solid waste, there is a risk that heavy metals, toxic organic compounds or inorganic materials present in the MSW will contaminate the organic waste. Inclusion of these substances in a compost pile threatens the biodegradation process and makes the use of the resulting compost difficult and hazardous. The composting process is more effective if waste is separated, but that requires a behavioral change from consumers. Compost also faces market barriers; while the production of compost requires energetic and monetary resources, the market value of the product tends to be low.

4.1.2.1.2. Anaerobic digestion

Anaerobic digestion (AD) is another bacterially mediated reaction, but it occurs in the absence of oxygen. Microbial communities consume biomass and release carbon dioxide (CO_2) and methane (CH_4), via three processes: hydrolysis, acidogenesis and methanogenesis (Khalid 2011). As a solid waste treatment process, it is often followed by aerobic digestion as a second step, to produce compost, for use in agriculture (De Baere 2006). In engineered systems, these reactions are conducted under mesophilic (30-35°C) or thermophilic (50-55 °C) conditions. Biogas (55-65% CH_4, remaining is CO_2; Christensen 2011) from anaerobic digestion, which tends to be higher for thermophilic systems (Hartmann and Ahring 2006), can be collected and used as a renewable fuel. The production of biogas from the AD process is dependent on the feedstock, the efficiency of the bioreactor, pH, temperature, moisture, the carbon to nitrogen ratio of the feedstock, and the nitrogen content of the substrate (Khalid 2011)

Digesting the organic fraction of solid waste offers a variety of environmental and economic benefits, when compared to landfilling and other waste treatment methods. Anaerobic digestion results in a large decrease in volume occupied by the waste, so less land is needed for waste disposal (Fricke 2005). AD also provides an opportunity for nutrient recovery. Effluent from anaerobic digestion can be used as compost or as fertilizer, replacing the need to extract new sources of nutrients. AD is one of the few waste treatment methods that is able to treat the wet fraction of waste (Hartmann and Ahring 2006). Energy production from anaerobic digestion is its greatest asset. Not only does the anaerobic digestion of organic waste in a bioreactor prevent the emission of CH_4, a potent GHG, from a landfill, its production can be maximized and captured under controlled conditions. The resulting natural gas can be used to power the digester or can be sold on the market.

Co-digestion of food waste and wastewater sludge – which differs from regular anaerobic digestion only in that it has two feedstocks instead of only one – offers some additional benefits. Biogas production has been found to increase with co-digestion (Edelmann 2000). In combining the two anaerobic digestion processes, communities would not have to invest in two different waste treatment methods (Verstraete 2005); this lower infrastructure option may make co-digestion more attractive to developing nations and rural regions (Edelmann 2000). With these benefits come risks. Anaerobic digestion is a variable process, mostly because the inputs (solid waste and sludge) are heterogeneous. Also, mixing food waste with human waste and its potentially high concentrations of pathogens creates a larger volume of effluent that may pose human health risks. If the effluent is used for agricultural purposes, the concentration of pathogens in the end product must be quantified.

Anaerobic digestion for treatment of solid waste is prevalent in China, where it has existed for centuries (He 2010) and in Europe, where solid waste policies restrict the landfilling of biodegradable waste. The Chinese government is seeking to increase the biogas production capacity from its current level (8 billion m^3, equivalent to energy produced from 5 million tones of coal) to 44 billion m^3 in 2020 (He 2010). The technology is used on a smaller, less engineered scale in agricultural settings throughout the world – farmers will cover animal manure, and connect the emitted gas directly to stoves for cooking – but the capital cost of an engineered anaerobic digestion system has limited its application. Anaerobic digestion is also widely used for wastewater treatment, in North America and Europe, but only Europe uses the technology at a large scale for solid waste treatment.

4.1.2.1.3. MSW TO FUEL

Two new technologies aim to convert solid waste to liquid fuel. The conversion of MSW to ethanol is not yet a commercial reality, but it is technically possible. Kalogo et al. (2007) describe the environmental flows associated with converting biodegradable waste to ethanol, using acid hydrolysis and gravity vessel technology. Producing ethanol from MSW is a promising technology because it uses a ubiquitous feedstock (MSW) and provides a cleaner liquid fuel for a world facing rapidly increasing motorization and CO_2 emissions. Two barriers to its widespread implementation, beyond its commercial development, are the need for well-separated organic waste, and the capital cost of building a specialized facility.

Another emerging technology uses the larvae of black soldier flies, grown on organic waste, to create biodiesel (Li et al. 2011). These two methods of liquid fuel production use a widely available substrate, and importantly do not use crop feedstock, recognized to contribute to global land use change (Searchinger et al. 2008). This fuel production process does not require a specialized capital investment.

Both of these methods offer a way to use biogenic waste as a resource, and provide a market incentive to separate waste at the source.

4.1.2.2. Non-biogenic waste transformation

4.1.2.2.1. Incineration (add citations)

Incineration is the controlled burning of waste at a high temperature (Rhyner 1995). During the burning of wastes, moisture evaporates from the fuel, and organic compounds are ignited in the presence of oxygen. The incineration process is designed to attain complete combustion of wastes; this means that all carbon in the waste is converted to carbon dioxide (CO_2), all the hydrogen to water (H_2O), and all the sulfur to sulfur dioxide (SO_2). By-products include ash, air emissions (NO_x, CO, CO_2, SO_2, PM, dioxins, furans, and others), heat, and energy. While the heat and energy provide societal benefits (and even environmental, depending on the type of heat and electricity being displaced), the air pollutants produced represent a burden. Modern incinerators are equipped with pollution controls that can lower the emission of harmful pollutants to acceptable levels, but these are very expensive.

Incinerating waste provides a number of waste management services: it reduces the volume of waste over a short period of time, it can destroy harmful chemicals and pathogens, and it can be used to produce electricity and heat (Tchobanoglous and Kreith 2002; Rhyner 1995). Modern incinerators are designed to completely combust waste products and minimize and treat emitted air and solid pollutants. Many types of wastes can be burned in an incinerator, including municipal solid waste, refuse derived fuel (RDF, pellets made from the high-energy fraction of waste), and hazardous waste (Rhyner 1995).

For an efficient combustion process, the chamber needs sufficient oxygen and a high temperature, and the waste should have a low moisture content (< 50%) and should have a relatively high heating value (>5 MJ/kg); if moisture contents are higher and heating values are lower, the wastes will require additional fuel to sustain combustion (Rhyner 1995). Generally, the two wastes used to produce electricity are MSW, which is unsorted waste, and Refuse Derived Fuel (RDF), which is a subset of MSW that has a higher average energy content. Because most developing country cities have waste with high moisture content and a low heating value (due to a high biogenic, and a low recyclable fraction), incineration is rarely a sensible choice for waste management in the Global South.

Incinerators have evolved significantly over the last century, and their adoption has been patchy. The first waste incinerator was constructed in England in 1874, and the first incinerator in the United States was built in 1885. In the early 20th century, in-house incinerators were very common in the United States, resulting in a remarkably high ash fraction in American garbage (43% in 1939). The fast growth of incineration in the US was halted by a growing environmental movement, which led to both increased legislation and a powerful grassroots movement that fought to keep incinerators from being sited in their communities, due to concern for the emissions they produced. Both the Resource Conservation and Recovery Act of 1976 and the Clean Air Act of 1990 set strict standards to which incinerators must comply (Louis 2004), leading to the implementation of air pollution control technologies on all modern incinerators. Though popular resistance to waste incineration is strong in the United States, incineration is accepted in other parts of the world; the waste management technology is used widely in Europe and Japan, which combusted 75% and 90% of its MSW in 2000, respectively (Tchobanoglous and Kreith 2002). Incineration is rare in the Global South, though open burning of wastes is commonly practiced.

4.1.2.2.2. INCOMPLETE COMBUSTION: PYROLYSIS AND GASIFICATION

Pyrolysis and gasification are two other thermal processes used to convert waste to energy. Where conventional incineration uses excess air to completely combust fuels, pyrolysis and gasification burn fuel in an oxygen deficient environment. Both are endothermic processes, meaning that heat must be provided to the process to keep it going.

Gasification occurs in a hot (T > 650 ºC) and "air lean" environment, where there is not enough oxygen to completely combust the fuel. The process results in two products: syngas (a combination of CO, CH_4 and H_2) and a solid (unburned waste and char, a carbon-rich solid). The syngas can then be burned as a fuel, and the resulting char can be used as a fuel or as a soil amendment (Rhyner 1995).

Pyrolysis is the oxidation of waste in the absence of oxygen. The process has been used widely, ranging from Amazonian indigenous people who used *terra preta* (char) as a soil amendment, to modern commercial processes that use pyrolysis to produce charcoal, methanol and coke. The overall process can be expressed as:

$$C_aH_bO_c + heat \rightarrow H_2+CO_2+CO+CH_4+C_2H_6+CH_2O + tar + char$$

Both tar (a carbon-rich liquid) and char (a carbon-rich solid) can be used as fuel. Higher pyrolysis temperatures (T > 760 ºC) favor the production of the gases (H_2, CO_2, CO, CH_4), and lower temperatures (450 ºC - 730 ºC) favor the production of the solid (char) and liquid products (tar) (Tchobanoglous and Kreith 2002; Rhyner 1995).

4.1.2.2.3. ENVIRONMENTAL IMPACTS FROM WASTE INCINERATION EMISSIONS

All combustion processes result in the production of gases and particulates that require control strategies and technologies to meet air quality standards. Prior to advances in air pollution control technologies, incinerators were a major health hazard; this history has resulted in sustained resistance to the siting of incinerators near residential areas.

The emissions from waste incineration depend on a number of factors, including the type of waste burned, the type of incinerator, and the conditions under which waste is combusted (especially temperature and the amount of excess air provided). Incineration of waste produces the same basic by-products as the combustion of any hydrocarbon: carbon dioxide (CO_2), water (H_2O), and particulate matter (PM). The sulfur in waste gets converted to SO_2, whose emission is implicated in the formation of acid rain. In the presence of high temperatures and oxygen, the nitrogen in waste gets converted to NO_x, which plays a role in the production of ozone (O_3). Heavy metals in waste, such as mercury (Hg), lead (Pb), cadmium (Cd) and arsenic (As), also volatilize and condense onto fly ash particles; these metals are harmful to human and ecological health. Incineration of chlorine-containing fuel (such as plastics) can result in the emission of dioxins and furans (Polychlorinated-dibenzofurans, Polychlorinated-dibenzodioxins), which are chlorinated hydrocarbons that are persistent, toxic, and bio-accumulating (Tchobanoglous and Kreith 2002).

To minimize the emission of harmful pollutants formed during combustion, a number of air pollution controls have been developed and are now standard in modern incineration facilities. These include cyclones, electrostatic precipitators, and fabric filters, which all act to remove particulate matter from the flue gas. Sulfur dioxide and other acid gases are removed by scrubbers, which use alkaline mists to neutralize the flue gas. Selective catalytic reduction (SCR) and Selective non-catalytic reduction (SNCR) use ammonia (NH_3) to convert the emitted NO to N_2.The emission of NO_x can also be minimized by reducing the temperature in the incinerator or reducing the amount of oxygen available in the chamber. Finally, the injection of activated carbon into flue gases removes dioxins, furans, and heavy metals, by binding to the harmful chemicals (Rhyner 1995).

Combustion of wastes produces ash, as well as some waste products from air pollution control technologies. Two types of ash result from incineration: bottom ash, which is the residue left over from burned waste, and fly ash, the ash that is removed from the flue gas. While bottom ash makes up 90% of the total ash produced, the fly ash contains most of the toxicity from incinerator waste (Tchobanoglous and Kreith 2002).

Ash can be disposed of or it can be reused. Disposal normally occurs in a specialized landfill (called an ashfill) because co-disposal with MSW can produce toxic leachate when the acids produced by decomposing MSW lower the pH of the leachate, which increases the solubility of toxic metals. For ash to be reused, it must first be treated to reduce the amount of leachable metals and salts, and to improve its chemical and physical stability. Ferrous metals, making up about 15% of ash, can be recovered using magnets. To make metals insoluble, fly ash can be mixed with lime and Portland cement. Once stabilized, ash can be used as aggregate for road construction, as part of asphalt mixtures, or as landfill cover. In Europe, ash is commonly used as a construction material (Tchobanoglous and Kreith 2002).

4.1.2.3. Recycling

Recycling is the reprocessing of discarded materials into new products. The environmental benefits of recycling derive from the savings in both virgin natural resources and energy (Christensen 2009). Because the natural resources saved, the energy consumed, and the products displaced by recycled vary locally, the environmental benefits from recycling also vary with location. For recycling to occur, waste materials must be collected and processed, and there must be a market for the product made out of recycled materials. The recycling process varies in formality across the globe, but there is an increasingly globalized market for recyclable materials.

There are two driving forces for recycling: the commodity value of materials and the service vale. The commodity value refers to the “intrinsic economic value of materials… in waste” (UNH 2010 p. 116). It is the resale value of the aluminum can collected out of the garbage. This commodity value is what drives all private recycling activities, as private recycling is driven by the profit motive. The service value is the “waste absorption capacity offered” by recycling. By removing recyclable material from the waste stream, recycling causes less waste to be disposed. This diversion value drives municipal recycling programs (UNH 2010), along with concern for the environment.

The recycling chain in the Global South is mostly unregulated; private actors collect and resell recyclable materials to market. These activities are driven by the commodity value of waste, so the collectors have a strong incentive to collect as much highly valued material as possible. Recycling in industrialized nations is mostly municipally-run and driven by a desire to divert waste from landfills.

Table 1: Types of recyclable materials, their incidence, and economic value. Adapted from UNH 2010.

Type	Examples	Incidence	Pre-modern approach	Economic Value
1: High intrinsic value, globally traded	High grades paper, aluminum and other metals	10-15% of household waste	Recycled by individuals or enterprises, private initiatives	Price paid for materials is greater than or equal to cost of collecting them
2: Moderate intrinsic value, locally traded	Glass, tin, steel, textiles, plastics	10-15% of household waste	Recycled by private enterprises when there are local markets	Recycling not profitable
3: Non-commodity materials with local reuse options	Kitchen, garden, livestock waste for composting	40% of household waste	Small scale private arrangements between farmers and generators	Not a commodity, but has use value
4: Negative value materials that damage environment	Health care waste, hazardous waste, e-waste, automobiles	< 5% of household waste	Illegally dumped, or partially burned to extract metals	Some residual value added but not enough to cover cost of safe management

Unfortunately, as a society, we produce many goods for which recycling is difficult or even hazardous. A portion of Type 1 and Type 2 recyclables are likely to be reused in most cities, because they have intrinsic value. Type 3 wastes are likely to be used beneficially in rural areas, or cities that are near rural areas. Type 4 wastes are those with a negative value, and these require a management plan not based on making profit; usually, this is done through government regulation.

4.1.3. BEHAVIOR CHANGE AS WASTE MANAGEMENT "TECHNOLOGY"

Waste reuse and waste reduction are two very effective methods of reducing the impact of waste on the environment, and their implementation relies on consumer behavioral change. In the United States, "old-fashioned habits of reuse and recycling have been virtually abandoned…disposal has been disengaged from whatever is left of household production and assigned to the technocrats who oversee…sanitary landfills" (Strasser 1999 p. 266). Not only has the American household ceased to be a center of material production and reuse, but the modernization of consumer products, and its emphasis on convenience and fashion, has led to the creation of lighter-weight, shorter-lived products. This has led, in turn, to the production of more, complex waste. Though vestiges of reuse remain – or perhaps a growing movement is beginning – through garage sales and craigslist exchanges, product reuse is a minor sink for waste products in the Global North. Demonstrating the rarity of these practices, in the United States today, people "who reuse junk in clever and innovative ways [are] considered artists" (Strasser 1999 p.287).

In marked contrast, many cities in the Global South remain centers of product reuse. Though few cities keep records of waste reuse activities, and academic attention to this phenomenon is scarce, much anecdotal evidence suggests the prevalence of reuse behaviors in developing economies. The streets of Bogotá, Colombia, on Sundays are lined with flea markets selling books, clocks and clothing recovered from the garbage. In an innovative model of entrepreneurship, “Trashy Bags,” a company centered in Accra, Ghana, pays consumers for their empty water sachets. These plastic bags are strewn about the city, as citizens purchase their water in these bags then discard them. The company uses these bags as raw materials to make bags, raincoats, hats, wallets, and other consumer goods. By paying consumers for their waste, the company gives citizens an incentive to collect their waste products, and fewer plastic bags are dumped openly.

Organic waste reuse is common in rural and agricultural settings throughout the world. But Municipal Solid Waste is directly used for agriculture in Bamako, Mali, in a practice called *Terreautage*. Informal collectors sell partially decomposed waste to famers, who apply it directly to their fields. “There is a lively market for both fresh and partially decomposed raw waste…and is a source of nutrients” (UNH 2010 p.49). This practice, however, stands in the way of institutionalized composting, and of developing a landfill, as full recycling of waste was historically possible.

Finally, there are examples of design for reuse and repair – a concept re-emerging in industrialized markets – still in place in developing cities. Refillable glass bottles are still ubiquitous in many cities, so are repair shops specializing in everything from shoes to tires to vacuum cleaners to electronics. But cultures of reuse and repair are under threat. The falling prices of consumer goods, the spread of a consumer culture, the design of products for obsolescence, and even the improvement of waste collection systems all act to make it easier for people to throw things away.

Source reduction – consumers’ intentional minimization of waste production – is another means by which individuals can reduce the environmental impact of their waste (Vergara et al. 2011). The benefits from producing less waste are analogous to Amory Lovins’ concept of Negawatts, the energy savings realized through conservation. Reduction may be a cultural practice, the way that our grandparents bought less ‘stuff’ and reused more (Strasser 1999), or it can be a form of environmental activism. Wilson reviews evidence of waste reduction campaigns, and finds “a coherent basket of measures will be required” (UNH 2010 p. 150) in order for this method to be a significant sink for waste products. Though waste prevention may seem like a simple fix – as compared to investing in technology – behavior change is difficult to enact. A number of barriers exist at a societal and individual level, including the allure of modern consumer culture, which associates status with product acquisition (Schor 1991), and the difficulty of breaking habits. For a more widespread adoption of waste reduction, Wilson found that people would require an increase in reuse infrastructure, access to more product refills, and services to replace product ownership, such as tool-lending libraries.

4.1.4. Waste disposal

Every waste management system requires a method of final disposal. In an urban world in which waste complexity is high, complete reuse and recycling of waste is very difficult. The most basic form of disposal, open dumping, directly exposes people and the environment to waste products. Toxic chemicals found in waste contaminate water bodies, waste impacts public health through the water quality impacts and the disease vectors attracted to the dump[3], and waste harms ecological health through the pollution and land use change from the dump. Sanitary landfilling is an engineer's solution to the problem of open dumping. Invented by Jean Vincenz in 1934, the sanitary landfill is an engineered facility, designed to limit the health and environmental impact of waste (Tchobanoglous and Kreith 2002). It is essentially a large container, designed to prevent waste from escaping. Fit with liners, leachate collection and gas extraction systems, sanitary landfills also treat the by-products of waste degradation. Between open dumps, completely lacking in environmental controls, and sanitary landfills, mimicking a long-lived plastic bag for waste, there exist a continuum of disposal options.

A consequence of landfilling waste is the production of methane. A landfill is an anaerobic environment, in which microorganisms degrade waste slowly. Anaerobic digestion occurs in several stages, and breaks down organic matter in a landfill, leading to the production of biogas (CO_2 and CH_4). The attendant drop in pH during the acid phase leads to the mobilization of heavy metals into the leachate. To contain the waste products of the landfill, venting systems manage and carry the gas produced, and pipes conduct the leachate produced (Tchobanoglous and Kreith 2002). Advanced landfills will also have gas collection systems to allow for the combustion of the captured gas, as well as leachate collection and treatment systems.

Though McDougall (2001) identifies the need for developing nations to transition from open dumps to sanitary landfills as one of the key obstacles that need to be overcome for these nations to implement Integrated Solid Waste Management systems, there are important trade-offs to consider. Because waste budgets are limited, if a city invests in a sanitary landfill, it is unlikely to be able to invest in other large waste infrastructure immediately. And due to the high proportion of organic waste in MSW in developing nations, landfilling this waste will necessarily result in the production of methane, a powerful greenhouse gas. Herein lies a trade-off: investing in sanitary landfills will immediately protect public and environmental health, but will lead to increased GHG production and will limit possibilities for waste reuse. Research should be directed towards the implementation of other technologies, such as composting or anaerobic digestion as central waste management technologies in developing country contexts.

4.2. Relative costs of technologies

The technologies available for waste treatment vary in cost, with the highly engineered systems having the highest capital costs. The lowest cost technologies include source reduction and reuse, because they provide an overall sink to the system, but their implementation requires will, not just funding. The appropriateness of a technology depends on its economic, social, and environmental viability. Because the actual cost of any technology is somewhat locally specific, I provide the relative costs of the technologies reviewed, from most to least expensive (Williams 2005): incineration and anaerobic digestion are the most expensive, followed by composting, recycling and landfilling, which vary depending on scale and type (Bogner et al. 2007).

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[3] Louis (2004) suggests that dumped organic waste was partially responsible for the Black Death in Europe.

4.3. GOVERNMENTAL POLICIES

Governments use waste management policies to encourage behaviors and the use of effective treatment technologies. These policies can take the form of regulations or incentives.

4.3.1. REGULATIONS

The most basic form of environmental regulation of waste is one that limits the emission of pollutants to the environment. Legislation such as the Clean Air Act and the Clean Water Act in the United States puts limits on the quantity of pollutants that may be released; more specific waste legislation, such as the Resource Conservation and Recovery Act, defines precisely where waste treatment technologies may be built and the environmental standards with which they must comply (Tchobanoglous and Kreith 2002). These legislations amount to "end-of-pipe" regulations; they regulate what may be released, and represent an engineering approach to environmental protection. This class of legislation is often the first step that a state takes towards protecting the environment.

Extended Producer Responsibility (EPR) is another class of regulation that, rather than requiring the limit of emissions at the end of the pipe, seeks to incentivize the production of more responsible waste. Many European states have looked to this type of regulation to manage wastes. The Green Dot system in Germany sets specific guidelines for packaging of materials – and the 'Green Dot' on the package signifies its compliance – and holds the producer of the goods responsible for its end-of-life management. Similarly, the Waste Electrical and Electronic Equipment (WEEE) directive, passed in Europe in 2003, gives producers of electric equipment full responsibility for their disposal (Ondongo 2011). The Netherlands has enacted their own policy, consisting of 'covenants,' declaring producers and importers responsible for the "recovery and safe end of life management of their products" (UNH 2010 p.77). These legislations take a very different approach from end-of-pipe regulations, instead seeking to change the nature of the waste over time, by incentivizing producers to design products that are easier to manage.

Bans are another form of regulation, particularly useful when there are materials that are harmful to environmental or public health. The European Union's Landfill Directive calls for the phasing out of landfilling of organic waste, where states must reduce the amount of biodegradable waste that they landfill to 50% of the 1995 levels by 2009, and to 35% by 2016 (Bogner et al., 2007). A number of cities and states have banned the use of plastic bags, including Delhi (India), the state of Maharashtra (India), San Francisco (USA), and Rwanda.

4.3.2. TAXES AND INCENTIVES

Taxes are another way that states (or cities) can affect the quantity or composition of waste produced by consumers. While most consumers pay for their waste management though a monthly flat fee, a system called "Pay As You Throw" (PAYT) taxes consumers based on the quantity of waste they produce. If you produce more garbage, you pay more (Kinnaman 2009; De Jaeger et al. 2011). The system is often implemented by charging consumers by the bag or can, though some weight-based systems exist in Denmark and Germany. PAYT has been implemented in the European Union, Australia, Korea, Canada, Mexico, and Japan (Sakai et al.

2008), and has been associated with waste reduction. "PAYT systems reward any and all behaviors (including recycling, composting and source reduction) that reduce the amount of garbage disposed" (Skumatz 2008, p. 2783). Though this form of taxation has been broadly successful in reducing waste production, it has also been associated with illegal dumping, at a small scale (Skumatz 2008; Sakai 2008).

Other taxes target specific types of waste that are harder to manage. Many European nations (e.g., Denmark), as well as China, levy a plastic bag charge, which sends an economic signal to consumers, discouraging their purchase, and also allows money to be collected for proper waste management (Chen 2010). Advanced waste disposal fees are commonly charged for electronic products – whose end of life management is complicated – and for products covered by Expended Producer Responsibility (UNH 2010 p. 77). In Sousse, Tunisia, importing plastics for packaging is taxed; this money is used for projects that aim to keep plastic out of the waste stream (UNH 2010 p.80).

4.3.3. Goals

Finally, like the targets set by nations seeking to reduce their greenhouse gas emissions, some states create goals for changing their waste management systems. The EU has set as a goal the elimination of biodegradable waste in landfills, and the state of California passed legislation in 1989 (AB 939) to reduce the amount of waste landfilled by 50% in 2000.

4.4. Metrics for assessing solid waste management technologies and policies

The purpose of waste management policies and technologies is to protect human and environmental health, and as such, there exist a number of metrics to assess whether these goals are being reached. Technology-specific metrics cover performance; specifically, these metrics may be the total resulting air and water emissions, and whether they meet the reigning standards. The effectiveness of a policy may be measured by the changes it has impelled. For example, a metric for PAYT programs may be the change in waste production per capita since the implementation of the program. Increasingly, waste management systems as a whole are measured by their life-cycle greenhouse gas emissions, and alternative waste management plans are compared using that metric (e.g., Vergara et al. 2011, Christensen et al. 2009).

Waste management metrics have also been created to measure citizen's access to waste services and effective governance of waste management. Indicators used in UN-Habitat's assessment of waste management in global cities include: % waste collected, % waste disposed in a controlled manner; % waste captured by system; user inclusivity, financial sustainability, institutional coherence, and the age of the last available waste report (UNH 2010). These indicators cover measures of access – how much of the population is served by a city's waste management system? – ideals of inclusivity to ensure that all stakeholders are benefiting from the system, and principles of effective governance.

4.5. Methods for assessing waste management technologies and policies

Life-cycle assessment (LCA) has emerged as an essential method to quantify the environmental benefits and drawbacks of solid waste management options (Bogner et al. 2007; McDougall et al. 2001; Council of European Union 2008). LCA is defined as “the examination, identification, and evaluation of the relevant environmental implications of a material, process, product or system across its lifespan from creation to waste, or preferably to re-creation in the same or another useful form” (Graedel 1998). In addition to following the standard guidelines of LCA outlined by the ISO 14040 (ISO 2006), recent waste LCA analyses (those that ask: “What should we do with our waste?”) have generally adopted a system boundary that includes the waste management system, from the moment of disposal until conversion to an emission or a reusable product (Finnveden 1999). Importantly, however, product manufacture, distribution, and use are outside the system boundaries for these analyses (Gentil et al. 2009b).

Assessment of waste management systems has improved from early modeling that considered components of the system (Morrissey and Browne 2004) to LCAs with more comprehensive scopes (Christensen et al. 2009). However, differences in system boundaries and allocation methods (especially for “avoided burdens”) among models have led to considerable variation in results, even when the same system is being analyzed (Chester and Martin 2009; Kalogo 2009; Heijungs and Guinee 2007; Winkler and Bilitewski 2007). Most waste LCA studies use a system boundary that includes the management system, but not the product manufacture and use systems, tracking waste from the moment of disposal until its conversion to an emission or a reusable product (McDougall 2001). However, studies within the field of waste LCA use a variety of system boundaries that include different combinations of the energy and forestry sectors, land use changes, and displacement of virgin materials, leading to inconsistencies between studies.

Accounting for the environmental “gains” of waste management varies across studies. In most cases, waste management technologies are sources of GHG emissions. These emissions can be reduced using various measures, but those savings – say the displacement of fossil-based electricity, or reduced manufacture of goods from virgin materials – are usually credited outside the waste management system (Gentil et al. 2009a). The variation in system boundaries is partially due to differing GHG reporting methodologies. Gentil et al. (2009) show that *who* is doing the accounting – whether a national organization, an LCA modeling group, a carbon trading mechanism or other organization – dictates the system boundary used. Though LCA is supposed to be comprehensive and account for problem shifting, the exclusion of a part of a system being analyzed by allocating it to another sector (Finnveden et al. 2009), shifting still occurs due to the variation in system boundaries applied to analyses, and it is the benefit (not the burden) that is most commonly shifted (Gentil, Aoustin et al. 2009). These differences in system boundaries, and the resulting inclusion and exclusion of environmental benefits and burdens, make the comparison of different waste LCA studies difficult. The use of different waste LCA models (e.g., USA’s WARM model, Denmark’s EASEWASTE) can also lead to different results when analyzing the same system, due to differences in system boundaries and other ingrained assumptions.

Waste LCAs have also embraced a “zero burden assumption,” which takes the waste managed by the system as a given, and ignores the upstream environmental burdens associated with that waste, implicitly attributing those burdens to the products themselves and not the waste *per se*

(McDougall 2001; Ekvall et al. 2007). Additionally, biogenic carbon from waste is widely assumed to have no Global Warming Potential (GWP), as its carbon was recently sequestered from the atmosphere (Barton et al. 2008; Christensen et al. 2009; Gentil et al. 2009a; Rabl et al. 2007). But the former two assumptions are not consistent; if waste carries with it no environmental burdens, then it should not carry with it any environmental benefits either. Taking waste as a given at the point of disposal, waste managers must determine how to minimize the emission of greenhouse gases to the atmosphere going forward; the source of those gases do not matter. Past work (Christensen et al. 2009) has found that, from a decision-making perspective, counting or not counting carbon dioxide from biogenic waste can be equivalent (if biogenic carbon dioxide count as +1, and stored carbon as 0; or biogenic as 0 and stored carbon dioxide as -1). Many waste LCA methodologies state that biogenic emissions should be reported even when given a GWP of zero (Gentil et al. 2009a), but this is often not done in practice.

Another major methodological choice that LCA waste modelers make is whether to perform an attributional or a consequential assessment, where the former describes the physical flows to and from the system studied (e.g., Stokes and Horvath 2011), and the latter attempts to describe how physical flows, including those outside the physical system, will *change* in response to changes in the life-cycle (Ekvall and Weidema 2004). Though both attributional and consequential LCA are inherently uncertain, the research questions posed by the author aim to understand how the waste management system will interact and affect the environment surrounding it. In striving towards a consequential analysis, this work utilizes marginal electricity data both for the energy used by waste treatment and for the electricity displaced by waste-derived energy.

Future waste LCAs should work on building a common framework for defining appropriate system boundaries, so that studies may be studied and compared (and differences between studies cannot be attributed to modeler choices). They should also consider their results under different scenarios of carbon accounting. Finally, the waste LCA field is shifting towards consequential modeling of decisions, and is broadening from being engineering exercises to considering the social, economic and environmental implications of waste decisions.

5. Solid waste and its impact on the environment

5.1. Emission of pollutants from solid waste

Solid waste affects the environment through the use of resources for its production, its management and its disposal. Its production and lack of effective management directly affects air quality, water quality, ecological and public health, and contributes to global climate change. But even the technologies that treat waste, designed to minimize the environmental impact of waste, create their own (new) environmental impacts. Less direct impacts of waste on the environment, through the consumption of natural resources and energy to produce the wasted materials, are less often considered.

The direct impacts of waste technologies on water, land, and soil were discussed in the previous section, but are summarized below.

	Dumping/ Landfill	Incineration	Composting	Land Application	Recycling	Transport
Air/ *Climate*	CO_2, CH_4, odor, noise, VOCs / *GHGs (CO_2, CH_4, N_2O)*	SO_2, NO_x, N_2O, HCl HF, CO, CO_2, dioxins, furans, PAHs, VOCs/ *GHGs*	Odor/ *small emission GHGs*	Bioaerosols, odor/ *small emission GHGs*	*Minor GHG emissions*	CO_2, SO_2, NO_x,odor, noise, / *GHGs (CO_2)*
Soil	Heavy Metals; Organic Compounds	Fly ash, slag	Minor impact	Bacteria, viruses heavy metals. PAH, PCBs	Landfilling of residues	
Water	Leachate: Heavy Metals; Organic Compounds	Fall out of atmospheric pollutants	Leachate	Bacteria, viruses heavy metals	Wastewater from processing	Spills

Figure 5: A summary of the direct environmental impacts of various waste technologies. Adapted from Giusti (2009).

5.2. WASTE AND CLIMATE CHANGE

Climate change is among the most urgent of society's challenges, threatening biodiversity and human security, and causing increased temperatures, increased extreme weather, sea level rise, and melting glaciers, among other impacts (IPCC 2007). Though it currently contributes to less than 5% of total greenhouse gas emissions, waste management has the *potential* to either be a net contributor to or a net mitigator of climate change (Bogner et al. 2007). Any waste technology can be a source or a sink of GHGs, depending on how it is implemented. This potential can be illustrated through an example. A well-operating recycling system will efficiently collect separated waste paper from the waste stream, and the collected paper will be used to produce new paper. This recycling system has three sources of greenhouse gas benefits. (1) By displacing the use of virgin paper, fewer trees need to be harvested. The trees left standing are a GHG sink. (2) Less energy is used in the production of paper from old paper than would be in making paper from the raw material (trees). (3) This paper no longer has to be managed as a waste, and the emissions resulting from its transport and disposal are saved. However, if that same paper is collected inefficiently, say by trucks collecting co-mingled waste, then a good deal of energy is expended, but few benefits are seen. Soiled paper cannot be recycled, so the paper is wasted, though a separate collection system has been implemented, so none of the above benefits are realized.

The largest contributors to GHG emissions from this sector are landfills, where anaerobic decomposition of biogenic waste releases methane, a potent GHG whose heat trapping potential is 24 times greater than CO_2 when taken over a 100 year timescale (72 times greater over 25 years; IPCC 2007). Though methane emissions from landfills in the Global North have stabilized, these emissions from the Global South are increasing, as population, consumption, and the creation of landfills are all on the rise.

Mitigation of climate change from the waste sector can take many forms: indirect GHG reductions through decreased waste production (and thus decreased need for collection, transport and treatment); indirect GHG reductions through increased recycling, whereby mining for virgin materials decreases; direct GHG emissions reductions from increased composting and/or anaerobic digestion, resulting in reduced methane emissions from landfills; direct decreases in GHG emissions through increased landfill gas collection; and avoided GHG emissions through displacement of fossil-based electricity. Though there exists uncertainty in the contribution and mitigation potential of waste to climate change (driven by a lack of reliable waste data), displacement of materials and energy offer the largest opportunities for GHG abatement (Bogner et al. 2007).

5.3. Waste and public health

Though the relationship between waste and public health is widely recognized, these impacts are locally-specific and vary greatly within a population. Giusti (2009) reviews the relationship between public health and waste management, highlighting the most important health impacts and pointing out the gaps in the literature. Waste affects people through both its mismanagement and its technological management. A lack of proper waste management allows for its accumulation, which attracts disease vectors, can clog drains and create habitats for mosquitoes. Open burning of waste (or incineration without proper controls) emits a number of toxic substances, which directly harm people. The illegal export of toxic waste exposes some populations – those receiving wastes – to more harmful wastes. But each waste management technology also carries with it some health burdens. Living and working near landfills has been associated with congenital birth defects; proximity to incinerators is linked with cancer incidence, and breathing air near composting facilities is correlated to respiratory illness (Giusti 2009). From a health perspective, phasing out open dumping and open burning of wastes are priorities (UNH 2010).

These impacts are differential; poor waste management affects the poor more than the wealthy (UNH 2010). Poor people are more likely to be exposed to waste, and they are also more likely to be waste workers, whose occupation necessarily involves exposure. Solid waste workers tend to have higher injury rates and higher infection rates, as well as higher occupational hazard rates than the baseline population (UNH 2010). Informal waste workers are the most impacted. Because of their economic status, "many…prefer to sell their gloves, shoes and special clothes in order to receive money and buy food" (UNH 2010 p.16). The root of this additional exposure is income inequality and poverty.

More health studies are needed, because those that exist seek to quantify their impact are observational, and suffer from missing data, a lack of evidence of direct exposure, and confounding factors (Giusti 2009).

5.4. Ecological health

Waste management and disposal are a form of land use change, altering the habitat of the species with which humans share the planet. But more acute than changes in the land, the emission of toxic chemicals is harmful to flora and fauna. The most hazardous of these wastes – hospital, electronic, and industrial hazardous – can be released directly to the environment if dumped or burned openly. The most visible, large-scale impact of garbage on our planet is the emergence of the Great Pacific Garbage Patch, a vortex of 3.5 million tonnes of plastic that covers an area the size of France, "causing birds and mammals to die of starvation and dehydration with belles full of plastics, where fish are ingesting toxins at such a rate that soon they will not be safe to eat" (UNH 2010 p. 104). This patch demonstrates the human ability to impact the health of the planet on a large scale.

6. Recent trends: towards building more perfect waste management systems

Waste management studies and policies are shifting in response to new information and new challenges. I identify some broad trends, and explore their implications. In terms of waste governance, there seems to be increased interest in public participation in decision-making, as well as a movement away from seeing waste management as a merely technical problem with technical solutions. Stemming from this broadening of waste management to include other disciplines and the public, there has been increasing attention given inside the household, to the consumer, as an active participant and potential change-maker. Concepts of Industrial Ecology encourage a new framing of the waste management system; this perspective holds that people, cities, and societies can be conceptualized as organisms, and an improved balance with our surrounding environment can be found by imitating waste management found in nature. Stemming from this interest in closing the loop from production to consumption, the importance of smart production and design for reuse, has emerged as another tool with which to improve the end-of-life management of materials. Globally, many waste management studies have concluded that waste management requires locally-specific solutions; there is no one-size-fits-all prescription for effective management. And finally, in the Global South, cities are attempting to 'modernize' their waste management, often through motorization, privatization, and a struggle to involve the informal sector.

6.1. New conceptual approaches: industrial ecology

Increased attention to resource recovery and recycling has prompted scholars, policy-makers, and even industries to consider new approaches to waste management. The field of industrial ecology was born out of the desire to re-conceptualize waste as an input, not only an output. The industrial ecology system, first defined by Frosh and Gallopoulos in 1991, is like a biological system, in that it seeks not only to minimize waste production, but also maximizes the use of waste materials as inputs into other processes (Frosh 1992). Though only recently defined, examples of Industrial Ecology reach far back in history. Desrochers (2002) looks at Victorian industries, and finds that reuse and repair were the dominant modes of 'waste' management for industries as well, because "creating wealth out of industrial by-products typically proved more favorable in the long run than throwing them away (Desrochers 2002 p 1042). In fact, he finds the birth of the Industrial Ecology concept a full century before it was given such a name. His work is replete with quotes from Victorian industrialists, such as Simmonds, who said in 1875: "wherever we turn we find that the most trivial things may be converted into gold, the refuse and lumber of one manufacture or workshop is the raw material of another" (Desrochers 2002). Desrochers argues, in contrast to other historians, that market barriers implemented in the 20th century, such as environmental legislation regulating the use of waste, are responsible for the widespread decline in industrial resource recovery.

The Industrial Ecology approach breaks substantively with the 'end of pipe' solutions that have long been the centerpieces of city's waste management plans. The field is even in opposition to pollution prevention and cleaner production, as these concepts define waste as a necessary environmental harm to be minimized, where IE approaches view waste as a resource (Erkman 1997).

An Industrial Ecology approach leads to three changes in waste management: a move from waste legislation to "material flow legislation" (Desrochers 2002), purposeful design of materials for reuse (Frosh 1992), and co-location of industries so that they may interact symbiotically. By ceasing to make a distinction between 'waste' and other products, governments will remove barriers to recycling and reuse. Desrochers (2002) gives the example of waste in Austria, where any product labeled as 'waste' must be considered under the very stringent waste management laws – even if the product is functionally equivalent to a non-waste product on the market. In the United States too, when a product has been labeled as 'discarded' or 'hazardous,' its further use requires major bureaucratic approval (Desrochers 2002). Designing waste for its repair and reuse facilitates its conversion to a useful product. A bicycle is an example of an object designed for reuse; it is easily disassembled, and as parts wear down, each may be replaced independently. Finally, the co-location of industries has occurred spontaneously in industrial parks, the most famous of which is in Kalundborg, Denmark. Here, an oil refinery, a coal-fired power plant, a gypsum board production facility, a pharmaceutical plant, the city of Kalundborg, and surrounding farms share water resources, waste water flows, steam, electricity, and feedstocks, such that wastes from one facility flow into the next as an input (Chertow 2000).

6.2. RECOGNIZING THE IMPORTANCE OF PRODUCERS AND CONSUMERS IN WASTE MANAGEMENT

Increasingly, waste scholars and policy makers are recognizing the important role of the producer of goods in creating waste that is more easily managed. Producers have the capability of making reusable products, but also have the power to use responsible materials. The "green chemistry" movement seeks to "design chemical products and processes that reduce or eliminate the use and generation of hazardous substances" (Mulvihill et al. 2011). This purposeful design has two benefits: by purposely selecting materials that are biological or contain less embodied energy (in the case of recycled inputs), producers decrease overall energy consumption and they facilitate the reuse of those products.

More research is now focusing on the step following production – consumption – as another process influencing the quantity and make-up of waste produced. Consumption is a social and cultural process, dependent on a variety of factors that are not fully understood. Understanding consumption – and what drives sustainable consumption – is essential for understanding how consumers may be a source of change for waste management. Consumers have also started their own movements, from voluntary simplicity – a movement to consume and produce little (Shaw and Newholm 2002; McDonald et al. 2006) – to green consumption. The green consumption movement is concerned with both decreasing material consumption and consciously selecting the products bought to be the most environmentally responsible (Peattie 2010). Understanding the factors that lead to sustainable purchasing and waste behaviors is an active area of research.

Green consumption may be divided into three categories: purchasing choices, habits, and recycling (Peattie 2010). An individual's purchasing habits are linked to a consumer's environmental attitudes; having a strong environmental ethic is associated with their willingness to pay more for green products, and to engage in more waste reduction and reuse behaviors. This association is absent for recycling behaviors, for which "normative social influence" has a dominant effect (Peattie 2010, p. 207; Ekere 2009). Normative behavior also impacts energy consumption; hotels have found that more people reuse towels when signs claim that the majority of people reuse towels than when signs simply state that towel reuse has environmental benefits.

A recent proliferation of environmental labeling suggests that consumer choices are based on the best-available information. However, there is evidence that most of consumption choices are not conscious; most consumer decisions are in fact mundane, habitual acts. Then, to affect behavior change, one would need to tackle baseline behavior, not just occasional purchasing decisions. Further complicating the methods with which to change consumer choices, a person's self-identity also affects their purchasing and behaviors (Peattie 2010); if one defines oneself as an environmentalist, one is more likely to engage in green consumption behaviors. From the perspective of policy-makers seeking to encourage environmentally-friendly waste behaviors, marketing approaches could help increase the adoption of green consumption behaviors, to make them more "normal" and mainstream (Rogers 1995).

Environmental labeling, while raising consumer awareness of the effects of the choices they make, has two unfortunate side-effects. One is that it can be misleading. If labels do not contain overall environmental assessments, they may be picking and choosing criteria that make a product seem more friendly than it is. Second, some green-sounding attributes may not actually be beneficial to the environment, as in the case of product biodegradability (Levis and Barlaz 2011).

6.3. Waste as more than just a technical problem, which requires public participation

The attention that both production and consumption are receiving as nodes in the waste management chain mark a more general trend, away from seeing waste management as a merely technical problem with technical solutions. Increasingly, waste management is seen as a process that requires cooperation from users, good governance, and public participation (UNH 2010). The need for stakeholder participation in the development of effective waste management is now accepted. In fact, "engaging users and facilitating their communication with the city and the providers is arguably the most important factor for effective waste collection" (UNH 2010 p. 102). The recognition of human factors in waste management is relatively new, but widespread. The definition of Integrated Waste Management actually requires inclusivity of generators, of providers, and of information. A telling example about how participation can make the difference between a poorly functioning system and a well-functioning one comes from

Tompkins County, New York, USA. The region needed to select a site for a new landfill, so the local authorities held town meetings in a number of potential locations. Engaging users by asking what they would want if their community were selected to host a landfill, the community made a list of requirements. In the end, the total cost of what the community desired in exchange for the landfill arriving in their community was a small fraction of what is normally spend in legal battles between communities and the waste company. The community was happy, and received a new school, a guarantee for stable housing prices, and a host community fee (UNH 2010).

6.4. The need for local solutions

Another trend in waste studies is recognizing that there is no "one size fits all" solution to managing waste. A great number of variables – environmental, social, cultural, and economic – determine the appropriate set of technologies and policies to govern and manage waste in a city. The diversity of cities, the diversity of the waste they produce, and the diversity of waste management methods available point to the need for local solutions, adapted to the local conditions. The need for local solutions is especially important to recognize, given a history of failed attempts to import waste solutions from the Global North to the Global South. In the past, many waste studies assumed that developing world waste systems were "incomplete copies of an ideal system that operates in developed countries" (UNH 2010 p. 4). Following this logic, many companies and governments sought to transfer technologies from north to south. In 1984, the Municipal Corporation of Delhi built an incinerator designed to process 300 tonnes waste/day and produce 3 MW power, with Danish technical assistance. The plant, however, was designed to treat source-separated waste, even though this behavior not practiced by households or the municipality. Because the waste composition was much wetter (and less energy-dense) than the designs called for, the incinerator closed down within a week. Similarly, in 2003, the Lucknow (India) Municipal Corporation built an anaerobic digestion plant, provided by private companies in Austria and Singapore, designed to produce 5MW energy and process 500-600 tonnes of Municipal Solid Waste each day. The digester did not operate a single day, due to "the difference between the design assumptions that were based on European waste and waste management practices and the actual field scenario in India…A better approach is the other way around, when the characteristics of the waste stream and a good understanding of local conditions form the basis for choosing management strategies and technologies" (UNH p114). Cities are recognizing the need for adapted, local, sustainable solutions.

6.5. Modernizing waste systems in the Global South

Finally, a combination of factors is leading to the "modernization" of waste management systems in the Global South. A number of forces drive this process, including those named above (public health, environmental protection, resource value, climate change, and modernity). As part of the modernization, there has been a trend towards the privatization and the motorization of waste management systems. Though privatization does give a financial incentive to operate efficiently, private companies do not have an incentive to provide full coverage to cities – rather, they have incentives to reach those who can afford to pay. In Sousse, Tunisia, collection has partially privatized waste collection, but the city has "plans to keep at least 25% in public hands so that it understands the costs, maintains competition, and maintains the human resources and institutional capacity to operate collection in the future. This decision prevents the municipality from being fully dependent on one company for the collection of a whole city" (UNH 2010 p. 80). Finally, the motorization of collection is a part of many cities' waste management plans. Bamako (Mali) recently outlawed the use of donkeys on paved roads, and plans on replacing them with trailers. But there remains a question about whether collectors will be able to afford the fuel to drive the motorized vehicles. Similarly, Bogota Colombia has passed a law outlawing the use of horses on streets by 2012, putting thousands of recyclers out of business. The implications of this law on their livelihoods and on the quantity of waste recycled in the city have yet to be seen. A final trend in the Global South is towards receiving carbon financing for their waste plans. The Clean Development Mechanism is used to finance carbon-abating projects in developing countries, and because a GHG accounting methodology exists for landfilling, the majority of waste projects financed in this manner have been landfills. Perversely, increasing the number of landfills in areas that have a high biodegradable fraction in their waste may result in greater greenhouse gas emissions than more open dumping (though of course dumping has many other negative environmental impacts; Bogner et al. 2007).

7. Summary and conclusions

Our planet is producing more, increasingly complex solid waste, and this waste is concentrated in cities. People have created a number of technologies and policies to manage this waste, and to minimize the environmental and public health hazards posed by it. Promising trends in the integrated management of municipal solid waste range from innovative institutional arrangements, to increased attention on the role that the consumer plays in creating and treating waste, to new technologies that effectively treat waste as a resource. Challenges still remain, and the largest among them include: integrating the informal sector into long term waste management plans in the Global South, collecting more data on waste production and treatment, using standardized definitions for waste, and abating the greenhouse gas emissions that arise from solid waste.

Because effective waste management is context-specific, the following chapters examine the climate benefits of reuse-centered waste management in two particular, different contexts. First, I focus on the state of California (USA), a state that has taken bold action on many environmental fronts, and is a prolific consumer of Municipal Solid Waste, and look for greenhouse gas reductions that can be found there in treating its waste as a resource. The final sections of this dissertation are devoted to the social and environmental trade-offs of the Bogotá's plans to formalize its recycling sector.

Chapter 2. Greenhouse gas emission reductions from alternative waste treatment strategies for California's Municipal Solid Waste

1. Introduction

1.1. Goal and Problem Statement

How waste is managed directly affects local and global environmental quality. Waste transport, treatment and disposal impact local and global air quality and can pollute water and contaminate soil. Waste management can also either aggravate or mitigate climate change (Bogner et al. 2007), an urgent global consequence to which the present discussion is directed. Though there are many important environmental effects of waste management, the focus of this paper is on its climate change implications because the urgency of climate change requires an analysis of the greenhouse gas implications of all aspects of our economy, and because there is uncertainty about the contribution of waste-related emissions to climate change. The most recent IPCC report suggests that post-consumer waste is responsible for less than 5% of global GHG emissions, though the IPCC analysis includes only the negative impacts of waste and is not a life-cycle assessment. Importantly, the authors state that this estimate is both highly uncertain and can be mitigated by increasing waste reuse, recycling, and energy utilization (Bogner et al. 2007).

A steady increase in global waste production provides both a problem – how to manage this waste without negatively impacting the environment – and an opportunity, as more waste can be combined with technologies and policies that can allow for improved waste reuse. This chapter analyzes the GHG emissions from several alternatives for the treatment of municipal solid waste in the United States, a nation that is one of the highest waste producers in the world. Because local conditions determine the political feasibility and the environmental impacts of differing waste management scenarios, this analysis is a case study in a place that has taken bold action on several environmental fronts (Hanemann 2008): California. It has the largest economy of all the states, and is a major producer of MSW. Due to these factors, it is a place where radical new waste management solutions may be implemented, and the case study serves as an illustration of the types of mitigation possibilities available for high waste-producing regions.

The purpose of this chapter is to answer: *what else can be done* with the material fractions that are currently reaching landfills. Because the recycling efforts in California are already strong and the low-hanging fruit of recyclables have already been picked, the assessment focuses on material fractions that can be effectively managed through new means: either with alternative technologies or behavioral change.

The aims of this paper are two-fold: (1) to help guide solid waste management policy in California by analyzing waste treatment scenarios for their climate mitigation potential, and (2) to explore uncertainties in solid waste life-cycle assessment (LCA) methodology used to analyze alternative management strategies. This study is an opportunity to examine the roles that alternative technologies and consumer behavioral change could play in reducing GHG emissions from California's waste, and also how modeling choices affect the final results of the assessment. I apply life-cycle thinking to look critically at alternative waste management plans, as suggested by the EU waste framework directive (Council of the European Union 2008). This is the first study that compares different treatment options for California's waste that includes both technological and behavioral solutions, and is the first analysis that uses the Danish model, EASEWASTE (Kirkeby et al. 2006), to analyze waste management in the United States. The results from this model are compared to those obtained using WARM, the US Environmental Protection Agency's model (2006).

1.1. Background

Life-cycle assessment is "the examination, identification, and evaluation of the relevant environmental implications of a material, process, product or system across its lifespan from creation to waste, or preferably to re-creation in the same or another useful form" (Graedel 1998). As such, LCA has emerged as an essential method to quantify the environmental benefits and drawbacks of solid waste management options (Bogner et al. 2007; McDougall et al. 2001; Council of European Union 2008). In addition to following the standard guidelines of LCA outlined by the ISO 14040 (ISO, 2006a; ISO 2006b), recent waste LCA analyses (those that ask: "What should we do with our waste?") have generally adopted a system boundary that includes the waste management system, from the moment of disposal until conversion to an emission or a reusable product (Finnveden 1999). Importantly, however, product manufacture, distribution, and use are outside the system boundaries for these analyses (Gentil et al. 2009b).

As discussed previously, waste LCAs generally apply a "zero burden assumption," which takes the waste managed by the system as a given, and ignores the upstream environmental burdens associated with that waste, implicitly attributing those burdens to the products themselves and not the waste *per se* (McDougall 2001; Ekvall et al. 2007). Additionally, biogenic carbon from waste is widely assumed to have no Global Warming Potential (GWP), as its carbon was recently sequestered from the atmosphere (Barton et al. 2008; Christensen et al. 2009; Gentil et al. 2009a; Rabl et al. 2007). Past work (Christensen et al. 2009) has found that, from a decision-making perspective, modes of accounting for carbon dioxide emissions from biogenic waste can be equivalent. This analysis explores whether counting and characterizing biogenic carbon emissions can alter the results of a waste LCA.

Another major methodological choice that LCA waste modelers make is whether to perform an attributional or a consequential assessment, where the former describes the physical flows to and from the system studied (e.g., Stokes and Horvath 2011), and the latter attempts to describe how physical flows, including those outside the physical system, will *change* in response to changes in the life-cycle (Ekvall and Weidema 2004). This chapter takes a consequential approach, and uses marginal electricity data both for the energy used by waste treatment and for the electricity displaced by waste-derived energy.

2. Methods

2.1. Scope and functional unit

The boundaries of this study are both theoretical and geographical. First, the study compares the downstream environmental benefits and impacts of the *management* of MSW, not the generation or production of that waste. Figure 6 provides a schematic of the system boundary used, which begins with its collection at the curb, and ends with its conversion to an emission or inert substance. This system has very important interactions with the outside world, namely in construction of each facility used, emissions to the environment, and in energy use and production. The spatial boundary is the California border, including only waste that is handled within the state. The state exports a small fraction (~1%) of its disposed waste (CalRecycle, 2010); this fraction is not included in the analysis.

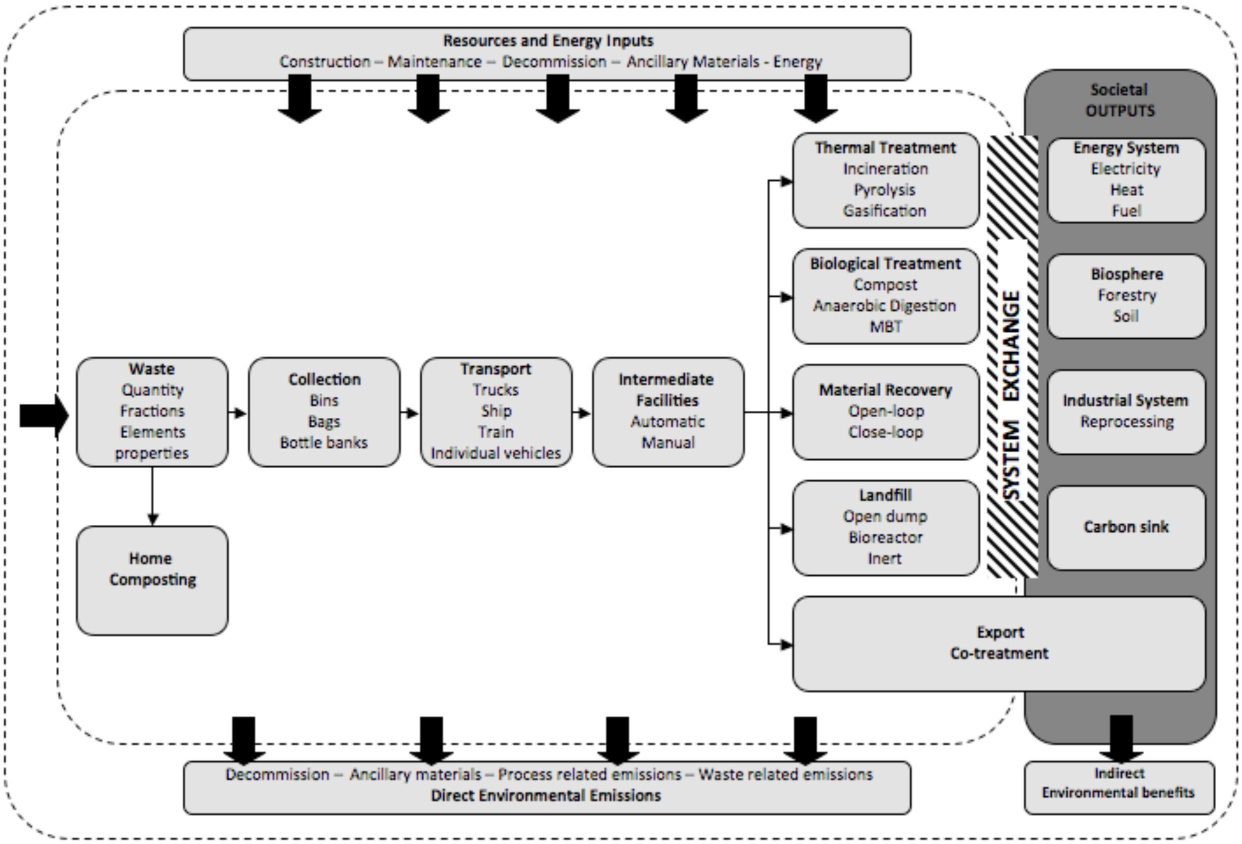


Figure 6: System boundary for LCA of solid waste management system. The dotted line shows the boundary for the waste management system, and the large box shows the boundary for the LCA. Used with permission from Gentil et al., 2010.

The functional unit for this analysis is 1 tonne of MSW produced in one year, as collected curbside. The composition of the waste considered in the study is that of California's residential and commercial solid waste in 2004 that was landfilled. Importantly, 48% of the waste generated has been removed from the waste stream, to be recycled, composted, or reused (CIWMB 2008). The net GHG emissions associated with the following waste management scenarios are analyzed:

(1) **Business As Usual** (BAU), the current management plan, in which all that is currently landfilled continues to be landfilled, and 64% of landfill gas (LFG) is collected during the active collection phase (based on median value for California landfill gas collection, Themelis and Ulloa (2007)).
(2) **40% Reduction**, in which 40% less waste, across all *residual* material fractions, is generated by Californians, but is managed like BAU. This source reduction can reflect a reduction in overall consumption (fewer purchases, same waste rate), or a reduction in what is thrown away

(same consumption, smaller waste rate).
(3) **Incineration**, in which inorganic non-combustible waste is sorted from combustible waste in a MRF and sent directly to a landfill, the energy-rich, combustible fraction of MSW (e.g., plastics and paper) is co-combusted with 20% of the biogenic waste (e.g., food waste) in an incinerator, producing electricity, and the rest of the waste is sent to the landfill.
(4) **Anaerobic Digestion** (AD), in which biogenic waste (mostly food waste, not including paper) is digested and methane is recovered and burned for electricity production, and the rest of waste is sent to the landfill.
(5) **Maximization of Waste-to-Energy** (MaxEnergy), in which biogenic waste is digested and methane is recovered and utilized, inorganic non-combustible waste is sorted from combustible waste in a MRF and sent directly to a landfill, and the inorganic combustible waste is incinerated to produce electricity.

The mass flows for each scenario, as well as the assumed distances that waste travels between treatment steps, are illustrated in Figure 7:

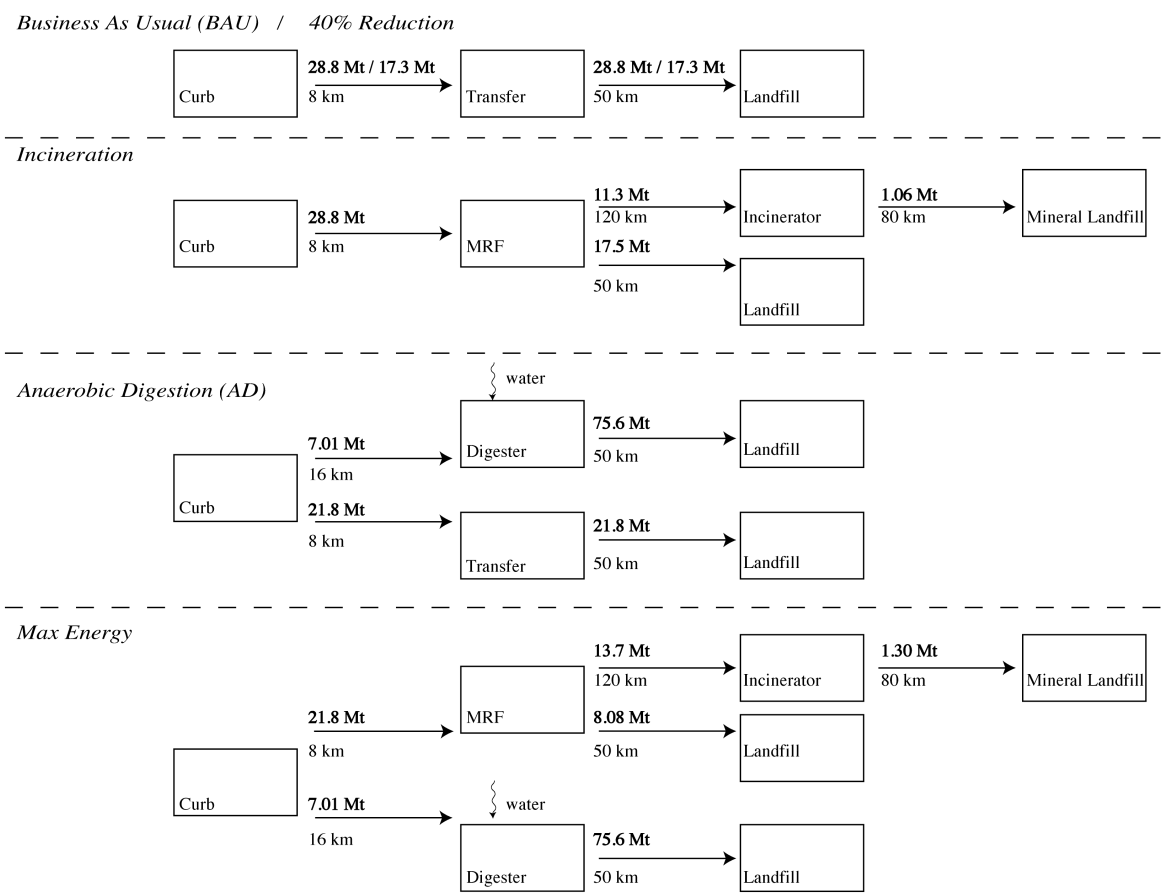


Figure 7: Mass flows (in Mt, million tonnes, CO2-e) and transport distances (in kilometers) for each waste scenario. Incineration and Max Energy scenarios include waste sorting at Material Recovery Facilities, and

the other scenarios do not require further sorting, and use transfer stations to move the waste to larger vehicles. All landfilled MSW goes to the same landfill.

The scenarios explored represent feasible changes to use California's waste as a resource. Business as Usual (BAU) describes the waste management system as it is currently, and thus is the baseline to which all other scenarios are compared. Scenario 2, 40% Reduction, describes a significant reduction in residual waste generation, but no change in the management of waste. Despite California's success in achieving 50% waste diversion – that is, keeping 50% of California's residual waste out of landfills – source reduction (decreasing the mass of waste produced by simply throwing less away, either through increasing reuse or decreasing consumption) is not currently being considered as a method to achieve the GHG reductions called for by California's Assembly Bill 32 (CARB 2008). I propose a 40% source reduction – a reduction in the amount of waste thrown away by Californians – as a feasible and potentially robust means of reducing GHG emissions from the waste sector. Scenario 3 explores anaerobic digestion of organic wastes; this technology is cited by the California Air Resources Board as being capable of reducing GHG emissions state-wide by 2 Mt CO_2-equivalents per year. This analysis independently assesses the emission reductions that can theoretically be achieved by digesting biogenic MSW. Finally, two scenarios analyze whether incineration of waste can play a role in reducing GHG emissions; one calls for the separation and incineration (with energy production) of inorganic and energy-rich waste components, and the other combines incineration with digestion of biogenic waste. Historically unpopular in California but widely used in Europe in waste management, incineration is not cited in the AB32 Scoping Plan as a strategy for reducing emissions from waste (CARB 2008).

To understand the environmental impact of these different waste diversion schemes, two models are used. The first is EASEWASTE, a model developed by the Technical University of Denmark, and fully specified in Kirkeby et al. (2006). This model is flexible, allowing the user to input values for every stage of the waste management process, and also contains empirical data and process models for the performance of solid waste transport and treatment technologies (e.g., trucks, material recovery facilities, landfills, digesters, incinerators). Anaerobic digestion and incineration are considered as potential technologies for California's waste because they have been applied broadly and successfully for solid waste treatment, most commonly in Europe, and thus can be feasibly and rapidly deployed.

The scenarios were also modeled using the Waste Reduction Model (WARM) (US EPA 2006), created by the United States Environmental Protection Agency, to see how the GHG benefits estimated differ by the model used. While WARM has been used broadly in US-based analyses, EASEWASTE has not yet been used in a US-context.

2.2. Data and Modeling Assumptions

This analysis relies on data from the California waste management system, as well as from its energy system. The main input to our model is the quantity and composition of California's disposed municipal solid waste, as collected curbside, over the course of one year. The "diverted waste" – to composting or recycling facilities – has already been removed. This analysis focuses on this disposed fraction of waste – the waste that is currently being sent to landfills – to explore what *else* (other than increasing material recycling) can be done to reduce GHG emissions with California's waste once it is thrown to the curb. The characteristics of California's residential and commercial MSW are shown graphically in Figure 8 (CIWMB 2004). From this figure, we can see that 70% of the MSW that is currently disposed can be used for energy production: 34% of waste is "organic," defined by California´s Integrated Waste Management Board as food waste, yard waste, textiles, and manure (this fraction is referred to as "biogenic"), 25% is paper, and 11% is plastic. This analysis excludes self-hauled waste. To input California's waste into EASEWASTE, the 66 material fractions specified in CIWMB (2004) were converted into the 48 material fractions used in EASEWASTE, and the 34 material fractions used in WARM.

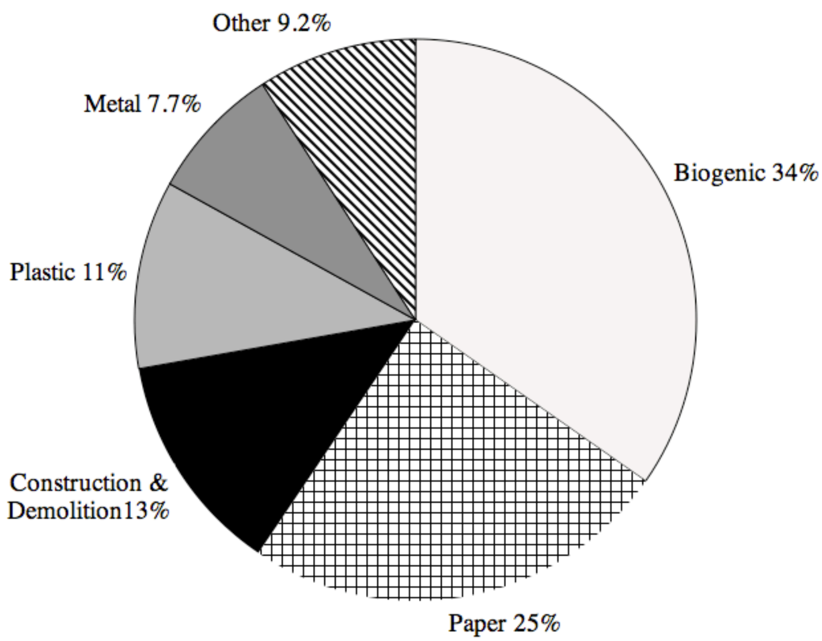


Figure 8: Material types in California residential and commercial Municipal Solid Waste, by mass. Source: CIWMB, 2006. "Other" includes glass (2.7%), electronic (1.4%), special waste (3.6%), mixed residue (1.3%) and household hazardous waste (0.2%). Total may not sum to 100% due to rounding.

Distances traveled by waste collection vehicles are modeled after average values for Alameda County, California (Carr 2008; Padia 2010) and are shown in Figure 7. Because most of California's population resides in one of two metropolises (the San Francisco Bay Area and the Los Angeles basin), waste transport in the state can be modeled as waste transport in an urban county. The assumption to model the system after an urban area is strengthened by the exclusion in the analysis of all self-hauled waste; this waste is likely to come from rural regions that are not served by municipal haulers. When using the EASEWASTE model, landfill behavior is modeled after Manfredi and Christensen (2008), and follows a generic landfill process model – 10 m deep and 100 year timeframe – found in EASEWASTE. Landfill gas capture data come from Themelis and Ulloa (2007), who provide empirical California landfill gas capture rates. Incinerator emissions and operation data are borrowed from an existing dataset on a conventional grate furnace incinerator in the Danish municipality of Aarhus, and anaerobic digester performance data come from a generic digester model within EASEWASTE. The life-cycle impacts of the incinerator are described fully in Riber et al. (2008).

For the WARM model, the user inputs are fewer. The waste composition for the baseline and alternative scenario and the overall distance traveled by waste are the same data used in EASEWASTE, and the landfill gas capture rate of the landfills used is taken from Themelis and Ulloa (2007). Other assumptions in the WARM model are described in US EPA (2006).

All scenarios specify energy recovery from waste. California's electricity baseload demand is met by nuclear power, hydropower, natural gas and other renewables (McCarthy et al. 2008). The technologies that ramp on and off according to demand include system imports and natural gas technologies (natural gas steam turbine, natural gas combustion turbine, natural gas combined cycle and system imports). In this analysis, I assume that any energy produced displaces the marginal unit of electricity in California, which almost always comes from natural gas combustion (Marnay et al. 2002, Stokes and Horvath 2009). Landfill gas collection from landfills for all scenarios begins 2 years after landfill construction, capturing 64% of gas produced for 35 years. Of the gas collected, 70% is used for electricity production and 30% is flared (Themelis and Ulloa 2007). After 35 years, gas produced in the landfill is vented, since at that point the concentration of methane is usually too low for combustion.

3. RESULTS

3.1. EMISSIONS FROM WASTE MANAGEMENT STRATEGIES IN CALIFORNIA, ASSUMING NATURAL GAS AS MARGINAL ELECTRICITY SOURCE

All scenarios are compared to "Business As Usual" (BAU) to see if alternative scenarios are preferable to how waste is currently being handled, from a GHG management perspective. I plot the results of this analysis in Figure 9. Here, we can see that collection and transportation contribute modestly to the life-cycle greenhouse gas emissions from each scenario, as compared to "treatment, recovery, and disposal." Even though emissions from collection and transportation are much smaller than the emissions from waste treatment, these emissions still total about half a million tonnes of CO_2-equivalent (CO_2-e), corresponding to about 10% of the total emissions savings from the transportation sector called for in AB32, the Global Warming Solutions Act of 2006 that established a GHG reductions goal as law. The waste reduction scenario (40% reduction) boasts GHG reductions from collection and transportation alone that would achieve 4% of the savings called for from California's transportation sector (CARB 2008).

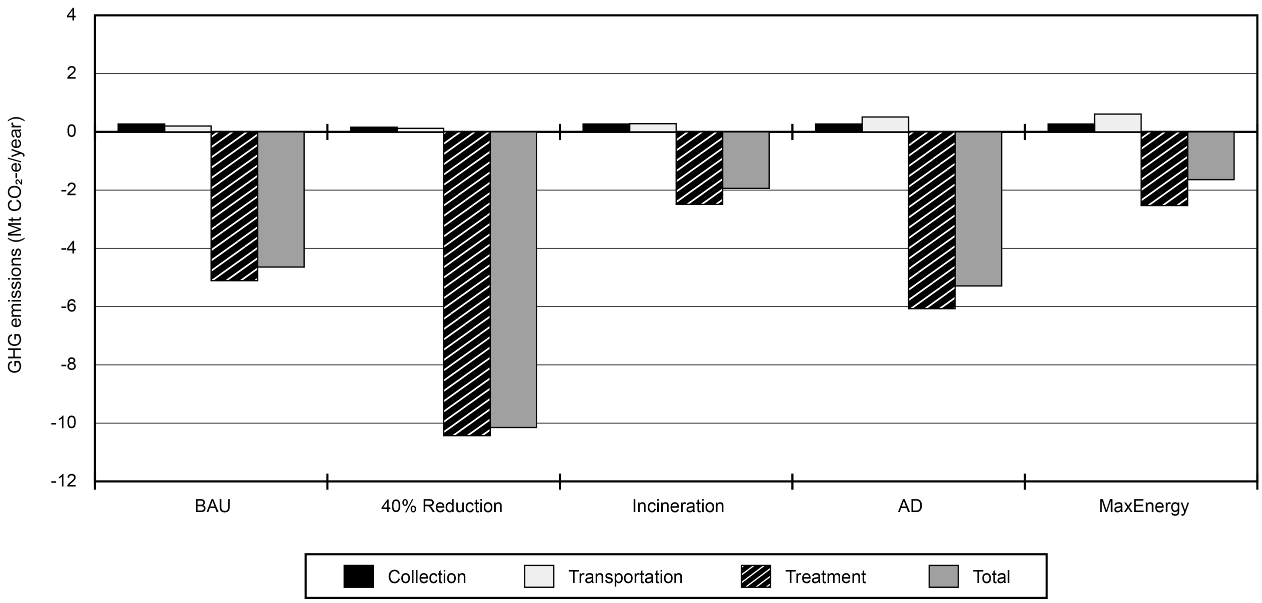


Figure 9: Life-cycle GHG emissions (in Million tonnes CO2-e) from alternative scenarios for managing California's Municipal Solid Waste, calculated using EASEWASTE.

Waste treatment – the category that includes all the processing of waste, including sorting, anaerobic digestion, incineration, and landfilling – contributes most to the GHG emissions from waste and to the variation between scenarios. Net GHG emissions vary greatly between scenarios, and two scenarios – Source Reduction and Anaerobic Digestion – achieve net GHG savings from Business As Usual. Focusing solely on California's biogenic, digestible waste and digesting it to produce electricity can lead to a GHG reduction of 0.6 Mt CO_2-e as compared to BAU; this estimate is slightly lower than CARB's estimate of 2 Mt CO_2-e from digestion (CARB 2008). Finally, even though 40% Reduction only receives credit for GHG savings that occur downstream of the materials becoming waste – the upstream savings lie outside the scope of this analysis (Gentil et al. 2009a) – the scenario has the lowest net GHG emissions. If Californians produced 40% less residual waste, GHG emissions from waste management would decrease by 6 Mt CO_2-e. Implementing either Incineration or MaxEnergy as waste management strategies would emit an additional 3 Mt CO_2-e to the atmosphere.

Figure 9 is computed using the broadly accepted assumption about biogenic carbon emissions: that they do not represent a net contribution of GHGs to the atmosphere. The argument is that biogenic matter recently sequestered this carbon, so its subsequent release does not represent an addition of carbon to the atmospheric stock.

3.2. Sensitivity Analyses

3.2.1. Landfill behavior

Figure 9 shows that there are methods to substantially reduce GHG emissions from California's waste management. To understand the robustness of these results, four sensitivity analyses are undertaken: on how the results would differ if biogenic carbon emissions were counted as contributing to global warming, on how sensitive the results are to assumptions about landfill gas collection rates, on how the selection of an LCA model can affect GHG emission results, and on the importance of the modeler's assumption of what sort of electricity is displaced. Understanding how the results are altered by these assumptions will allow for an understanding of the conditions under which GHG reductions can be achieved.

Figure 10 shows how the estimated GHG emissions from BAU change with varying assumptions about landfill behavior by comparing BAU to two other bounding scenarios: LFG16, in which 16% of generated landfill gas is collected over 35 years for electricity production, and LFG80, in which the landfill gas recovery rate is 80% over 35 years. The variation between the three landfill scenarios results in life-cycle GHG estimates that differ from the average LFG collection rate by a factor of 1.5. The reason for this large difference is that the uncollected methane is a more potent greenhouse gas than carbon dioxide, and the higher collection rates mean a larger amount of methane converted to CO_2. Assumptions about landfill performance can, therefore, greatly impact the results of waste life-cycle analyses.

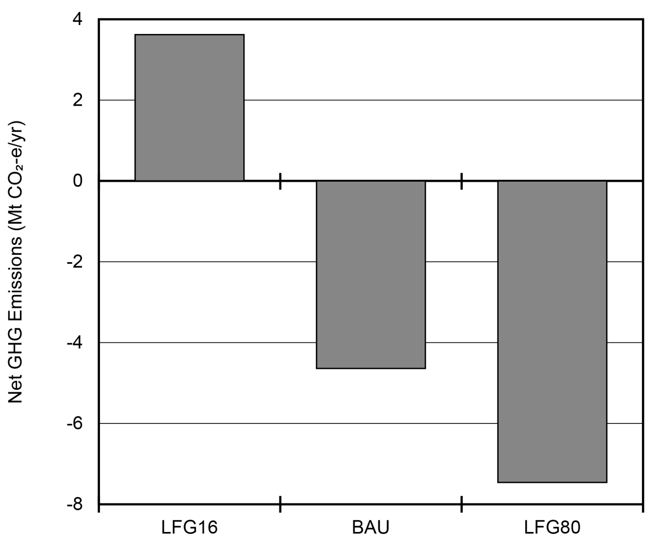


Figure 10: GHG emission sensitivity to landfill gas collection rates, calculated in EASEWASTE, in Million tonnes CO2-e. LFG16 represents a BAU scenario, but with landfills with low gas collection (16% over 35 years); LFG80 is a BAU scenario with high landfill gas collection (80% over 35 years). BAU has a landfill gas capture rate of 64% over 35 years.

3.2.2. ELECTRICITY DISPLACEMENT

All scenarios shown in the above figures assume that any electricity produced from waste displaces the marginal source of electricity in California, natural gas (combined cycle). To explore how sensitive the results are to this assumption, Figure 11 shows the changes in net GHG emissions for each scenario if the waste-derived energy were instead displacing coal or wind power, which represent extremes of carbon intensity for electricity production, and thus are bounding cases. Coal may be displaced by waste electricity in the short-run in places that rely heavily on coal-fired power plants, and wind power may be displaced by waste in areas that have adopted a policy like a Renewable Portfolio Standard, requiring a certain percentage of electricity to come from renewable sources. In this case, entry of a new renewable source to the grid would simply knock off another, more expensive, low-carbon source of electricity. It is unlikely that the entry of a large amount of electricity to the grid would result in the displacement of only wind power, however, given its intermittency. Figure 11 shows how the life-cycle GHG emission results for each scenario would change if the displaced electricity were altered.

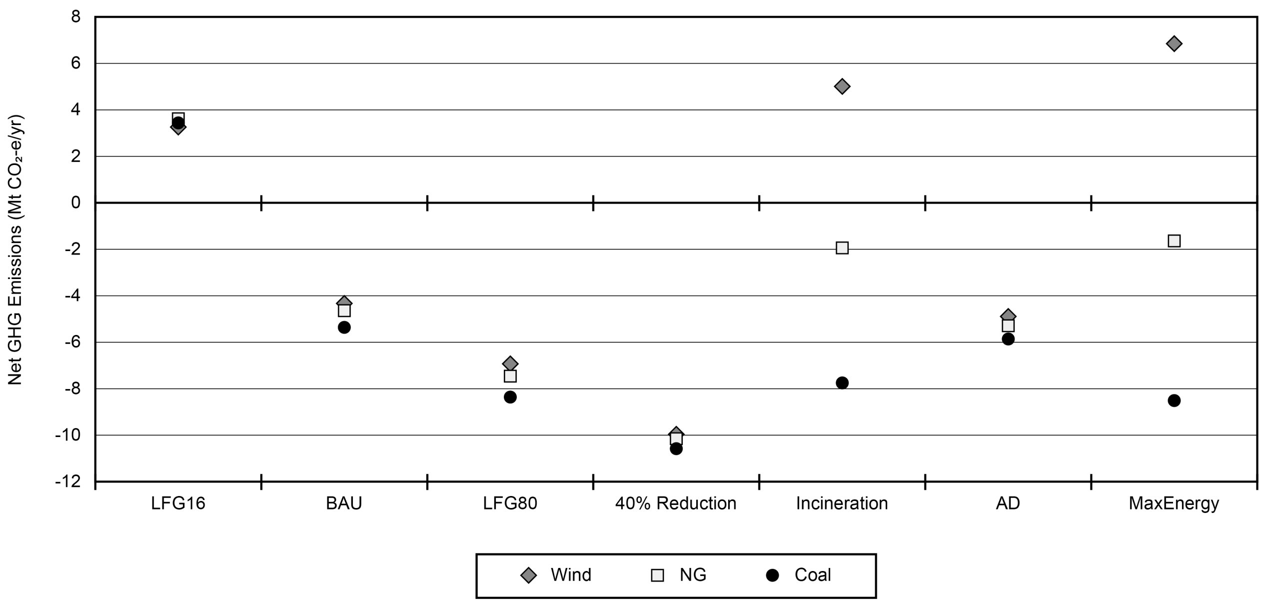


Figure 11: Electricity type displaced by waste-derived electricity affects climate impact (in Million tonnes CO2-e) of scenarios for treatment of California´s MSW. Calculated using EASEWASTE.

The distance between bounding cases (triangles to circles) grow larger as more electricity is derived from waste. This makes intuitive sense: the more coal that is displaced, the larger the GHG benefit, and the more wind that is displaced, the larger the GHG burden. Thus, for the case of LFG16 (BAU but with very low landfill gas collection), the three displacement scenarios are roughly equivalent. With higher gas collection (in the case of LFG80), the difference between scenarios grows.

For the high energy producing scenarios, Incineration and MaxEnergy, the selection of electricity type displaced greatly affects the estimate for life-cycle GHG emissions. In fact, if MaxEnergy's waste electricity displaces coal, it becomes one of the lowest emitting scenarios; if its electricity displaces wind, it is the highest emitting scenario. Similarly, for Incineration, when its electricity replaces coal it is among the lowest emitting scenarios, and when it instead knocks wind off the grid, it is among the highest emitting scenarios. The life-cycle emissions associated with each scenario varies strongly with the assumed electricity displaced; this assumption alters the order of preferred scenarios, and shows that it is extremely important to understand that changes to waste management impact the energy system and vice versa. Understanding the nexus between the waste and energy systems is crucial to understanding the environmental impacts to changes in waste management programs.

3.2.3. Variation between models

I compare the results using EASEWASTE with those obtained from running the scenarios using the US-based model, WARM. Unfortunately, only a subset of the scenarios can be analyzed using WARM, because the program does not consider anaerobic digestion as a waste treatment technology. Figure 12 shows the net emissions predicted for three scenarios using WARM, and the variation in the estimates according to the assumed landfill gas capture rate.

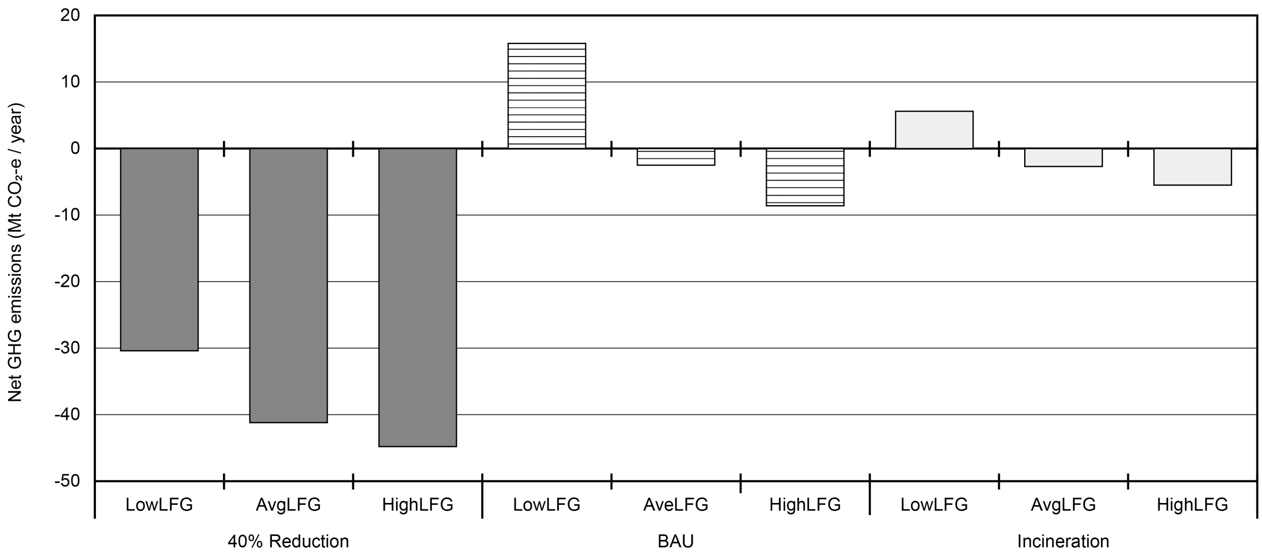


Figure 12: Life-cycle GHG emissions for alternative treatment scenarios for California's MSW, using the US EPA's Waste Reduction Model (WARM), in Million tonnes (Mt) CO2-e.

Though both models predict that 40% Source Reduction is the scenario that emits the least greenhouse gases to the atmosphere, WARM finds that, unlike EASEWASTE, incineration of waste has roughly equivalent GHG emissions as BAU for the average landfill gas collection scenario. From Figure 12, we can see that reducing the production of waste leads to major GHG savings (approximately 40 Mt CO_2-e for the average landfill gas collection scenario). The landfill gas collection rate is responsible for variation in life-cycle GHG emissions over a factor of 1.1 for the source reduction scenario, 6 for BAU and 2 for incineration. The variation is greatest for the BAU case because it is the case for which the greatest amount of biodegradable waste is arriving to the landfill, and its subsequent methane production has a very high GWP.

There are several sources of the variation between models. The WARM model has far fewer user inputs – only waste composition, travel distances, and LFG collection rates – than EASEWASTE, a model in which every technological process and distance is defined by the user. A very important source of variation comes from assumptions about electricity generation. The WARM model does not allow the user to define the source of electricity used in waste treatment processes, nor the type of electricity displaced by electricity production from waste. The WARM model assumes that the electricity produced and avoided is the average *fossil-based* electricity in the United States – roughly 45% more carbon intensive than the average electricity mix in the U.S. (US EPA 2006) – which does not represent the actual grid in any region. The emissions from this average fossil electricity mix falls somewhere between coal and natural gas power in its life-cycle emissions, and the exact mix determines where on the vertical axis of Figure 11 the emissions from each scenario fall. This mix can also affect which scenarios look better or worse, from a GHG perspective, as shown in Figure 11. The difference in the type of electricity displaced between the two models contributes to the differences in the emissions reductions estimated by each.

WARM´s estimate of the emissions from 40% Reduction is much lower than is EASEWASTE`s because of a difference in the system boundary definition between the two models. In WARM, the savings from 40% Reduction include upstream avoided production, so the scenario gets credited with emission reductions from all the products that never need to be manufactured when people consume less. These avoided emissions are much greater than the direct emissions that would have been released if the waste had been generated. This avoided production falls outside of the system boundary for EASEWASTE, so the emission reductions from 40% Reduction in this model are smaller.

3.2.4. ACCOUNTING FOR BIOGENIC CARBON EMISSIONS

Figure 13 shows the life-cycle GHG emissions if biogenic carbon releases from the waste management system are counted as a contributor to Global Warming. As discussed previously, waste LCAs often assume that waste entering the system carries with it no environmental burdens from its production and consumption. However, it is also widely assumed that the waste *does* carry with it some benefit: carbon from waste of biogenic origin is assumed to be carbon-neutral. While there are conditions in which these two assumptions can be reconciled (Christensen et al. 2009), they can also lead to a bias towards releasing biogenic carbon (Searchinger et al. 2009).

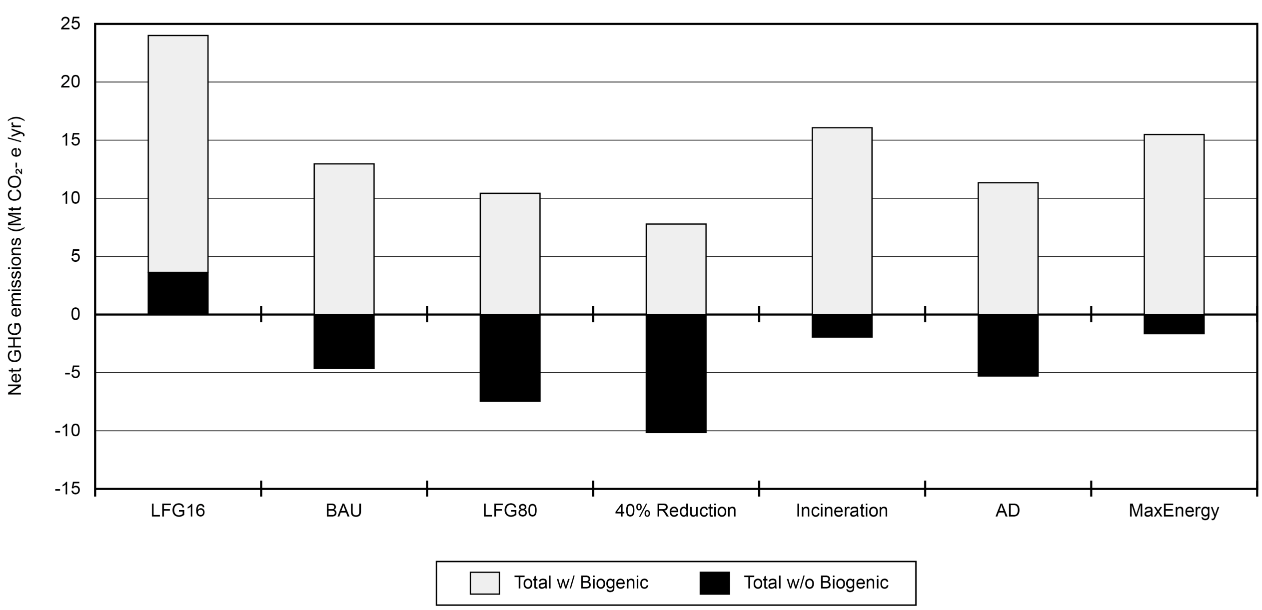


Figure 13: Counting biogenic carbon does not change the ranking of preferred waste treatment scenarios, but does change the net greenhouse gas emissions estimated from each scenario.

In agreement with Gentil et al. (2009a), Figure 13 shows that counting the biogenic carbon emissions does not change the order of preferred scenarios, but does change the magnitude of the emissions associated with each scenario. In all previous figures, biogenic releases were given a value of 0, and stored carbon was given a value of -1; here in Figure 13, biogenic releases are counted as 1, and stored carbon as 0. Figure 13 compares the ordering of scenarios for the cases under the two biogenic carbon accounting schemes. In ascending order, 40% Reduction is the lowest-emitting scenario, followed by LFG80, Anaerobic Digestion, and BAU. Incineration and MaxEnergy follow, and are about equivalent, and LFG16 has the greatest GHG emissions. The scenarios that produce the most energy, under the expected case in which natural gas is displaced, are among the highest emitters. The energy producing scenarios are the highest GHG emitters because paper is burned in the two incineration scenarios (Incineration and MaxEnergy), resulting in a one-time pulse of biogenic carbon contained in the paper. In the other scenarios, the paper in the waste stream is landfilled, and much of that carbon (bound in lignin) remains sequestered in the landfill. In comparing the scenarios in which biogenic carbon is counted as contributing to Global Warming to those in which it is not, a small discrepancy is noted: MaxEnergy and Incineration switched places in the scenario ranking between the two accounting methods. This difference can be attributed to model-based error. In EASEWASTE, the calculations for how much methane is generated from a fraction of waste and the biogenic carbon content for a fraction of waste are based on empirical measurements, and these measurements are not always derived from the same waste sample. That these two parameters are therefore not 100% correlated can lead to small changes in the carbon emissions estimated from Municipal Solid Waste, and can lead to variation in the emissions.

From a GHG perspective, two scenarios are preferable to BAU: 40% Reduction and Anaerobic Digestion. Source reduction emerges as the preferred waste management scenario; it results in the lowest emission of GHGs and also provides environmental benefits outside of the waste management system. In this scenario, additional carbon is sequestered outside of the waste management system, due to natural resources that are never extracted, and the products that are never produced. This decreased production allows that biomass to be used for other purposes, both anthropocentric (e.g., energy) (McKone et al. 2011) and not (e.g., land preservation).

The use of waste as an energy resource should focus upon alternative organic waste management. Digesting biogenic waste in California leads to GHG benefits as compared to BAU; this scenario maximizes the extraction and utilization of the methane that is released from the waste, and allows the landfill to function solely as a carbon sequestration site. Though incineration for electricity production in California may be preferable to the use of fossil fuels when comparing the carbon footprint of energy sources, incineration is not preferable when we are comparing alternative fates for the waste we produce.

There are additional possible benefits to separating and treating organic waste. First, drying the digestate before it is transported to the landfill can reduce the emissions associated with anaerobic digestion further. The digestate can also be returned to farmland, thereby recycling valuable nutrients (N, P, K); this may become especially important in the future when phosphorus is likely to be a limited resource. Finally, separating organic waste can improve the recycling rates for other products; if paper and plastics are not mixed with biodegradable waste, they can be more easily recovered. Both digesting organic waste and improving landfill gas capture rates can be done using already existing infrastructure. Conventional wastewater treatment plants already have anaerobic digesters for liquid wastes (Stokes and Horvath 2010), and co-digestion of liquid and solid wastes has been shown to increase methane generation (Edelmann 2000; Sosnowski et al. 2008), though the mixing of liquid and solid wastes brings on added risks of pathogens, and can limit the possibilities for land application of the waste (Murray et al. 2008).

Business As Usual functions mostly as a carbon sequestration project, provided that landfill gas capture is sufficiently high, because a large fraction of disposed waste in California is paper, which resists degradation. Landfill performance is a decisive variable: if at least 64% of landfill gas is captured, then it is among the best waste management strategies from a GHG perspective. However, lower rates of landfill gas collection (e.g., 16%) result in large emissions of methane, which override any benefits in sequestration, and result in the highest GHG emissions of all scenarios considered. Improving landfill gas capture in already-existing landfills provides an opportunity to decrease waste-related GHG emissions.

4. Uncertainty in results

The uncertainty in the waste LCA results – the fact that a couple of parameter variations can alter the order of preferred scenarios – highlights the importance of sensitivity analyses in waste LCAs. The analyses in this chapter show that both landfill gas collection rates and energy displacement strongly impact the estimated emissions from waste treatment and the ranking of waste treatment scenarios, and that biogenic accounting schemes affect the magnitude of the estimate. The model used to analyze waste treatment scenarios also impacts their estimated GHG emissions; this analysis showed that EASEWASTE and WARM differ in their assessments, largely because of a difference in their system boundaries.

How one counts biogenic carbon does not affect the rank-ordering of scenarios (Christensen et. al 2009) and is ultimately a question of time scale. At geologic time-scales, all carbon is "biogenic," having been relatively recently sequestered. At very short time-scales, all carbon is fossil, having been sequestered relatively long ago. Waste LCA analyses normally consider a time period of 100 years, and comparatively, biogenic waste in MSW has a very short carbon cycle, and thus the common assumption of neutrality of its emissions is reasonable. It is important to realize that the accounting scheme is another source of variation in the results of a waste LCA; even if it does not impact the ordering of scenarios, it does impact the estimate of the magnitude of the emitted GHGs, and thus impacts how using waste as an energy resource compares to using other energy resources. As such, analyses should also consider results under both carbon accounting schemes: one in which biogenic releases are counted as positive emissions, and one in which these emissions are carbon-neutral, but carbon storage is given a negative atmospheric carbon value. Though both accounting schemes are coherent and equivalent in a waste LCA decision-making context, counting carbon emissions from biogenic carbon makes methodological sense; if a decision maker is choosing how to treat our waste, all that happened to that waste before it was thrown away is irrelevant. All of its environmental burdens and benefits upstream of curbside disposal do not affect the decision of what do to with an existing tonne of waste; its downstream carbon flows determine the preferable waste treatment option.

Analyses should also consider the energy context of any waste-to-energy project. High energy-producing waste decisions can either be net carbon mitigators or net carbon contributors depending on the source of electricity they are displacing. The most GHG mitigation will occur where the marginal source of electricity is fossil based (e.g., coal), and the least will occur where the marginal source is low-carbon (e.g., wind) (Pacca and Horvath 2002). Presenting these key sources of variation is essential to understanding the robustness of waste LCA results, and to guiding decision-makers to make effective decisions.

5. Conclusions and Policy Recommendations

5.1. Conclusions

Although there are various effective alternatives for reducing the GHG emissions from California's solid waste management, the amount of GHG reduction obtained from pursuing alternative treatment scenarios depends strongly on the efficiency of landfill gas collection rate, the electricity displaced by waste electricity, and how biogenic carbon emissions are accounted for. The model used also affects my estimate of these reductions. The former sources of variation can change the order of preferred treatment scenarios. Assuming that natural gas is displaced by waste-derived electricity, as is most likely the case, then only 40% Reduction and Anaerobic Digestion achieve GHG savings when compared to the Business As Usual case. The same is true if wind power were displaced. It is very unlikely that waste-derived electricity would displace wind electricity, however, unless a tough Renewable Portfolio Standard is set for the state and it is already flooded with renewables. But if coal is displaced by waste derived-electricity, all scenarios except for LFG16 outperform BAU. The landfill gas collection rate determines whether Business As Usual is among the best or is the worst alternative for waste treatment. The manner in which biogenic carbon is counted does not affect the order of preferred scenarios, but does affect the magnitude of the GHG emissions (or savings) associated with each waste management plan. Future waste analyses should consider results under both carbon accounting schemes (biogenic releases as positive emissions, or biogenic emissions as carbon-neutral but carbon storage given a negative atmospheric carbon value), and also consider the energy context of any new waste management plan. Finally, model selection should be considered when analyzing results. The two models used, WARM and EASEWASTE, differ in system boundary selection, in assumptions about the type of electricity used and displaced by waste management, and in which aspects of the waste management system can be specified by the user. These inherent differences between models can drive differences between scenarios analyzed.

Given the uncertainties in electricity displacement, and in landfill gas collection over the long life span of a landfill, reducing the amount of waste that is produced in California – either by consuming less or wasting less– is the most robust greenhouse gas abating option; its emissions are certainly lower than those of the business as usual case, and its emissions do not vary strongly with landfill behavior or the type of electricity displaced. Further, reducing waste has upstream benefits outside of the waste management system that are not captured by most waste LCA analyses (though they are estimated in the WARM model). The challenge in source reduction is not in capital investment, as it may be for other scenarios, but in incentivizing and achieving long-term behavior change among consumers. Ensuring high landfill gas capture rates within the current management plan, or digesting biogenic waste and designing landfills to maximize carbon sequestration provide two effective alternatives for greenhouse gas mitigation from waste management.

Importantly, carbon emissions are not the only measure that should determine a region's waste management strategy. This analysis focuses on the climate implications of waste management because it is an important piece of how waste affects our environment. However, how waste is managed also directly affects air quality, resource depletion, public health, and ecological health; the economic and social costs of waste management alternatives also play an important role in the selection of the optimal waste policy. There is likely no single metric for waste practices that applies everywhere and always; local landfill conditions and practices affect effective carbon sequestration, and public perception of waste technologies and of community priorities determine what kinds of treatment are acceptable. Depending on local priorities, it may be preferable in one community to burn natural gas and sequester fossil plastics in a landfill to minimize processing and handling costs and local air pollution, and another community may choose instead to burn plastics, in order to avoid construction of a new landfill in an ecologically sensitive area and to have a source of domestic fuel. Decisions about how to handle waste depend both on the question asked – whether we ask how to best handle waste or from which energy source to create electricity affects the result – and on the priorities of the community affected by the answer.

5.2. Policy recommendations

To realize the potential gains from source reduction and from anaerobic digestion of organic waste, strategies must be implemented to lower the barriers to the adoption of these measures. Waste reduction involves long-term behavior change. Educational outreach can help consumers realize the impacts of their waste production. Creating incentives for consumers to produce less waste is more likely to have an impact. Such incentives can include taxing waste production – either directly through Pay-As-You-Throw programs, whereby consumers pay for their waste disposal according to the amount they produce, or by increasing the tipping fees at landfills – or paying consumers to separate their green waste.

Diverting organic waste from landfills can provide climate benefits through two avenues: fuel displacement and carbon sequestration. The diverted waste can be digested as an energy resource, displacing more carbon-intensive fuels, and without the organic waste, the landfill will become drier and more able to serve as a carbon sequestration site. But there are many barriers facing the implementation of anaerobic digestion of organic waste in California. The obstacles that wastewater or waste treatment facilities face in generating electricity from biogas are similar to those faced by farms seeking to digesting their own waste. These obstacles include high capital costs, finding appropriate financing, uncertainty about the value of produced electricity, high transaction costs in connecting to the grid, and a lack of incentive to produce electricity beyond what the waste producer consumes (Rickerson et al. 2008, Gloy and Dressler 2010, Dowds 2009). This disincentive is produced by California's net metering policy, which allows small generators to offset their own electricity costs by providing electricity to the grid, but does not compensate them for any electricity produced beyond what they consume. An additional barrier has been placed by state utilities, which have set a cap of 50 MW on the total allowable digester capacity in the state (Rickerson et al. 2008). This cap both discourages the construction of new facilities and can force digesters to flare excess gas produced instead of utilizing it.

Some of these barriers are being addressed by recent policy measures, but more could be done to encourage electricity generation from waste. Two policies in California make it easier for small digesters to supply the grid with waste-derived electricity. The first is the Renewable Portfolio Standard, stipulating that 33% of California's electricity must be generated from renewable sources by 2020. Because biogas is eligible as a renewable fuel, this provides incentives for small generators to compete to fulfill the renewable requirement. The second is California Assembly Bill 1969, which obligated the California Public Utilities Commission (CPUC) to create a "standard offer contract," a contract stipulating a fixed-price from which utilities may purchase electricity from small renewable generators (Rickerson et al. 2008). The bill lowers the transaction costs for small biogas producers by creating a standard mechanism for the exchange between generators and the utilities, and also provides an alternative to the net-metering structure. Germany uses a similar policy, a feed-in tariff, to pay producers a premium for their renewable energy generation, thus providing an incentive for investment. In California, however, the electricity produced under this mechanism is sold to utilities at a Market Price Referent (MPR), a price set annually by the CPUC at the avoided cost of generation, meaning the price the utility would have paid for electricity from a new natural gas-fired power plant, if that renewable source did not exist (Rickerson et al. 2008). Importantly, this price does take into account the temporal value of electricity, differentiating between the price during peak and non-peak times. Also importantly, no such feed-in tariff contracts have yet been awarded because the retail rates in California are almost always higher than the feed-in tariff rate, so most generators prefer to use net metering to offset their own electricity demand (Rickerson et al. 2008, Gloy and Dressler 2010).

Because biogas production has not increased in response to these policies, it is clear that more is needed to incentivize biogas producers' entrance to the electricity market. Specific policies could spur investment in anaerobic digestion by:

2. helping to financing capital costs by providing special loans or subsidies for construction of digesters (Gloy and Dressler 2010)
3. encouraging energy production by altering the net metering policy so that utilities pay for excess energy delivered (CEC 2009)
4. encouraging organic waste diversion by increasing the tipping fee at landfills,
5. providing a method to value the positive environmental externalities of producing energy from biogas (e.g., carbon taxes, renewable energy premiums; CEC 2009).

Digester operations themselves could invest in storage facilities that would allow them to operate as peaker plants, only selling to the grid at the most valuable times (CEC 2009), cooperating with other organic waste producers to implement co-digestion and thus benefit from the resulting economies of scale and giving them more negotiating power with the utility, or by selling co-products (e.g., fertilizer, animal bedding material; CEC 2009, Dowds 2009).

For electricity to be produced in large quantities from food waste, a feedstock whose production is assured and whose methane-generating capacity must be well-managed, one or more of the preceding policy measures must be enacted by California.

Chapter 3. The efficiency of informality: modernity, waste, and recycling in Bogotá, Colombia

1. Introduction

Waste poses a risk to cities. As an emblem of and a threat to modernity (Moore 2009), waste production is increasing in the same sites where population growth and urbanization are concentrated, in small and medium sized cities in the Global South (Cohen 2004). This coincidence threatens public and ecological health, as cities' capacity to effectively manage waste is exceeded by the speed of its production. Waste recycling and reuse effectively lessen the environmental impacts of waste production, by decreasing the amount of waste that needs to be removed from the city and by reducing the demand for natural resources to produce new consumer goods. While these activities occur largely through informal, or unregulated, means in cities in the Global South, recycling has been largely privatized and formalized in the Global North, and many developing cities are now seeking to formalize their recycling sectors in the name of modernity and efficiency. How waste is managed has the potential to provide environmental gains – in the case of effective recycling –and how recycling occurs impacts social wellbeing. I analyze the implications of this formalization process on social and environmental outcomes.

In this chapter, I explore the case of Bogotá, Colombia, a rapidly growing and urbanizing city with an extensive informal recycling sector. This dispersed network of informal actors diverts approximately a thousand tonnes of waste from the landfill per day, reclaiming the material for reuse and recycling, motivated solely by a profit motive. The municipal government is forcibly eradicating this system, seeking to replace it with a mechanized and regulated recycling scheme, operating by mandate, despite the fact that the unregulated recycling system is able to recycle far more than can the municipal system, with no financial input from the city. The forced removal of the informal waste sector reveals an understated driver in the overhaul of the municipal recycling system: the quest to build a modern city.

2. Background

2.1. A brief history of waste and recycling in Bogotá

Bogotá's waste management system has evolved in response to multiple drivers. As the city urbanized, the increase in population density and the decreasing agricultural activity of its residents – decreasing their ability to reuse their waste products within the home – led to the formation of dumps. By the 1960s, the municipal government began hauling trash away from residents, using horse-drawn carriages to dispose of waste into rivers. When residents demanded that trash no longer be dumped in the same rivers where they would wash their clothes, dumps were established at the city limits. Where there were dumps, poor people followed, living directly in and off of discarded goods. This reclaiming practice became more formalized in the 1970s, when Colombian industries began using recycled goods (first glass, then paper) as raw materials in manufacturing. Industries paid scavengers to collect and deliver these goods, from the dumps to the factories. As demand for these materials increased, a complex network of collectors, transporters, and sorters developed. When the municipal government built a state-of-the-art landfill, Doña Juana, in 1988, to collect the waste produced by the metropolis, the recycling industry moved away from dumps, and dispersed over the curbsides where residents set out their garbage. In 1991, the new Colombian constitution declared in article 355 that the provision of city services such as garbage collection was essential for the protection of public health (Ruiz, personal interview, 2010). Since 1994, four private companies have collected city waste and transported it to the landfill. And since 2006, the city has piloted a new recycling scheme, in which private companies collect recyclables from the curbside and transport them to a city-owned recycling facility.

This process reveals an overlapping sequence of drivers, noted by Wilson 2007, propelling changes in municipal waste management: institutional responsibility (as noted in the constitution, and revealed through the establishment of waste hauling), public health protection and public awareness (in removing dumps from the inner city), the resource value of waste (seen by the persistence of a strong informal recycling sector), and environmental protection (in both the replacement of dumps with a sanitary landfill as well as the establishment of a formalized recycling scheme). These drivers can also be understood as differing "modes of governance," which drive how waste is managed so as to "attain [these] distinctive objectives" (Bulkeley et al. 2007, p. 39). To Wilson's list of historic drivers of changes to waste management, I add the allure of modernity. In the case of Bogotá, the municipality's desire to build a modern city partially motivates its establishment of its new recycling program.

2.2. BUILDING A MODERN CITY

The UAESP (*Unidad Administrativo Especial de Servicios Publicos*), the branch of the municipal government handling public works, began a pilot recycling scheme in 2006. Remarkably similar in appearance to recycling systems in the United States, the project breaks strongly with Bogotá's current recycling system, which for the past several decades has been composed of a chain of informal collectors, people who store and separate materials, and industrial actors that re-incorporate the materials into new products. Four private companies, the same ones responsible for collecting garbage, drive trucks along predefined routes to collect recyclables from upper-class neighborhoods and deliver them to a large recycling facility called La Alquería. The overall vision set forth by its District Recycling Program (DRP) involves concentrating and mechanizing the recycling chain, specifically aiming to formalize recyclers, motorize collection, establish 6-12 permanent and strategically located recycling centers, and encourage free market competition between recyclers (UAESP 2007). With this vision, the municipality provides the following goals that motivate the new recycling project: (1) *modernization* of the public works provision; (2) *social inclusion* of vulnerable populations; (3) economic and *financial sustainability*; (4) *environmental responsibility*. We explore the differences between the unregulated recycling system, and this pilot scheme, using these four metrics outlined in the DRP.

To understand the first goal – modernization of public works – I look at the context of recent city-building schemes in Bogotá, as well as to theories of modernity. The modern city relies on both connection – networks of transportation, water, electricity – and the hiding of these flows, making invisible the "human labour and social power relations involved in the process of [their] production" (Kaika and Swyngedouw 2000, p.123), so as to make these "icons of progress" seem "miraculous." Modern urban residents are unaware of the source and the fate of these flows. Modern waste systems follow suit, actively "distancing… garbage from urban spaces [and] from its citizens" (Moore 2008, p. 430). Separating people and waste requires minimizing interaction between the two, and making waste increasingly invisible. In a modern city, "garbage disposal [becomes] a matter of throwing things in a hole in the wall, which miraculously makes trash and smell disappear" (Kaika and Swyngedouw 2000, p. 134). The business of garbage is dirty, and the modern city is clean (Kaika and Swyngedouw 2000; Thieme 2010). This causes a tension, because the production of waste itself – an emblem of modernity – threatens the cleanliness of the modern city (Moore 2008).

In addition to cleanliness, the modern city offers a vision of aesthetic order. The city actively manages its appearance, by "limiting uses [of] public spaces that … are unattractive" (Berney 2011, p. 18) and by removing garbage, an act essential "to the normative vision of a modern city – clean, rationally ordered, and armed with modern technology" (Moore 2008, p.428). Importantly, modernism is characterized by the *appearance* of rational order, not necessarily its existence. The modernist "vision required a sharp and morally loaded contrast between what looked modern (tidy, rectilinear, uniform, concentrated, simplified, mechanized) and what looked primitive (irregular, dispersed, complicated, un-mechanized)" (Scott 1998, p. 254). Thus, a poorly functioning system that appears orderly on the outside is "modern," while a well-functioning system that appears to be messy is not.

States seek to create this aesthetic order to serve two purposes: to illustrate a break from a past perceived as less well-functioning, and to create a city that is legible and more easily governed. Modernization plans are futuristic, tend to negate the past, and at their most radical, make "no compromise… with the preexisting city… [and] completely supplant its predecessor" (Scott 1998 p. 94). Replacing an existing, messy city with a singular plan allows a coherent vision to be projected. This future vision is often realized through large infrastructure projects, which are in themselves emblems of progress that demonstrate the power of the postcolonial state (Mitchell 2002), and also serve "to dispel most visitors' first impression that [this] is a country soaked in poverty" (Ghertner 2011, p. 2). Cities that conform to rational plans, exhibiting straight lines and set schedules, are easier to govern from afar and allow for models to be replicated. In creating plans that are independent of the city in which they are implemented, the modern city acquires a universal quality. "In their neutrality, they could be anywhere at all" (Scott 1998, p. 104). The legibility of these "universal" cities "is achieved today…by [taking] an idealized vision of the world-class city gleaned from refracted images and circulating models of other world class cities…and [asking] if existing territorial arrangements conform to this vision" (Ghertner 2011, p.12). So when picturing a modern city, we see tall glass buildings, fast transportation networks, and clean streets, but we don't see where it is; it could be anywhere.

Bogotá has emerged in recent decades as a model city (Roy 2011). Since the 1990s, the city has worked to "[leave] behind the image of chaotic, disorderly and insecure city, has gotten international visibility and has become a [model] for other cities [in implementing] 'creative solutions' … to [solve] urban problems" (Duque 2008, p. 1). The city's modernization is an active attempt to both address urban problems and reimagine itself. It has invested tremendously in transportation infrastructure, building a Bus Rapid Transit system called Transmilenio, whose name and appearance evoke visions of the future. Its elevated platforms allow people to access the system only at pre-defined stops, in contrast to the *colectivos*, small, polluting buses that run throughout the city and do not have posted schedules or routes (though residents know exactly where they go). Mayors Peñalosa and Mockus are credited with investing in parks, libraries, and bike paths, "demonstrating that planning had returned to Bogotá and…helping [to] create the physical appearance of a world class city" (Berney 2011 p. 21). It is in this context, in the active construction of "the narrative of Bogotá as a safe, desirable place to do business, to live and to visit" (Berney 2011, p. 28) that the municipal government has decided to overhaul its recycling system.

3. Bogotá's recycling system

3.1. Methods

To understand the implications of a move away from unregulated and towards municipally-planned recycling – a process that has been undertaken in many industrialized nations, and one that is well documented in Strasser's (1999) tale of American garbage – I used observation, semi-structured interviews, and document analysis to uncover and characterize the key players governing, mediating and participating in Bogotá's recycling scheme.

Table 2: Methods used to understand Bogotá's recycling system.

Key player	Main Role	Methods used to characterize
Consumer	Waste generator	Document analysis
Free market recycler	Collection of recyclables	Observation, key informant interviews (n=25); document analysis
Bodega owners	Sorting, storage, sale of recyclables	Observation, interviews (n=20), document analysis
Industry groups	Use of discarded materials	Key informant interviews (n=5); document analysis
Municipal Government (UAESP)	Regulation of waste and recycling systems, publication of waste management plans, contracting for operation of waste facilities, running pilot recycling plant, community outreach and education	Key informant interviews (n=5), site visits and observation, document analysis
Private waste companies	Collection of solid waste and recyclables	Observation, key informant interviews (n=5)
Private entrepreneurs, educational institutions	Implementation of innovative waste reuse and recycling	Observation, interviews (n=25)

Quantitative analysis of the recycling schemes relies on data collected through interviews, observation and data analysis, to characterize the recycling processes. I also use GIS analysis to calculate the distances traveled to collect recyclables under the pilot recycling program. The UAESP released the results from their 2011 census of recycling in Bogotá in July 2011, and provides a very valuable source of data on the characteristics of collectors and bodegas. Though the results may be biased towards more formal players in the recycling chain, as participation in the census was voluntary, the census still provides the most comprehensive view of recycling activities in Bogotá.

3.2. Characterization of Bogotá's free-market recycling system

3.2.1. Overview

The resource value given to waste is evident on the sidewalks of Bogotá. A complex system has evolved over the last several decades that recovers discarded materials from trash bags left on curbs, and eventually brings them to industries that use them as raw materials to make new products. The recycling chain is comprised of three stages: collection, storage and separation, and manufacture, with transportation systems connecting each stage. Specialized workers perform each stage's task; collectors do not own bodegas, nor do bodega workers usually manufacture goods using recyclable materials. Much of this work is 'informal,' meaning it is unregulated by the government. About 60% of Colombians are employed in the informal sector (UAESP 2004). The recycling system is pictured in Figure 14, which shows the path taken by a recyclable material in Bogotá:

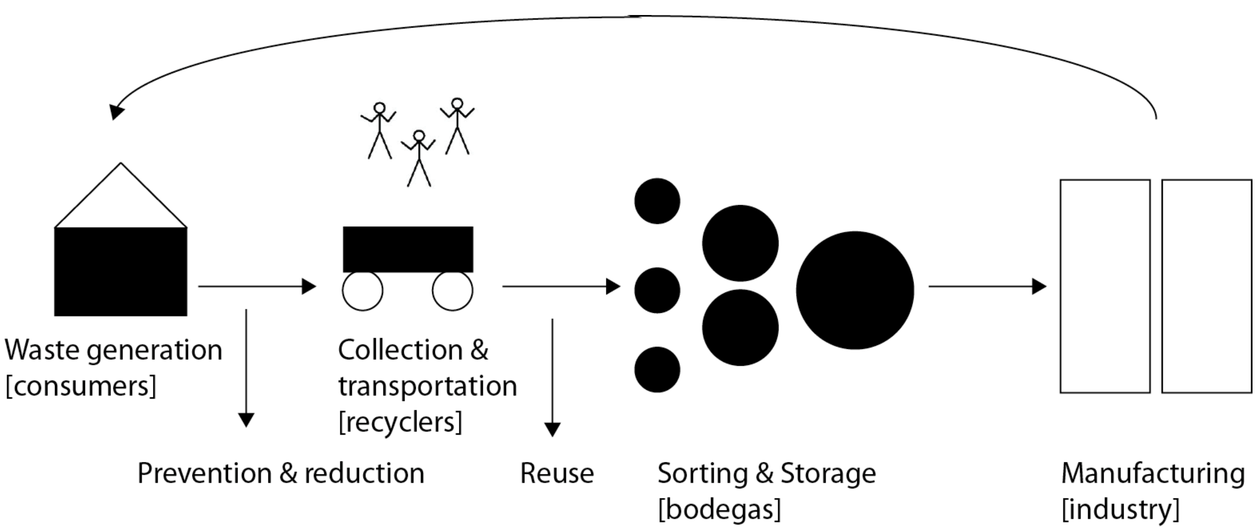


Figure 14: The flows of recyclable materials in Bogotá.

Before waste is thrown away, households may practice reuse and recycling behaviors; these result in waste prevention and reduction. After the consumer discards his waste, a recycler will sort through bags on the sidewalk, recovering materials that have a market value. He will then transport his goods to a *bodega*, where his goods are weighed, and he is paid. Typically, a material will travel through four bodegas before reaching industry (Espinosa 2011). Any materials not collected for recycling are landfilled.

3.2.2. Waste generation

Waste generation is inherently variable – what people throw away is influenced by a mix of social, economic, geographic, and cultural factors, and it varies over time. Bogotá is a middling city when it comes to garbage production; in 2010, its residents threw away approximately 1 kg per person each day (compare to over 2 kg per person in the USA and 0.3 kg per person in India; UNH 2010). Almost 6000 tonnes reached Doña Juana landfill daily in 2010. This quantity reflects only what is disposed of; materials that are recycled or reused are pulled out of the waste stream for alternate uses before this. By comparing the quantity and composition of the waste reaching the landfill (this is measured daily; UAESP 2011) to the estimated generation (Gomez 2011), I estimate that about 1000 tons of material are informally removed each day from the waste stream for recycling and reuse. The consumer leaves his mixed garbage in plastic bags on the curb, for pickup by the trash hauling companies; source separation of waste is rare, outside of educational institutions and public parks.

3.2.3. Modes of informality: Collection

Between the time that the consumer leaves the bag of waste, and the garbage truck arrives, informal collectors will sort through the bag to remove valuable goods. Reusable items, such as clothing, bags and electronics, are usually sold directly in flea markets, while raw materials (e.g., plastic, paper, metal) are collected and sold to bodegas. People who collect recyclable materials vary in their degree of formality, and they collect materials in response to their market value. Commonly called "recyclers," these workers are estimated to number 20,000 in Bogotá (UAESP 2004). According to a census published by UAESP in 2004, about half of these are "occasional" recyclers, who find a variety of means with which to make their living, collecting recyclables among them, and the other half are "professional" recyclers, dedicated exclusively to the resale of discarded goods. This dichotomy obfuscates the gradient of informality expressed in the modes of recycling. Recyclers vary in their *dedication* to recycling, in their *means* of recycling, in their *affiliation*, and in their *institutional arrangement.* These differences directly impact how much they recycle in a given week, as well as the implication of their labor being lost.

These four descriptors refer to the *mode* of recycling undertaken by these workers, and they are interrelated. I define "dedication" as the proportion of total hours worked as a collector. Among recyclers, there are people who live on the street and will employ varied means to earn enough for their daily meal, collecting just enough recyclable material to eat. Many recyclers have regular collection routes that they navigate on a daily basis, working for perhaps 12 hours a day. Recycling is their major occupation, but they will often seek other side jobs, such as cleaning houses or selling at flea markets, to supplement their income. The most dedicated recyclers have the most definition to their employment; an educational institution or a residential complex has hired them to work for a defined number of hours, collecting and sorting their waste.

A recycler's means of recycling – the vehicle and storage mechanism he uses – directly impacts the quantity they are able to collect, and thus influences their income. Those that have the smallest storage capacity make the least money. On foot, a recycler might use a *costal*, an over-the-shoulder burlap bag, a *carro esferado*, a wooden board on wheels pulled by a rope, a shopping cart, or a *zorrillo*, a large, human-powered cart, or a tricycle. Those with the smaller carrying devices can collect no more than 50 kg per trip, and earn between USD$2-7/day, while a recycler with a large cart or tricycle can carry up to 200 kg and may earn up to USD$15/day. (Incidentally, the minimum wage for formal employment in Colombia is about $300/month, or $12/ workday). Horse-drawn carriages are an important mode of transportation and storage for recyclers who have invested in that capital. Because of their large storage capacity, and their ability to move around the city, horse-drawn carriages allow recyclers to make around $40/day (El Espectador 2010). They can carry over 500 kg, and can move around the city easily, accessing areas that have good materials even if they are far apart from each other. Importantly, a small subset – fewer than 2 % (Ruiz 2010) – of recyclers that move around by horse are metal buyers, not the typical collectors. They use a loudspeaker to alert neighborhood residents that they are buying metals, and people approach them with their wares. This mode of transport that is the most threatened by the city's modernization plan. Finally, some recyclers use a motorized vehicle (usually a pick-up truck) to collect recyclables, but this mode of transport is fairly rare.

According to the latest census, approximately one third of recyclers use small-scale collection devices (costal or carro esferado), about a third use a human-powered cart, and about a third use a horse-drawn cart (Ruiz 2010; Martinez 2011, UAESP 2011). The estimated percentage of recyclers using each mode of transport is shown in Figure 15. Because the majority of recyclers use the least-capital intensive modes of collecting, it is estimated that the average recycler's income is $3.50/day, though most recyclers do not collect every day (Ruiz 2010a). Normalizing by the quantity recycled, however, I find that the average tonne of recyclable material comes from recyclers using horse-drawn carriages.

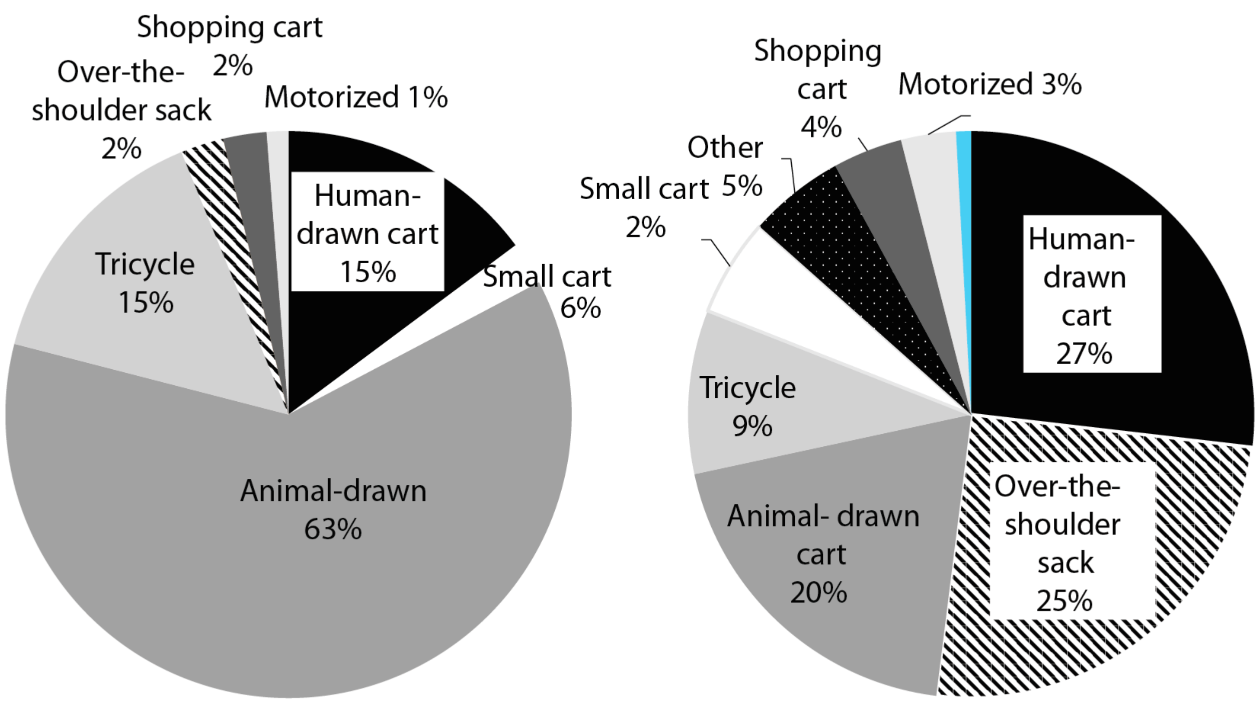


Figure 15: Mode of collection, by mass of material recycled (left) and by number of informal collectors surveyed (right). Data source: UAESP 2011

Most recyclers are not affiliated, though those that are tend to collect more recyclable material, as they tend to be more dedicated to recycling. The latest census estimates that 11% of free-market recyclers were members of a cooperative in 2003 (UAESP 2004); there are about 80 such organizations in Bogotá, and 5 umbrella cooperatives. Though being part of a cooperative offers concrete benefits, such as collective bargaining power, increased professionalism, and access to more markets, most choose not to affiliate, due to a lack of knowledge or skepticism of the benefits that it would bring. Many workshops and job opportunities found by cooperatives are open only to members of cooperatives (Ruiz 2010b).

Institutional arrangements used in Bogotá's recycling system vary tremendously, from a low to a high level of organization. At the lowest end of organization, recyclers wander and *occasionally collect* available recyclable material. The majority of recyclers, however, travel on predetermined *street routes* that have been negotiated with other area recyclers. Their schedule depends on when the garbage is collected in that particular neighborhood; the collectors aim to gain access to the bags before the garbage collection trucks arrive. This arrangement is common among recyclers employing each kind of vehicle. *Agreed exchange* occurs when residents and recyclers decide to cooperate. For example, a group of residents might give a particular recycler access to their source-separated recyclables, if that recycler promises to leave the area in front of their house clean, swept and free of garbage. These types of arrangements are most common among recyclers who have been working a particular route for a long time. *Paid exchange* is a variation of the previous arrangement, but it involves payment. Here, a university or an office building hires a recycler to work with them, full- or part-time, to manage and sort the organization's waste. The recycler gets to keep the recyclable material, and is charged with properly disposing of garbage. Finally, a recycler may employ a *mixed strategy*, combining multiple institutional arrangements.

3.2.4. Sorting, storage, and sale

Following collection, the recycler will sell his materials to a *bodega*, a warehouse where the waste is sorted, separated, and sold as recyclable material. These are privately owned businesses that vary in size, material accepted, and their institutional arrangement with suppliers and buyers. Bodegas may be small, with a capacity less than 2 tonnes – some as small as trucks that move around the city buying materials, but most are garages or small storefronts. The small bodegas tend to buy directly from recyclers, tend to accept all types recyclable materials (e.g., paper, plastic, metal, glass), and usually will sell to a larger bodega. Recyclers tend to sell to the same bodegas over time, either due to proximity, happiness with prices offered, or because they have an arrangement with a particular bodega. For example, some bodegas will rent out carts to recyclers – as these have higher storage capacities than other modes of collection, a recycler can earn more with a cart – and in exchange, the recycler commits to selling all of his material to that bodega. A medium sized bodega (capacity between 2 and 10 tonnes) will receive materials from a mix of recyclers and bodegas, and as they increase in size, they will be more selective in the materials they receive. The largest bodegas (capacity greater than 10 tonnes) tend to be the most specialized, receiving only select materials (or only one material) from other bodegas, and usually sell their large volume directly to industry, which will reincorporate them into new products. The larger the bodega, the more selective it can be, and the higher the profits made on recyclable materials. The size distribution of bodegas surveyed during the UAESP's census is shown in Figure 16. It shows that most bodegas in Bogotá are medium-sized (between 40 and 500 m^2), and that these bodegas handle a large portion of the flows of recyclable goods. Notably, the largest bodegas are few in number, but receive a disproportionately large share of recyclable material; this reflects the tendency for industry to purchase from large bodegas. Similarly, the smallest bodegas receive disproportionately less material than we'd expect based on their prevalence.

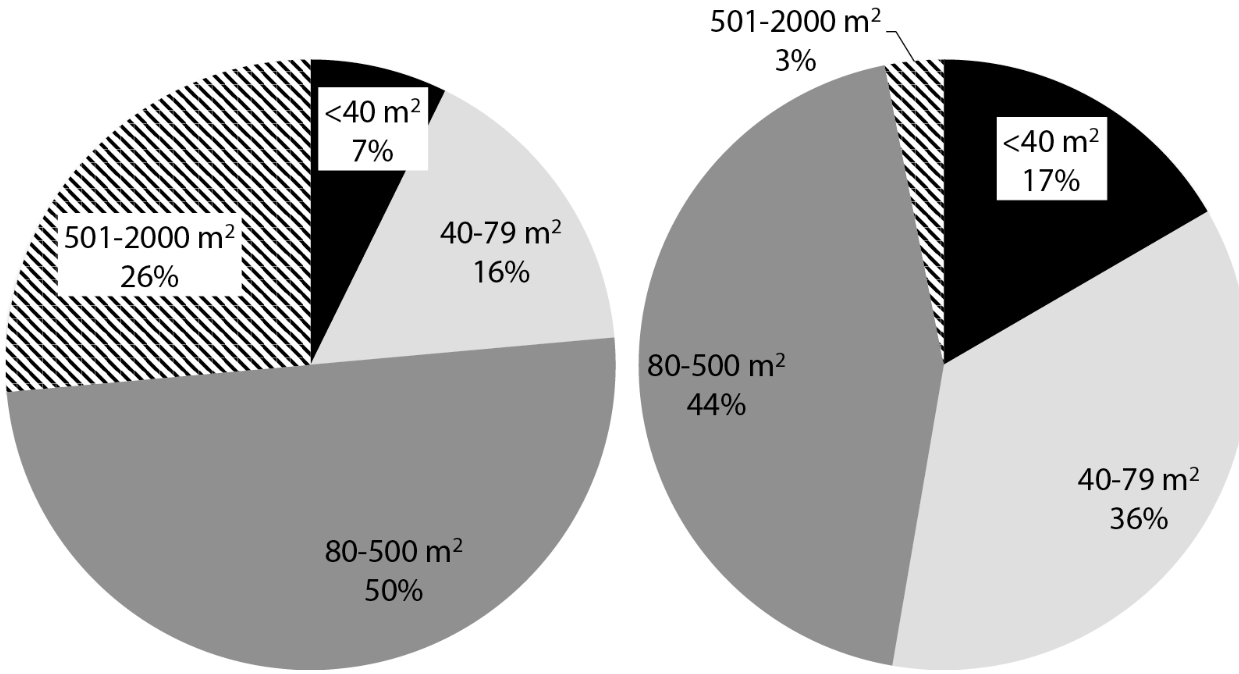


Figure 16: Characterization of surveyed bodegas in Bogota. Left figure shows the percent of total mass recycled that passes through bodegas of each size. Right figure shows the number of bodegas, by their area. Data source: UAESP (2011)

Though there appears to be no significant different between the propensities for specialization between small and medium sized bodegas, large bodegas are more likely to be highly specialized. Only 30% of large bodegas are unspecialized, where about half of small bodegas are not specialized.

3.2.5. RE-MANUFACTURE

Once a recyclable material has passed through the chain of collection, sorting, storage, and sale, it is reincorporated in a manufacturing process. Some materials are incorporated in domestic industrial processes, and some materials are sold to foreign markets, where they become part of the global recycling trade. Plastic is a material found in all sectors of the economy, and its market value is relatively low, since the heterogeneity of the product makes it difficult to recycle. The market for used plastic in Colombia is a domestic one, and the materials are used to produce a variety of products, such as toolboxes, brooms, synthetic wood, shoes, and even parts of the Transmilenio. About 15% of plastic produced is recycled, and if ever there is not enough recycled plastic entering the recyclable market within Colombia, industry will purchase resins from the global recycling market (Fernandez 2010). Unlike plastics, metals have a high market value – with high variation between metals – are easily recyclable, and very little ends up in a landfill. There is fierce competition for copper, a metal not found naturally in Colombia, so the only domestic source of it is through recycling. Much of what is found within its borders is currently being exported; the same is true for aluminum. Steel, however, is produced in abundance domestically (1 million tonnes/year). Metals are used for a variety of purposes, ranging from electronics, construction, tools, to machinery. But because of this high market value, the path of metals is a bit different than the path of other materials; rarely do people give away metal, the way they do other recyclables, so even the collectors pay for it at the first step in the chain (Lesmes 2010).

Used paper is also consumed voraciously within Colombia (7.3×10^5 tonnes/year), and waste paper is imported to meet the needs of industrial production (9.6×10^4 tonnes/year), while exports are minimal (2.1×10^3 tonnes/year) (Uribe 2010). Recycled paper is used to produce more paper, as well as cardboard. Glass is mostly recycled domestically, with one company (Peldar 2010) having a near monopoly over glass production. Recycled glass is melted and re-made into bottles, furniture, and windows (Peldar 2011).

3.3. Modernizing recycling: the municipal pilot recycling plan

The preceding section outlines a dispersed but highly evolved network, through which discarded materials are reincorporated into the production of new goods. It is a highly illegible system, as it is neither centralized nor well-documented. The municipal government started a pilot recycling scheme in 2006 to organize, centralize, consolidate and run recycling activities.

3.3.1. Collection

The pilot collection system is highly mechanized. The city has contracted the same companies that pick up garbage to collect recyclables along predefined routes on a public, weekly schedule. The pilot project provides selective coverage of the city; only the higher income neighborhoods are currently served (Pardo 2010), as those tend to throw out the most recyclable material. The municipal plan asks residents to separate their waste – a job normally done by the informal sector – by placing white bags of recyclable material (as opposed to the black garbage bags) on the curb once a week for collection. Drivers do not see what is inside the bags, and they are not paid according to the quality of what they collect. Instead, they are paid hourly rates. An example "microruta," showing the route for one truck's weekly collection, shown in Figure 17 (Castillo 2010). In contrast to the path taken by unregulated collectors, the municipal collection system is legible, predictable, and aesthetic.

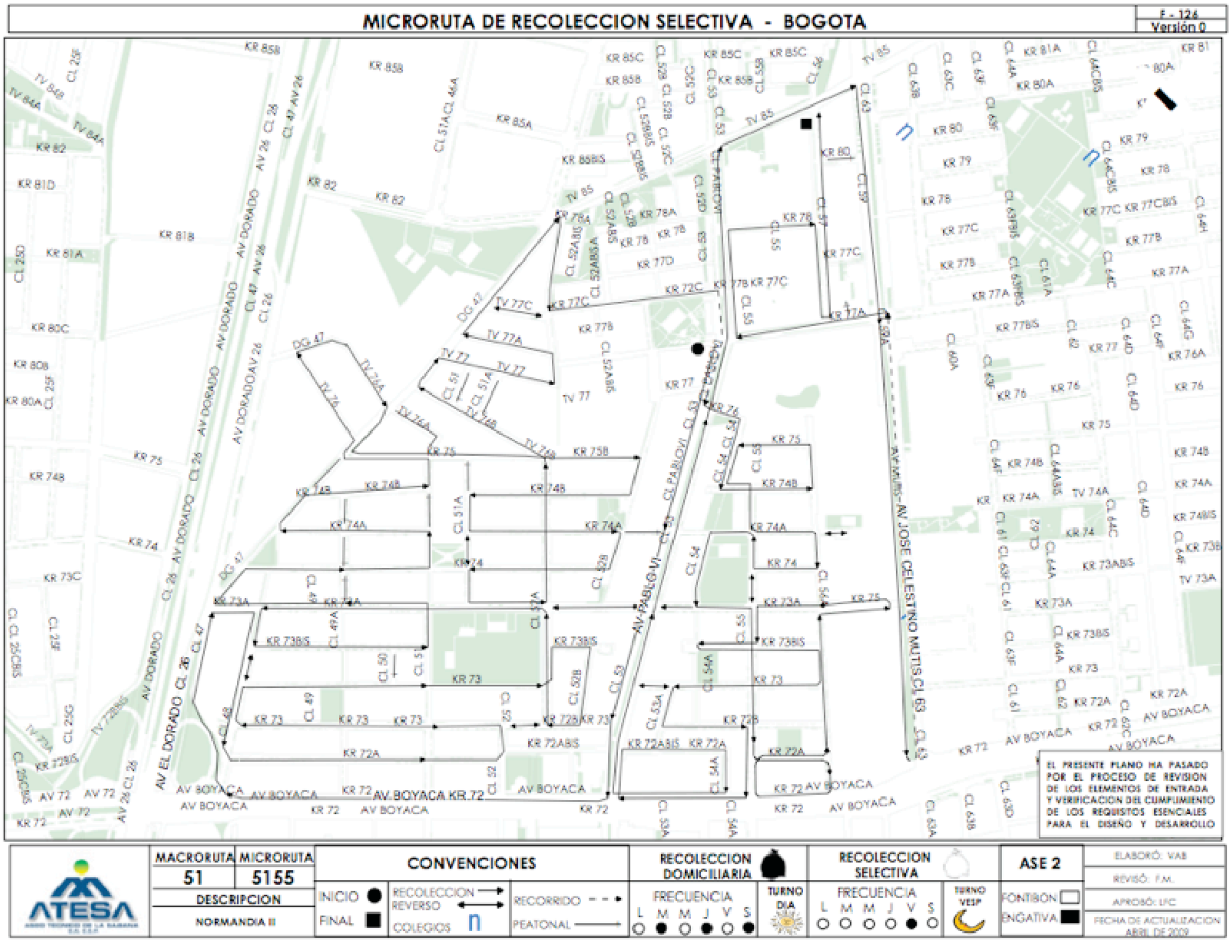


Figure 17: Example of a weekly micro-route to collect recyclable material. Source: Castillo, 2011.

3.3.2. Sorting and storage

While the municipality's vision for Bogotá's recycling plan is to have several (5-10) full-scale recycling centers where all sorting and separation occurs, local protests from neighbors who do not want to live alongside a recycling facility have prevented all but one center to be constructed. All the white bags are transferred directly to the pilot recycling center, La Alquería, whose capacity is 20 tonnes/d, though only half of that capacity is being used, and the average amount of material received daily is 5 tonnes (Calderon 2010). Fifty on-site employees, all affiliated recyclers, separate recyclable materials from waste materials, and sort the recyclable materials into like groups. They wear identical uniforms, including hats, gloves, and boots, and are paid minimum wage with benefits for their regular, 8-hour shifts; their income does not depend on how much material they sort, nor how much is collected. Waste material is sent to the landfill, and recyclable materials are sold directly to industry.

3.4. Legislation supporting a new recycling plan

The municipality has been active in promoting the new recycling plan, using bold legislation and marketing to not only encourage users to cooperate with the new routes, but also to make the current mode of recycling illegal. The city passed an ordinance stating that waste belongs to the state once in public space, meaning that sorting through it is illegal (Castillo 2010). Though this ordinance was contested in court, as have all legislation that threatens the livelihood of free-market recyclers, it marked the beginning of an attempt to criminalize informal recycling. Many other laws have followed, making sorting through waste in public spaces illegal, requiring all recyclers to participate in a census, and prohibiting horse-drawn vehicles in Bogotá by 2012 (Decreto 1666; Castillo 2010).

4. FREE-MARKET VERSUS REGULATED RECYCLING: ECONOMIC SUSTAINABILITY, SOCIAL INCLUSION, ENVIRONMENTAL RESPONSIBILITY, AND MODERNIZATION

I compare the long-standing free-market recycling system with the pilot recycling project along the four metrics proposed by the national recycling plan: economic sustainability, social inclusion, environmental responsibility, and modernization. In the free-market recycling system, every stage of recycling (collection, storage, separation, re-manufacture) operates as a business, and as such, turns a profit. The profit margins grow with position on the recycling chain – the collectors make the smallest margins, and the large bodega owners make the largest – but in order for every player on the chain to persist in their trade, they must be making at least some money. Regulated recycling operates by mandate, and its existence does not rely on economic gain.

4.1. ECONOMIC SUSTAINABILITY

4.1.1. PILOT RECYCLING PROJECT

I estimate the cost of collection of recyclables for the pilot project using the following equation:

$$Cost_{collection}\ (\$/ton) = diesel\ cost\ (\$/L * L/km * km\ traveled/week * week/tonnes\ collected) + maintenance\ (\$/km*km\ traveled/wk * wk/tonnes\ collected) + truck\ cost\ (\$/week * week/tonnes\ collected + labor\ cost\ (\$/hr * hr/week * week/tonnes\ collected)$$

The cost of running the sorting facility is:

$$Cost_{sorting}\ (\$/ton)=\{labor\ cost\ (\$/day) + maintenance\ cost\ (\$/day)\} * day/tonnes\ collected$$

The total costs are normalized by tonne of recyclable material, to facilitate its comparison with the cost of informal recycling. (This is different than total tonnes of arriving material, since mixed waste arrives to the recycling center, and garbage is sent to the landfill. Approximately 40% of the material that arrives to the Alquería is garbage (non-recyclable material)). The costs of transportation to industry and to the sanitary landfill are added to the cost of collection.

$Cost_{transport}\ (\$/ton) = Cost_{landfill} + Cost_{transport\ to\ industry}$, *where*

$Cost_{landfill}(\$/ton\ received)$ *= diesel cost (COP/L * L/km* km traveled to landfill/week * week/tonnes waste) + operation cost landfill ($/tonne)*

I determine the number of trips to the landfill taken per week by dividing the total mass of trash per week by the size of the largest collection vehicle used (5 tonne capacity), finding that 5 weekly 17 km trips are needed. Because these trips are short, and the same drivers who collect waste also transport it to the landfill, I assume that the labor costs are included in the earlier collection calculations.

$Cost_{transport\ to\ industry}\ (\$/ton\ received)$ *= diesel cost (COP/L * L/km* km traveled to landfill/week * week/tonnes waste) + truck maintenance ($/km*km traveled)*

$Cost_{total}\ (\$/ton_{recyclable}) = \{Cost_{collection} + Cost_{sorting}\}*(\$/ton_{recyclable})$

Using publicly available maps showing the routes taken by recycling trucks each week, I use ArcGIS to calculate the total distance traveled for collection, and use data collected through interviews to calculate the maintenance costs of the trucks and the recycling facility. Figure 18 is a map of the city, with the formalized recycling routes.

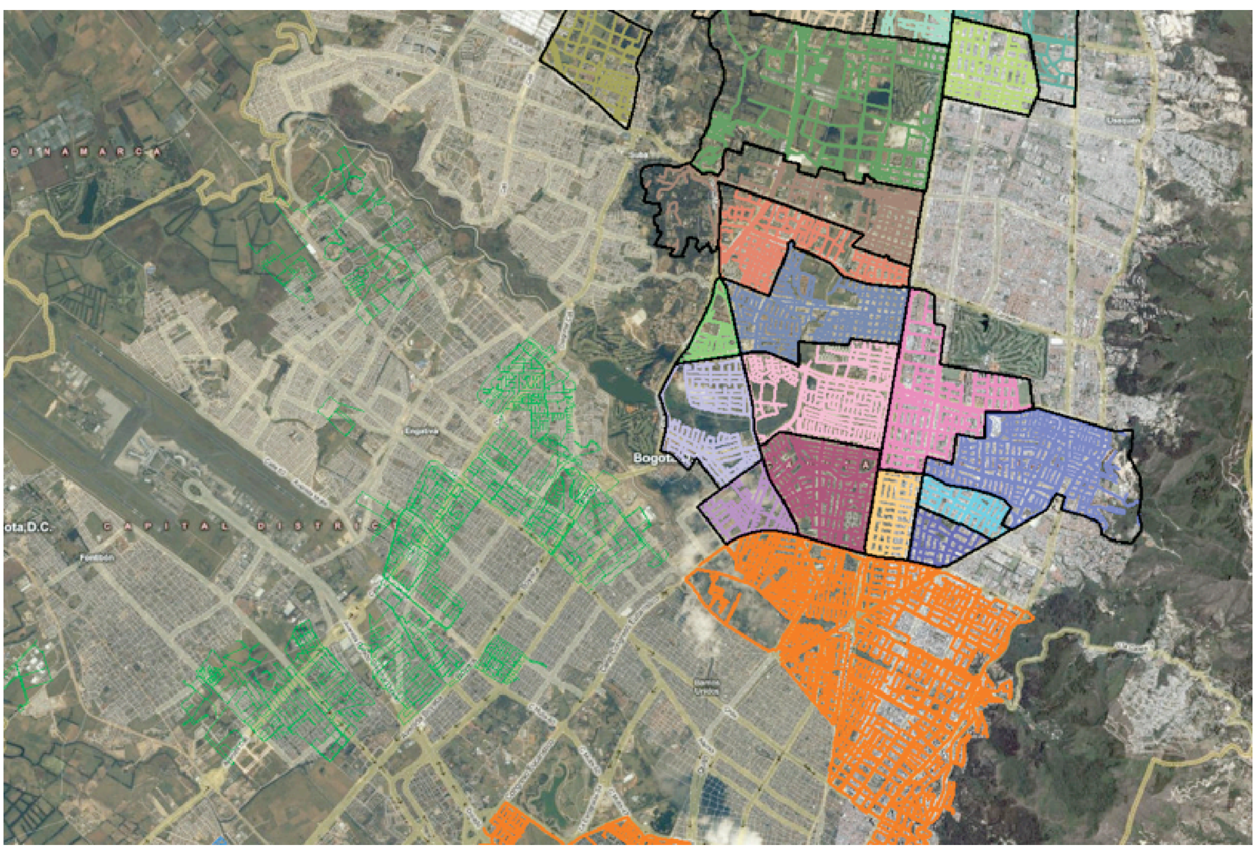


Figure 18: Map of Bogotá's formal recycling routes. Created by author, using data from UAESP (2011).

The total cost of running the pilot facility is COP$740,000/tonne recycled material, or about USD$415/tonne of recycled material. About half of this total cost (47%) comes from the collection of recyclable material, and 86% of the cost goes to salaries.

4.1.2. UNREGULATED RECYCLING

Similarly, I calculate the cost of collection via the free market system, by looking at three representative modes of collecting recycled goods: an over-the-shoulder bag, a hand-drawn cart and a horse drawn cart. For each mode, I calculate the cost of collecting, sorting, and transporting recyclable goods to industry, assuming that each tonne of recyclable material passes through three bodegas before reaching industry: one small, one medium, and one large. From collection to the first bodega, recycles transport their goods over a short distance, using mostly non-motorized vehicles; as goods move along the recyclable supply chain, they are stored in larger sorted volumes, and the vehicles used to transport them from one place to the next are larger. I assume that material traveling from a small to a medium bodega moves via pick-up truck, from medium to medium in larger collection trucks, and from large to industry in the same types of trucks used to collect garbage.

$Cost_{collection}$ (\$/ton) = maintenance cost (\$/week(week/ton) + labor cost (\$/week * week/ton)*
*$Cost_{sorting}$ (\$/ton)={labor cost (\$/week)+ maintenance cost (\$/week)} * week/ton*

*$Cost_{transport}$ (\$/ton) = maintenance cost (\$/week * week/ton)+ truck cost (\$/week* week/tonnes collected) + labor cost (COP/hr* hr/week*week/tonnes collected)*

The labor cost is an estimate, and in reality is highly variable. From the interviews conducted, I estimate that a recycler collecting with an over-the-shoulder bag makes about 7000 COP/day ($4/day), a worker using a hand cart will make about 15000 COP/day ($8/day), a collector using a horse-drawn cart will make about 74000 COP/day ($41/day), and a truck collector will make about 30000 COP /day ($14/day). Two important clarifications must be made here. First, recyclers may often make more than minimum wage, but this income is in no way guaranteed; their daily income changes day-to-day, with season, competition, market prices for materials, availability of material, and the hours that they work. Second, these numbers reflect their total income in a day – and they may work more or less than 8 hours to reach their ideal daily income – which includes their effective wage as well as their profits. Thus, in calculating the costs of free-market recycling, I do not include their profits. I only estimate the cost of their labor, assumed to be the minimum wage, though in practice, each recycler may ‘adjust’ his own price of labor, decreasing it when work is scarce, and increasing it when work is plentiful.

Though I calculate the cost to run each node of the informal recycling sector, for comparison sake, it is important to note that the costs are borne by different actors in the two systems. In the pilot system, the municipal government and some outside donors bear all of the costs: from collection to transport to sorting, and all of the labor and administrative costs that go along with those activities. Income made from the sale of recyclable materials comes back into the system, but today, these sales do not come close to meeting the costs of running the system.

In the free-market recycling system, each node operates as a business. Collectors collect because they make a profit off of their sales; they exchange their labor for the resource value of the goods that they collect. Bodegas add their own labor to separate and agglomerate recyclable materials, and sell what they collect at a higher price than the price they paid to purchase it. These businesses receive no subsidies so the costs that are tallied here simply reflect business expenses that are outweighed by their profits. Because each bodega works to maximize its profits, bodegas inspect all material before they purchase it, so as to only accept recyclable material. Consequently, bodegas report a waste rate of less than 1%.

The total cost for the modeled unregulated system is COP$3.4 million/tonne of recycled material (~USD$1900/tonne). Collection is a small fraction of the total cost (0.2%), and almost 100% of the collection cost comes from the labor of the recyclers. Half of the cost of the operation of the informal recycling chain (49%) is labor cost. These costs are absorbed within each node, so the direct cost to the municipality of collection is zero (though there are indirect benefits – environmental and social – and burdens – disorder, open dumping and aesthetic concerns – to this recycling system).

4.2. SOCIAL INCLUSION

For each mode of recycling, I estimate the number of people employed, and at what salary they are employed, per tonne of recyclable material collected[4].

4.2.1. REGULATED RECYCLING

Employment through the regulated recycling system is known. The system employs 111 people directly (45 drivers, 60 workers in the recycling plant, and 6 administrators) to manage approximately 10 tonnes/day of recyclable material. In the municipal pilot recycling system, then, 11 people are employed per tonne of recyclable waste collected (or, 18 people per tonne of marketable recyclable material). Because this system is formal, the number employed is fairly constant, and those who are employed are not from the very lowest echelons of society; they have resumes and have applied for these jobs.

4.2.2. FREE-MARKET RECYCLING

The unregulated waste sector recycles between 600 and 1500 tonnes each day in Bogotá (ILO 2009; Gomez 2011; Ruiz 2010). Using these estimates as bounding cases, along with average collection rates for each mode of recycling, it is possible to estimate the number of people employed through collection of recyclable goods in Bogotá as a function of their mode of recycling. This estimate varies greatly, as a function of total quantity recycled (which itself changes daily, seasonally, and annually), with the mode of accounting for those who depend on recycling. I again calculate bounding estimates. The minimum number of workers needed is the

[4] Because the pilot plant has a high wasting rate (40%), then calculating the number of employees per material recycled will inflate the number of people employed per material recycled.

number of collectors required to collect all the city's recyclable materials, while working full-time. This minimum number is between 900 and 2,200 full-time collectors. In reality, however, many of these recyclers work as family units – especially in the case of collectors using horse-drawn carts, who are responsible for recycling the most material – and many recyclers are in fact occasional recyclers, collecting materials infrequently, as needed to supplement their income. The 2002 census found that about half of recyclers in Bogotá were occasional recyclers. Including occasional recyclers, then, between 3,500 and 9,000 people work as recyclers. Including occasional recyclers and those dependent on recyclers, there are between 14,000 and 35,000 recyclers in Bogotá. This estimate is validated by comparison with the 2011 census' implicit estimate (using their estimate of the average quantity collected per recycler of 450 kg/d; UAESP 2011): between 15,000 and 37,000. The two data sources – my own and the UAESP's – generate estimates shown in Figure 19. The initial estimates, shown in the four sets of bars on the left side of the figure, use the total quantity recycled and my own estimates of the amount recycled per collector to calculate the total number of recyclers. The set of bars on the right uses the census estimate for the amount recycled per collector. We can see that the final two sets of bars are in close agreement.

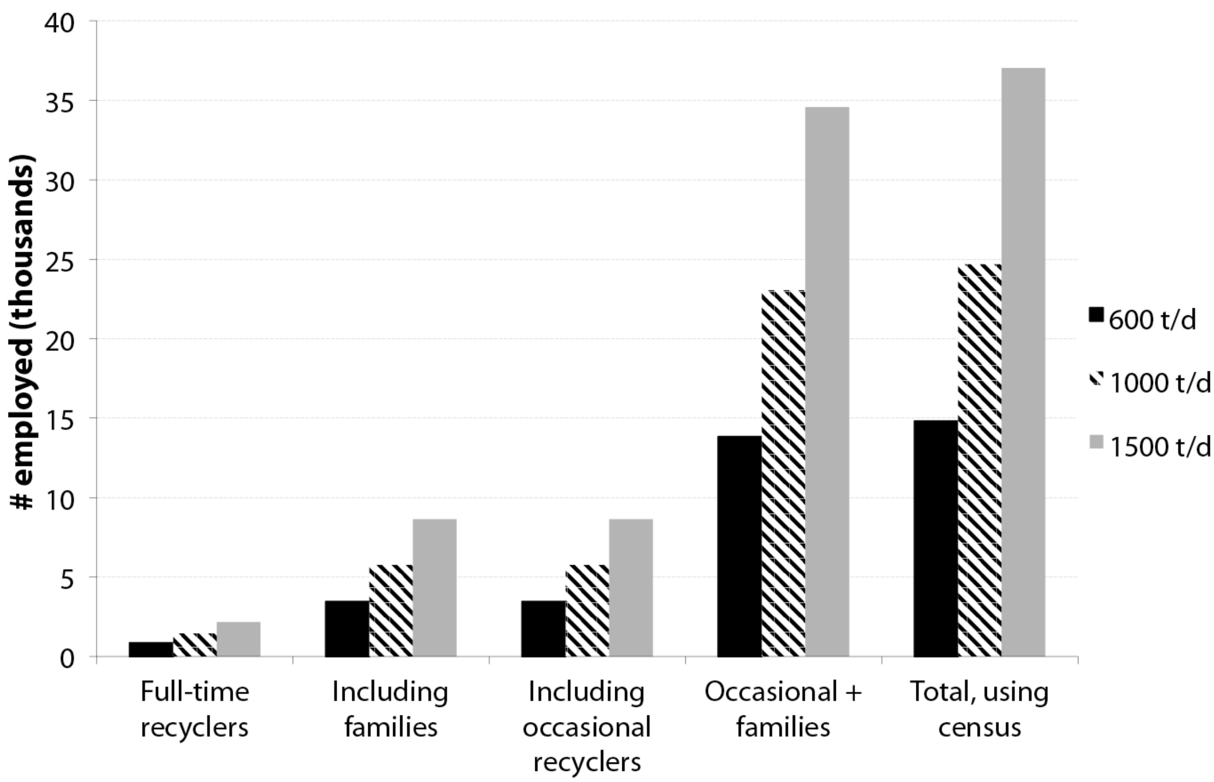


Figure 19: Estimates of the number of people employed by collecting recyclable materials in Bogotá, as a function of quantity of recyclables generated and mode of recycling. The four sets of bars on the left are estimates derived from the total quantity recycled in Bogotá, and the final set of bars on the right uses census data.

The average quantity recycled by a full-time recycler (4.86 tonnes/week, shown in Table 3) can be used to find the number of people employed through unregulated recycling in Bogotá. In sum, two full time recyclers are employed to collect each tonne of recyclable material. Including occasional recyclers, the employment grows to six collectors per tonne. In the most generous definition of employment, which includes both occasional recyclers and their dependents, 23 collectors work per tonne of recyclable material. The latter estimate reflects the number of people dependent on recyclable material coming through the informal collection chain.

Table 3: Modes of collection, number of collectors per mode, and quantity recycled by mode. Data from UAESP (2011) and interviews.

Collection Vehicle	Number	% Recyclers using mode	Collected (t/person-wk)	% Quantity by mode
Zorrillo (Hand-cart)	2,982	27	0.72	15
Costal	2,792	25	0.12	2
Horse-drawn carriage	2,183	20	3.00	62
Tricycle	1,037	9	0.72	15
Carro esferado (small cart)	622	6	0.12	2
Shopping cart	442	4	0.12	2
Motorized vehicle	348	3	0.06	1
No information	95	1	0	0
Total	11,109	100	4.86	100

After collection, recyclable goods travel through a sequence of bodegas. These bodegas employ sorters and drivers. I assume that the bodegas share the characteristics of those surveyed by the UAESP, and that every tonne of recyclable material travels through one small (employing 3 workers), two medium (employing 5 and 10 workers, respectively), and one large bodega (employing 30 workers) before reaching industry. Recognizing again that the rate of recyclable production is both variable and uncertain, I estimate the number of bodegas in Bogotá and the number of employees in those bodegas under the three production cases; these results are summarized below and plotted in Figure 20. The sorting process employs between 17,000 and 42,000 people, and Bogotá has somewhere between 1,400 and 3,500 bodegas. As in the case with estimating the number of collectors in Bogotá, however, these estimates may be lower than reality, due to the preponderance of informality and occasional workers in the recycling industry. Sorting and separation employs 28 people per tonne of recyclable material. In sum, then, the free-market recycling system employs about 50 people per tonne of recyclable material, and many of these workers are informal and occasional workers.

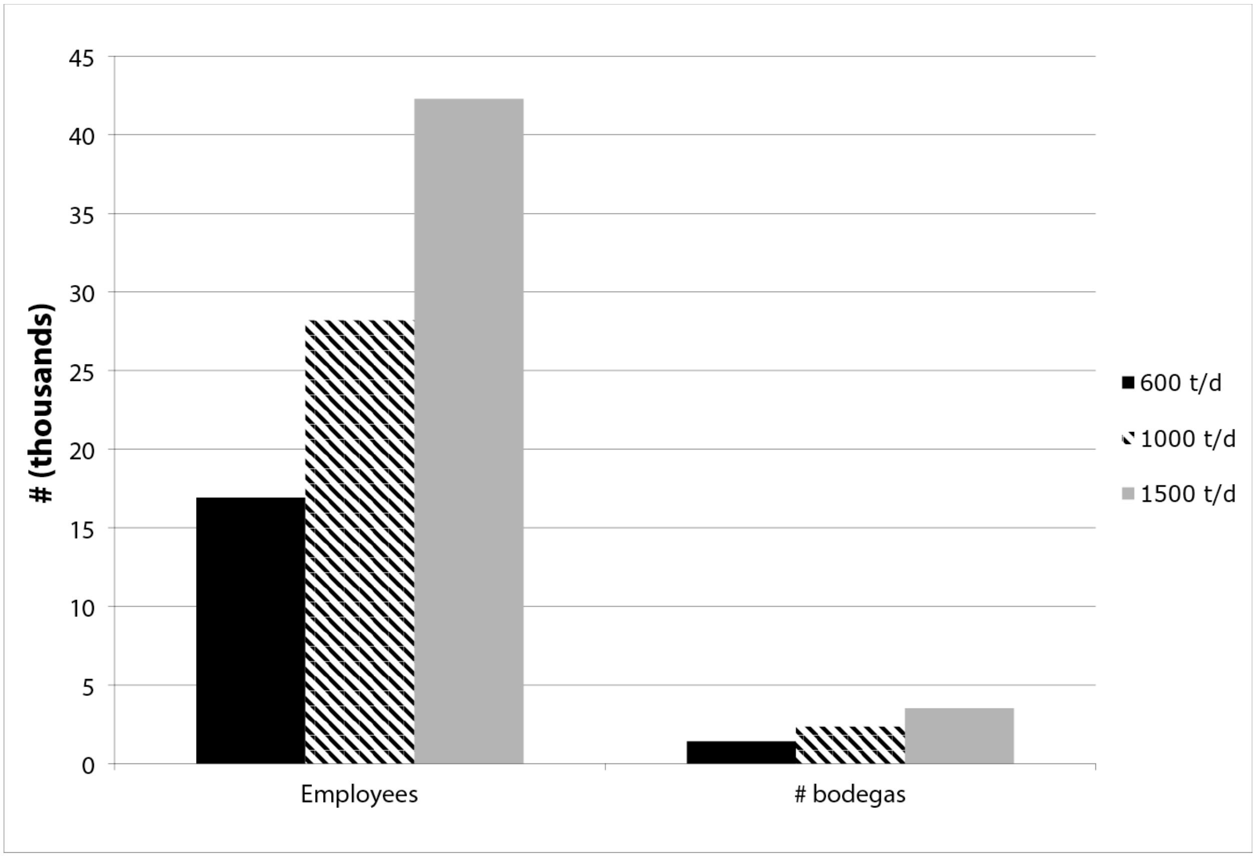


Figure 20: Estimated employment from and number of bodegas in Bogotá, under different recyclable production rates.

4.3. Environmental sustainability

Two measures of environmental outcomes are used in this chapter: quantity of waste diverted from the waste stream into recycling, and vehicle miles traveled per tonne of recyclable material. The quantity of waste diverted provides three kinds of environmental benefits: it minimizes the amount of waste that has to be transported and treated in a landfill, it displaces some of the need to mine for natural resources to produce new goods, and it decreases the amount of energy needed to produce those goods. Vehicle miles traveled per tonne of recyclable material is a measure of energy intensity in the recycling process; it is correlated with emission of air pollutants that pose public health and environmental risks.

The main environmental benefit of the free-market recycling system currently is that it removes material from the waste stream and by doing so, converts it into a raw material. That which is not collected by these collectors is transported to the landfill. Because this system already exists, the addition of the regulated recycling system does not necessarily keep material out of the landfill; it only changes where it goes and who collects it. However, as the regulated system does not select material based on its market value (the way the free-market collectors do), it may collect more low-value material (e.g., plastics) from the waste stream that could otherwise go to the landfill. The yearly average composition of the material recycled by the two systems are presented in Figure 20; data come from one particular bodega, representing the free market, and from La Alquería, which keeps careful record of all materials passing through. The free-market bodega has a higher percentage of materials with higher market values (paper, metals), and less plastic, which has a lower market value, and glass, which is both heavy and inexpensive.

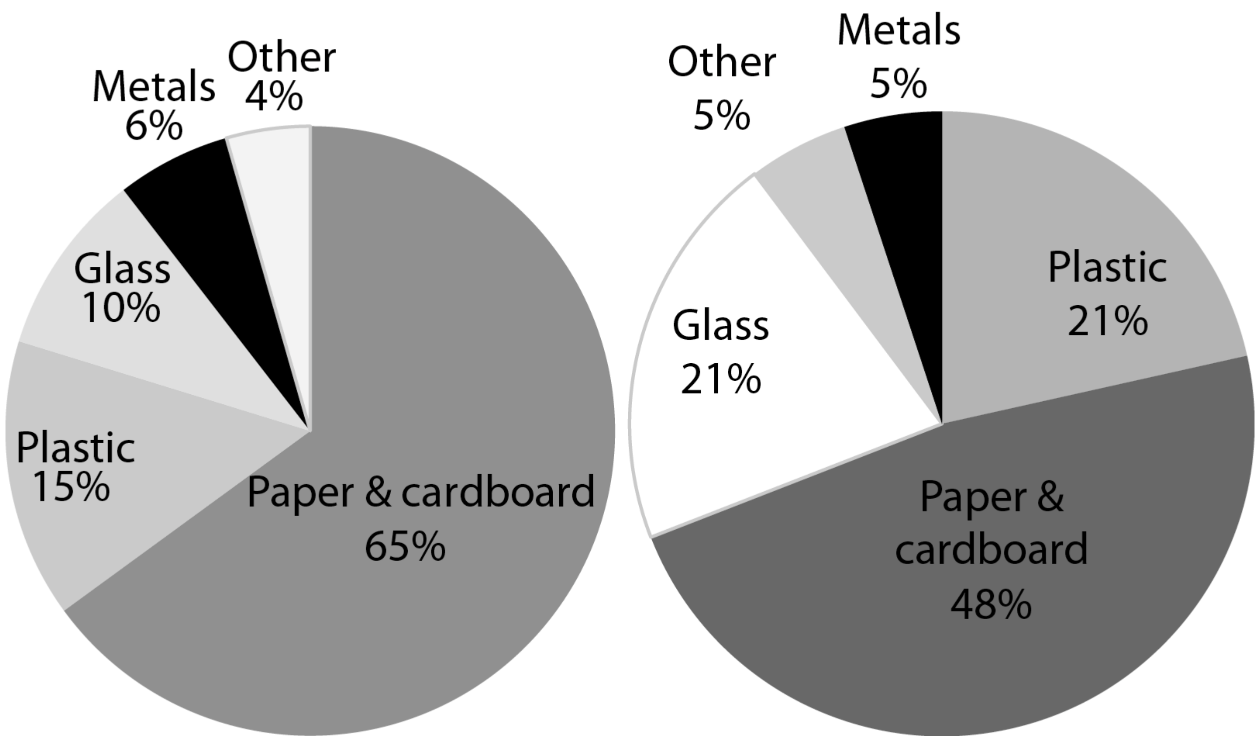


Figure 21: Composition of materials sold from an unregulated bodega (left) and the municipal recycling facility (right) in 2009.

The regulated system is a pilot project, so its scale is necessarily quite small. It currently diverts about 5 tonnes/day from the waste stream, while the informal recycling system diverts between 600-1500 toness/day from the waste stream. Each tonne of material travels approximately 15 vehicle kilometers between the bodegas before reaching industry (Espinosa 2011), and a negligible quantity is sent to a landfill. In the regulated project, each tonne of collected material travels about 260 vehicle kilometers; this is largely due to the mechanization of collection.

Assuming that the regulated system were scaled up to collect more of the city's recyclable material – the municipal recycling program currently collects less than 1% of the total recycled material – then the waste management system would become considerably more mechanized, adding more vehicles to the congested streets of Bogotá.

4.4. Modernization

I explore the extent that the free-market recycling system and the proposed regulated recycling system fit the criteria of a modern city, invisible connections, aesthetic order, cleanliness, and universality.

There is no question, in comparing the regulated to the unregulated recycling system, as to which is more modern. In replacing collectors who rip open bags on sidewalks, the regulated recycling system attempts to hide garbage from the consumer, "rendering occult the social relations and power mechanisms that are scripted in and enacted through these flows" (Kaika and Swyngedouw 2000, p. 121). Not only does the waste itself remain inside a secured bag, the people who depend on that waste for their livelihood, and the work that they do, are made invisible. Hiding the work that is done by thousands of urban workers makes it possible to forget and replace them with another system, even if that system recycles less. More abstractly, making these collectors invisible allows a city resident to become less aware of the poverty and inequality that exists in their home.

In the pilot recycling program, trucks replace these thousands of people. These trucks and their planned, mapped routes are connective, bringing individual homes a swift and technological service. By mechanizing the collection of recyclables, the municipal government is planning to create cleaner streets. No longer will garbage bags be mined for resources on the streets – sometimes leaving messes behind – instead, the un-aesthetic bags will be opened in the confines of a recycling facility. The city's pilot plan reflects a common aim of modernizers: to "[make] the city the reflection of a single, rational plan" (Scott 1998, p. 111). Mapped routes and a set flow of materials to one (or more) central recycling facilities represent a rational, unchanging plan that can be seen from above. What is more, the mapping of the system makes it visible; "the 'it' [of recycling] is plainly invisible" until "it is made visible [through]…charts and lists" (Latour 1962, p. 14). In contrast, the current free-market recycling plan is dispersed, flexible, adaptable, and does not reflect the implementation of one plan, but rather the individual plans of thousands of workers who have built a network to gain profits from the recovery of recyclable goods. It is indeed a sharp "contrast between what looked modern (tidy, rectilinear, uniform, concentrated simplified mechanized) and what looked primitive (irregular, dispersed, complicated, un-mechanized)" (Scott 1998 p. 254). The pilot recycling scheme is tidy, concentrated, and simplified. The current free-market recycling system is dispersed across the city, it relies on the labor of many rather than the implementation of technology, and it is irregular, changing day to day in response to market prices, and waste production. Though there are ways that the current system could be "modernized," such as the proliferation of cooperatives, uniforms, standardized collection carts, or more institutionalized arrangements between collectors and waste producers, the pilot program is certainly more modern than the current system. Finally, the pilot program is universal; it is very similar to the recycling programs found in cities in the United States and Europe.

5. Discussion & Conclusion

What are the implications of shifting away from free-market recycling towards regulated recycling? This formalization of recycling systems is occurring in many industrialized cities. Table 4 below summarizes the metrics used to analyze the economic sustainability, social inclusiveness, environmental sustainability and modernity of each recycling system.

Table 4: Summary of social, economic, environmental, and modernity indicators for the municipal and unregulated recycling systems. All numbers are given in tonnes of recycled material,

Indicators	Unregulated	Municipal
Economic		
Cost ($/tonne)	$1,900	$415
Labor ($/tonne)	*$935*	*$357*
Social		
Employment (#/tonne)	34-51	18
Environmental		
Amount collected (t/day)	~1000	~8
Amount recycled (t/day)	~1000	~5
Vehicle km traveled/tonne	15	260
Waste rate	<1%	40%
Modernity		
Aesthetics	Low	High
Cleanliness	Low	High
Invisibility of connections	Low	High

From an economic point of view, unregulated recycling is both more expensive and more 'efficient' than the regulated system. Though the aggregate cost of handling a tonne of recyclable material is more expensive than handling it through the regulated system, these costs are borne by each node of the system – collection, storage, and sale – and still operates at a profit. Conversely, though the regulated system operates at a lower cost per tonne, it is losing money every day that it is in operation and is relying on donations to remain afloat. Why does this seeming incongruity occur?

First, there is an important difference in incentives for the two systems, leading to a difference in the composition of recyclables for the two materials. Because collectors and bodegas in the unregulated system are paid based on the quality and quantity of the particular materials that they bring in, they are choosy. They will select and separate the highest-value materials that they find. Because those working for the regulated system do not have the same incentive – they are paid by the hour, regardless of the materials collected – it is expected that the free-market recycling system will collect all of the highest-value materials. Thus, they will collect the highest revenue from their goods, while the regulated system is left with the lowest quality goods, some of which may cost more to process than they are worth in re-sale.

Second, the free-market recycler's work is flexible. He may work as many hours as he needs to in order to bring in enough revenue (the consumption-labor-balance principle). It also means that he can adjust his own wages as needed. When material is scarce, he might value his own labor very lowly, working many hours for a meager profit, to make just enough to sustain himself and his family. When material is abundant, he may work fewer hours and focus on collecting materials with higher values, so his profits are higher. Workers in the recycling plant, however, cannot adjust their labor. Even though waste production and composition are variable, the workforce is constant. It is also likely that people work harder when they see the fruits of their increased efforts – they see a direct relationship between the amount they work and the amount they are compensated – than when they are working for a larger organization, especially if that organization pays them a flat rate.

So the costs of running an informal recycling system are higher, because of the number of people and institutions and the amount of time involved in the handling of each ton of recyclable material. Importantly though, these costs are not borne by one central institution, but rather by a consortium of people and businesses, which each derive wealth from this process. Also importantly, the revenue from the informal system is higher than the regulated recycling system – high enough to compensate for the increased costs. So the disintegrated system is more costly in aggregate but still more competitive than an integrated system in practice.

The unregulated system employs more people – full-time and occasional – than the regulated system, and those employed include the poorest members of society. Many countries implement government-subsidized employment programs to reach those at the bottom of the pyramid, with the aim of improving the lives of those who are most needy, and in so doing, prevent societal harms (e.g., theft, homelessness). Free-market recycling operates similarly – it is a source of employment and livelihood for those most needy (those who are not as needy will seldom select this mode of employment), but is a scheme that does not need to be managed by anyone.

The environmental benefits of informality seem to be greater than the regulated system. With a high number of employees per tonne of waste, the amount of sorting done is greater than that of the regulated system, allowing a higher percentage of what is collected to be recycled. Because collection under the free-market regime is almost entirely un-mechanized, the vehicle-kilometers traveled are much lower than that of the regulated system. Lower rates of mechanization have ancillary societal benefits: less road congestion, better air quality, and fewer greenhouse gas emissions. However, free-market recyclers do not have strong incentives to avoid open dumping, which causes negative environmental and social impacts.

Free-market recycling outperforms the regulated system in three of the four stated goals for the city's recycling program: economic sustainability, social inclusion, and environmental sustainability. But the fourth goal – modernization – seems to be weighted strongly by the municipal government. The municipal recycling plan is legible, aesthetic, planned, and it helps the government build a clean, modern city. The allure of modernity overrides the other stated goals for the city's recycling system.

Chapter 4. Trade-offs to municipal waste 'modernization' plans: greenhouse gas implications of formalizing the waste recycling system in Bogotá, Colombia

1. INTRODUCTION

1.1. BACKGROUND: THE CHANGING NATURE OF WASTE

If a sewer is the conscience of a city (Hugo 1884), then garbage is its fingerprint. "What people have owned – and thrown away – can speak more eloquently, informatively, and truthfully about the lives they lead than they themselves ever may" (Rathje 1994, p. 54). Waste production reflects cultural preferences, behaviors and attitudes, and changes in waste over time can reveal broad cultural shifts. Globally, waste production is changing, in quantity, composition, and distribution. The rapid growth in urbanization and rates of consumption has concentrated waste in low and middle-income cities in the developing world. Because the accumulation of wastes has strong and direct impacts on public and environmental health, cities must rise to the challenge of managing increasing quantities of increasingly complex waste. How they choose to do this has important consequences. Taking climate change as an example impact category – for it is a consequence to which many environmental analyses are directed – waste management may represent either a net source or a net sink of greenhouse gases to the atmosphere (Bogner et al. 2007). If waste is treated as a resource, and used for efficient recycling or beneficially reused, waste management can be a net sink of GHGs, and can reduce a city's overall energy consumption and resource extraction, with the environmental co-benefits that come with it. If waste is simply disposed, or managed inadequately, it poses a burden on cities, and can present a source of GHGs. So the question is: how will cities adjust their current waste management schemes, many of which rely on informal arrangements to meet the challenge of increased waste production? What are the environmental consequences of their modernization plans?

The case of Bogotá, Colombia, is used to explore these questions. The city is experiencing many of the changes that are occurring on a global scale. The world is urbanizing at an unprecedented rate, and Latin America is at the epicenter of this demographic shift. The global urban population is estimated to nearly double between the year 2000 and 2030, from 2.86 billion to 4.98 billion. Within a world that is already majority urban, the concentration of populations in large cities is the most striking in Latin America, where a third of the population lives in cities with populations greater than 1 million (Cohen 2004). Most of Colombia's people – 72% – live in urban areas, and the capital city is the largest population center (PAHO 2005). Bogota's population has increased from under half a million in 1950, to 3 million in 1975, to over 7 million in 2010 (Secretaría Distrital de Planeación 2009).

The city is also undergoing a shift in consumption. Globally, what people throw away is a function of income, climate, demographics, culture, and technology. As people gain wealth, they tend to throw more away, and what they throw away contains materials that are more complex (Bogner et al. 2007, Johnstone and Labonne 2004; Kinnaman 2009, Zhen-Shan 2009, Gomez 2009). Latin American consumers have kept up with trends: they are consuming more, and adopting (and throwing away) more complex items. Colombian consumers are part of the "new consumers" – newly-affluent people from 20 developing and transition nations whose combined spending capacity equals that of all US consumers (Myers and Kent 2003). This newly-affluent population is rapidly increasing their consumption of meat, cars – the cars owned in the Global South grew 89% from 1990 to 2000, with China's fleet increasing 445% and Colombia's 217% –

electricity, and other consumer goods (Myers and Kent 2003). Latin Americans have adopted electronic goods at nearly the same rate that industrialized nations have (Silva 2008). On the other end of these consumptive trends lies an increase in waste generated. Though data on waste production at the point of generation is scarce, the municipal government of Bogota keeps very good data on the quantity and composition of waste that is disposed of in its landfill, Doña Juana. While PAHO estimates that Bogota's waste generation rate is 0.71 kg per person daily, I estimate that generation is 0.9 kg/person-day (due to often neglected 'system losses'), placing its waste generation rate between that of Kunming, China, and Sousse Tunisia (UNH 2010), two other middle income, developing cities.

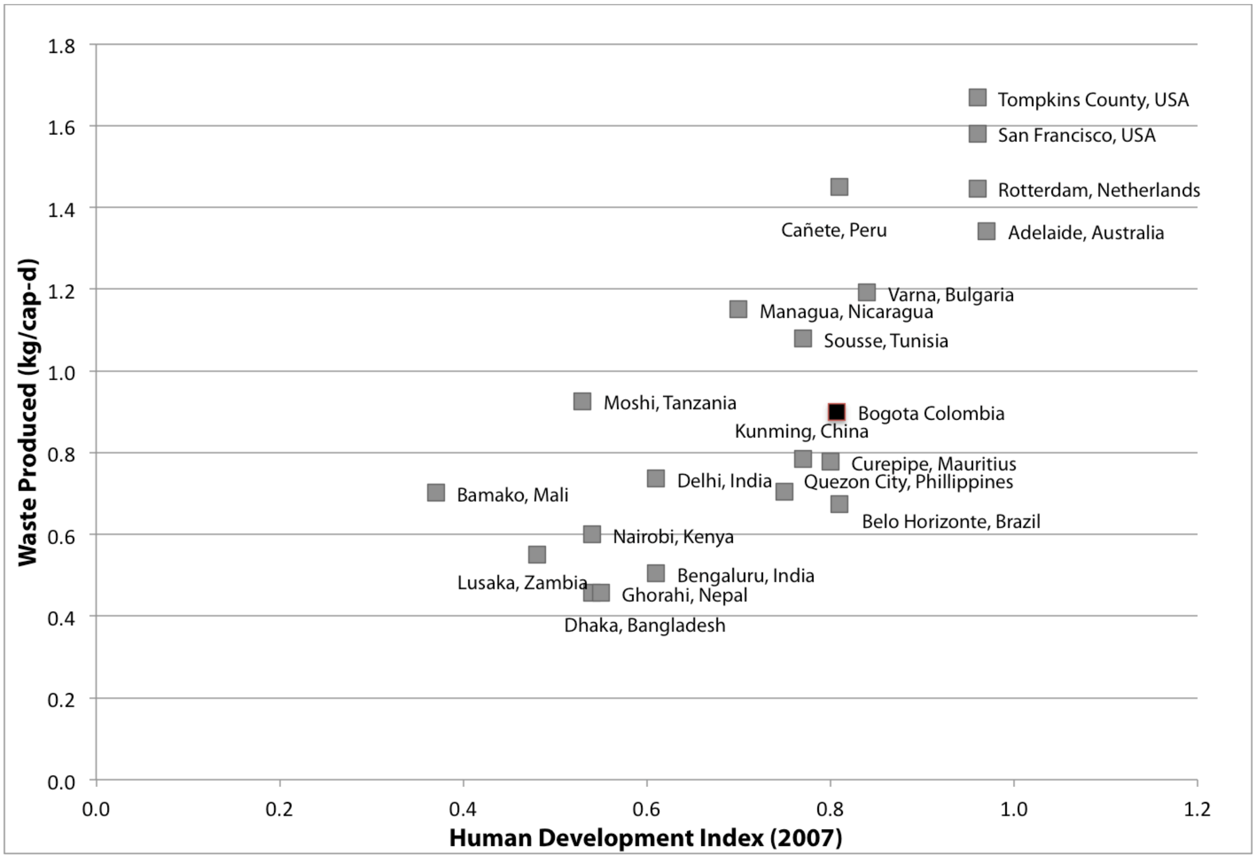
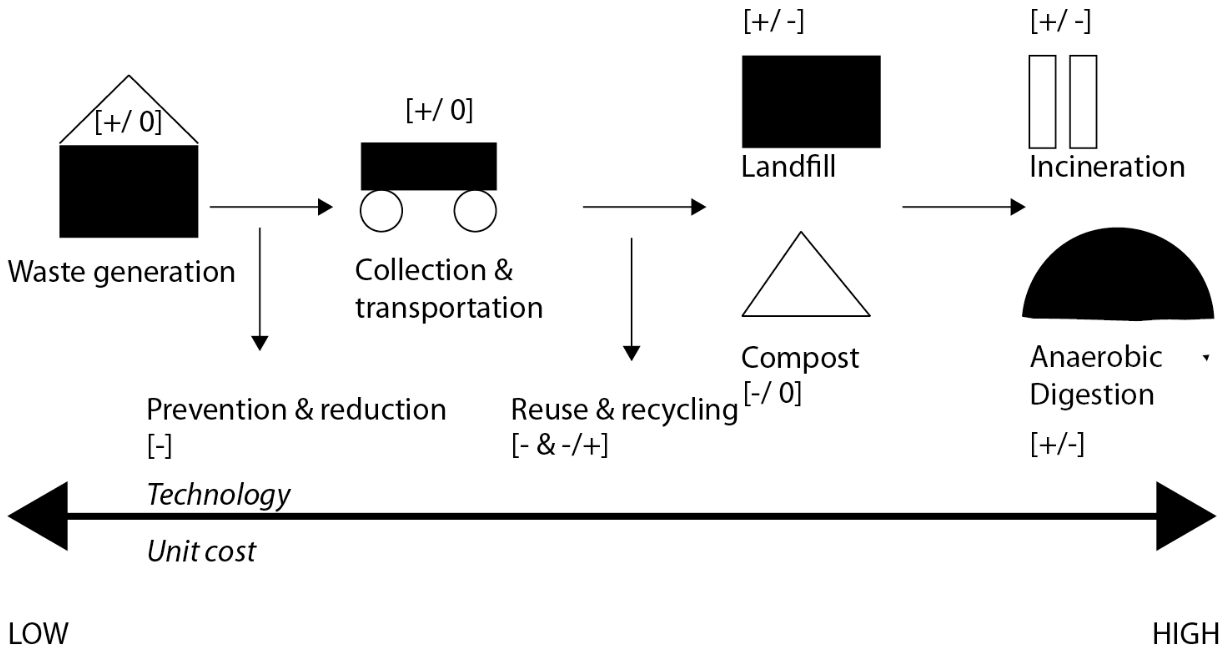


Figure 22: Waste generation of a selection of global cities, and their Human Development Index. Data from UNH (2010); author added Bogotá, Colombia (though Bogotá's data does not come from the same source).

1.2. Waste management and the environment

With increasing waste production comes the challenge of effectively managing it. There are many environmental and social consequences of doing so poorly. Openly dumping and burning lead to the most negative environmental consequences, by directly polluting waterways and land, and producing toxic air pollutants, respectively. These impacts are also borne by people, who consume the polluted air and water, and disproportionally by poor people, who are more likely to live near or work with waste (UNH 2010). Within each functional element of a waste management system – waste generation, waste handling at the source, collection, transport, transformation, and disposal (Tchobanoglous and Kreith 2002) – lays the potential for environmental improvement and degradation. Waste generation is a social process, and its presence requires the functioning of a waste management system. Its reduction leads to environmental benefits, as less waste needs to be handled. Handling of waste at the household level defines subsequent processing; high levels of source separation allow for increased reuse and recycling. Collection and transport of waste can take many forms, mechanized or not, but the former leads to emission of air pollutants and greenhouse gases. Even waste transformation technologies, which were developed to minimize the environmental consequences of waste, carry with them environmental burdens. Incineration, the controlled burning of wastes, produces toxic chemicals that can be controlled by efficient management of the process and advanced pollution control technologies. Organic waste transformation – composting, anaerobic digestion, or conversion to liquid fuel – leads to wastewater production and emission of odor and greenhouse gases. Recycling can also lead to GHG emissions from processing. Finally, disposal, which can fall along a continuum from uncontrolled to highly engineered, leads to the production of GHGs and leachate, both of which are collected and treated in modern sanitary landfills.

I focus on the impact of waste management decisions on climate change for two reasons: climate change is an urgent threat to the functioning of our biome, and carbon released has become an essential metric for decision-making in waste management. Additionally, greenhouse gases released under different waste management scenarios can function as an indicator for overall environmental impact, since lower emissions are usually correlated with less energy consumption and resource extraction. Commonly used waste management technologies are shown in Figure 23, along with their relative costs and level of technology, as well as their possible contribution of greenhouse gases. Most waste technologies can represent either net sinks or net sources of GHGs, depending on the context in which they are implemented.



Legend:
[+] = net emissions of GHGs
[-] = net GHG sink
[0] = GHG neutral

Figure 23: Waste management technologies and their potential net GHG emissions. Adapted from Bogner et al. (2007).

Waste management is responsible for roughly 5% of global greenhouse gas emissions, but that estimate is both variable and uncertain (Bogner et al. 2007). It is variable because the net emissions from a system depend on the context of its implementation, which may change over time. It is uncertain because data quality, on the global quantity and management of Municipal Solid Waste, is lacking. As shown in Figure 23, most waste technologies can be either net sinks or sources of greenhouse gas emissions. A state-of-the-art landfill may function as a long-term carbon storage site (ibid), as well as an energy production source, if landfill gas is captured and combusted. A poorly operated landfill may release great quantities of methane, a powerful greenhouse gas, to the atmosphere. Thus landfills can be a source or a sink for GHGs. Landfills are the greatest source of GHG emissions from waste management systems, contributing to 9% of global methane emissions (IPCC 2007), and these emissions are increasing in developing nations. Recycling systems can also take various forms. An effective recycling system will collect separated waste, and manufacturers will use the gathered materials to create new goods. The provision of these waste materials decreases the energy consumed by manufacturing, and lowers the demand for the extraction of natural resources. Both of these result in decreased greenhouse gas emissions. A poor recycling system can be a source of greenhouse gas emissions. A collection system in which co-mingled materials are gathered will recover fewer materials for re-processing, and if the energy saved from recycling is exceeded by the energy consumed by the collection system, then the overall recycling system will have added GHGs to the atmosphere. There are few waste technologies that are inherently GHG-abating – reuse and waste reduction are – most can be, depending on how they are implemented.

1.3. Drivers for improved waste management

Wilson (2007) identifies four imperatives that drive the development of waste management plans: public health, environmental protection, resource recovery, and climate change. Any of all of these might be driving changes in a city's waste management system at a given moment, though the dominant driver is likely to change over time. Most cities begin to institutionalize their waste management systems though a concern for public health, and recycling and reuse normally have their roots in an interest for resource recovery. Environmental protection emerges as an important driver once waste is no longer threatening public health, and climate change is emerging as an important driver in the Global North and South. Industrialized nations are the world's largest GHG emitters, and many seek to find ways to decrease their emissions to meet targets; many industrializing nations are eager to identify sources of emission reductions through improvements in their waste system so that they may obtain funding for these improvements use the Clean Development Mechanism.

In addition to climate change, another emerging reason cities are looking to modernize their waste management systems is aesthetic. In developing country contexts, "the importance of recognition, image and municipal pride in keeping streets clear cannot be underestimated" (UNH 2010 p. 98). Cleanliness and order are necessary components to building a modern city (Thieme 2008; Kaika and Swyngedouw 2000), and these are not generally characteristics of developing nation waste management systems. Bogotá is attempting to modernize its waste system as a part of a broader modernization effort. Since the 1990s, the municipal government has worked to "[leave] behind the image of chaotic, disorderly and insecure city, has gotten international visibility and has become a [model] for other cities [in implementing] 'creative solutions' … to [solve] urban problems" (Duque 2008, p. 1). The city's modernization efforts aim to address urban problems and reimagine itself. It has invested in transportation infrastructure, building a Bus Rapid Transit system called Transmilenio, whose name and appearance evoke visions of the future. Its elevated platform allow people to access the system only at pre-defined stops, in contrast to the *colectivos*, small, polluting buses that run throughout the city and do not have posted schedules or routes (though residents know exactly where they go). It is in this context, in the active construction of "the narrative of Bogotá as a safe, desirable place to do business, to live and to visit" (Berney 2011 p. 28) that the municipal government has decided to overhaul its recycling system.

1.4. The informal waste sector

The informal sector is an important player in waste management in Bogotá, as it is throughout the developing world. Here I define as "informal" the economic activities that occur outside of the purview of the state (Mitchell 2008); they are unregulated activities. In resource-poor countries, a high proportion of employment is found through the informal sector – in Colombia, more than 50% of work is informal (Medina 2007) – and informal workers play an important role in waste management systems. While the most noted informal players in waste management are the *Zabbaleen*, who are responsible for the world's highest waste recycling rate in Cairo, Egypt (Assaad 1996, Fahmi and Salah 2005), informal workers also provide primary waste collection in cities such as Delhi, India, and are responsible for plucking materials out of the waste stream and re-routing them to the recycling chain in Bogotá, and in cities all over the world (UNH 2010). Medina (2007) estimates that 2% of the global urban population depends on waste for their livelihoods.

The informal waste sector acts in the interstices of government presence, and fills gaps in the provision of public goods (Medina 2007; Tripp 1997). This "other private sector" is indeed a major provider of public goods in urban developing cities; in Latin America, 25% of the population depends on small-scale private providers for water services and 50% of the population relies on non-state actors for sanitation services (Solo 1999). Though sometimes involved in waste collection and disposal, informal waste workers are most commonly involved in the recycling sector, as itinerant waste buyers, street-pickers, dump-pickers, truck-pickers, workers in junk shops, or processors of waste materials (Wilson 2006; UNH 2010). The incentive for retrieval of recyclable goods is purely economic: they are paid for the market value of what they collect. In Cañete, Peru, and Bogotá, Colombia, informal collectors remove materials from bags of waste that would otherwise be sent to landfills; they reroute materials from a path of waste into a recycling chain. In many cities, workers collect recyclables farther along on the waste chain. In Nairobi, for example, 1000 waste pickers live on the dump at Dandora, and remove valuable items to resell (UNH 2010).

Informal recycling provides an environmental service to developing cities. In most industrialized cities, recycling is a regulated industry, paid for and carried out by the municipal government. Cities chose to prohibit the informal recycling that was prevalent early in their industrialization (Strasser 1999) and had to rebuild a recycling sector decades later. Many cities in the Global South, like Bogotá, remain centers of material recovery because of their active informal sector. Informal recycling is spontaneous – recyclers make money from the intrinsic value of the materials they recover, the so their incentive to collect recyclable material is strong. Because their wages come from resale of collected materials, and not through contracts with the city, informal sector recycling provided without cost to the municipality; it is "a subsidy by the poor to the rest of the city" (UNH 2010 p 138) that provides a livelihood for workers (Gutberlet 2008; Gutberlet 2010). By re-routing recyclable goods from the landfill to the recycling chain, informal waste workers catalyze environmental improvements, through a savings in energy production and resource extraction. If not for this work, these materials would instead be landfilled, and manufacturers would use more energy and require virgin resources to produce new goods. Importantly, not all goods that can be recycled are recycled, because there is not an incentive to recycle materials for which there is not a good market. Table 4 (in the previous chapter) separates waste materials into types, showing their relative value and the ways in which they are recycled. Thus, informal work offers (at least) two types of benefits: it provides employment to the poor, and it provides an environmental service to the cities in which it operates. The benefits from this work must be – but have not yet been – quantified in order for developing cities to transition to socially and environmentally desirable waste management plans (McDougall 2001; Gutberlet 2008). In Bogotá, quantifying the environmental benefits of its informal waste sector would be a prudent first step, before overhauling the current recycling system, and replacing it with a municipally-managed one.

1.5. Goal and Problem Statement

The purpose of this paper is to analyze the greenhouse gas implications of the municipal government's proposed changes to Bogota's recycling system, from a largely unregulated, informal system, to a regulated, municipally-run system. This work is important for three reasons. First, because cities are facing rapid growth in population and waste production, they face pressure to improve their waste management systems, resulting in a general trend towards modernization, which has included the side-lining of informal waste actors in many cities (Mitchell 2008). I want to question the implication of the modernization trend. Second, while much qualitative research has explored the functioning of the informal waste sector in various cities (see Fahmi and Salah 2005; Assaad 1996; Wilson 2006), there is a notable absence of quantitative research. No study has yet quantified the environmental benefits from informal waste management. Finally, I analyze the greenhouse gas implications of formalizing recycling because climate change is an urgent threat to our biome, and greenhouse gas emissions must be reduced by all cities and sectors. Additionally, GHG emissions from alternate waste management options may be an indicator of other environmental outcomes, such as energy use and air pollution emissions. More pragmatically, carbon emissions are the primary metric by which most environmental policies are now measured.

2. Methods

2.1. Scope and functional unit

This chapter analyzes alternative scenarios for managing municipal solid waste in Bogotá, Colombia. Using a life-cycle assessment framework, this analysis considers waste produced within the city over a period of one year, from the point of generation until its conversion to a new product, for materials recycled or reused, or until its final disposal in the city's landfill. The functional unit for the analysis is 1 tonne of MSW generated in Bogotá in 2010. To analyze the greenhouse gas emissions of alternative scenarios, EASEWASTE, a waste LCA model, is used (Kirkeby et al. 2006).

2.2. Data and assumptions

I lived in Bogotá in 2010-2011 and used several research methods to try to understand the functioning of the recycling system in the city. These methods included: semi-structured interviews with key informants and selected players in the recycling chain, document analysis, and observation of various nodes on the recycling chain. The research methods used in this chapter are summarized in Table 5.

Table 5: Key players in the recycling system in Bogotá, and the data collection methods used to understand their role.

Key player	Main Role	Methods used to characterize
Consumer	Waste generator	Document analysis
Free market recycler	Collection of recyclables	Observation, key informant interviews (n=25); document analysis
Bodega owners	Sorting, storage, sale of recyclables	Observation, interviews (n=20), document analysis
Industry groups	Use of discarded materials	Key informant interviews (n=5); document analysis
Municipal Government (UAESP)	Regulation of waste and recycling systems, publication of waste management plans, contracting for operation of waste facilities, running pilot recycling plant, community outreach and education	Key informant interviews (n=5), site visits and observation, document analysis
Private waste companies	Collection of solid waste and recyclables	Observation, key informant interviews (n=5)
Private entrepreneurs, educational institutions	Implementation of innovative waste reuse and recycling	Observation, interviews (n=25)

2.2.1. THE RECYCLING CHAIN IN BOGOTA

Recycling in Bogota is a free-market enterprise, involving actors who make a profit from what they collect and sell. Recyclers collect materials from waste thrown out by consumers, and that which is not recovered is collected and taken to the state-of-the-art landfill, Doña Juana, by four private companies contracted by the municipal government. A recyclable material will pass through a number of hands from the time it is removed from the waste stream, until it is converted to a new product by industries. Figure 24 illustrates the path that a recyclable material takes. Consumers generate waste, and recyclers remove valuable materials from it, and sell the materials to bodegas. A material will ordinarily pass through more than one bodega, where recyclables are sorted and stored, and then sold to industry, which will use the raw material to produce a new good for market.

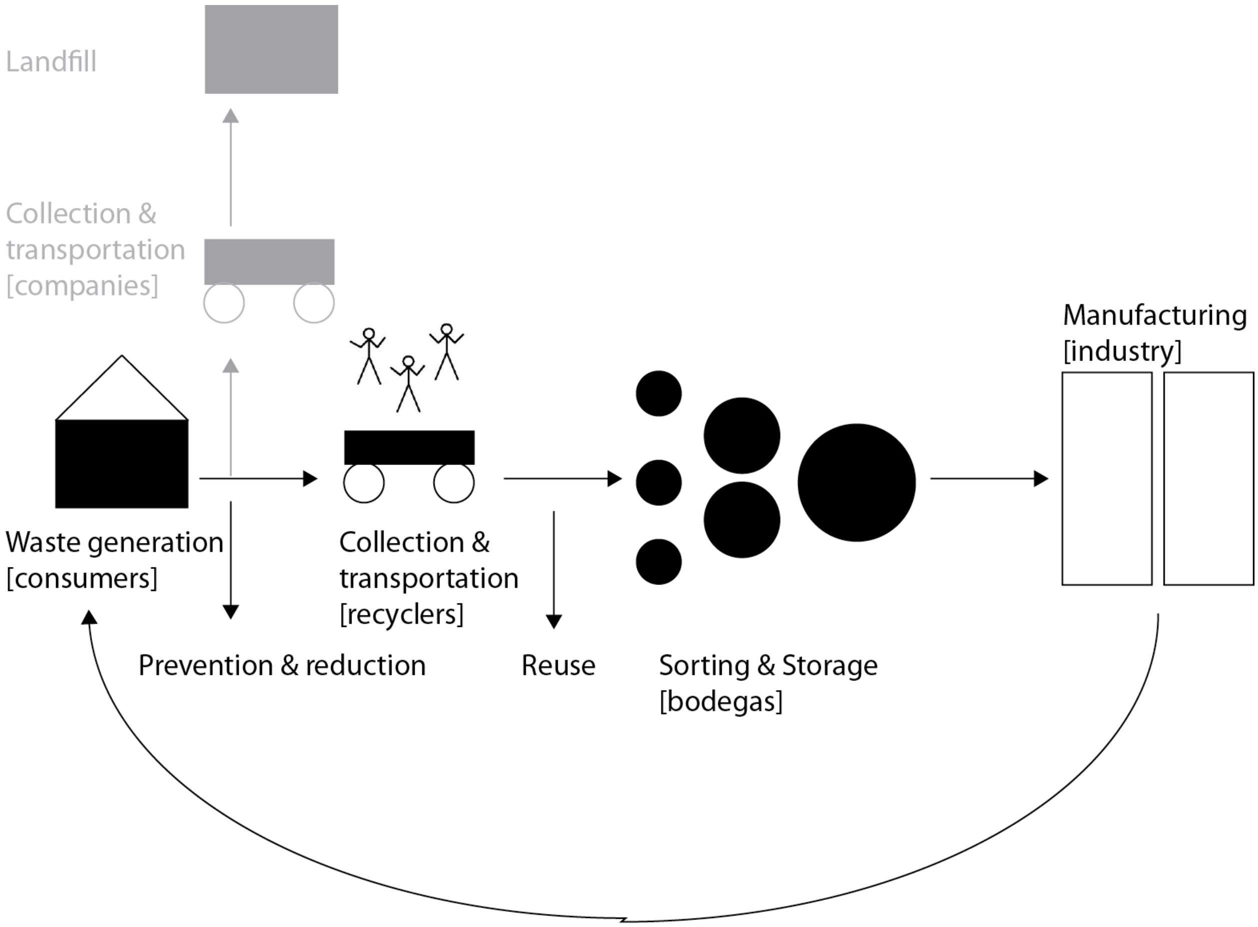


Figure 24: The movement of materials through the recycling chain in Bogotá.

2.2.1.1. Generation

Most cities do not gather data about "system losses," sinks for waste that are outside of the government's control. But the branch of Bogotá's municipal government that handles waste management, UAESP (Unidad Administrativo Especial de Servicios Publicos), keeps excellent data on the quantity and composition of the waste that reaches the landfill. With these data, combined with interviews with waste experts – recyclers, waste consultants, and government officials – it was possible to estimate the quantity and composition of waste that is generated in Bogotá. The difference between what is generated and what is disposed equals what is recycled and reused in the city. An overall mass balance for the waste generated in Bogota, along with the composition of waste generated, landfilled, and recycled, is shown in Figure 25. I estimate that 9,000 tonnes of waste are generated per day in Bogotá, almost 1,200 tonnes of non-biogenic waste are recycled and reused through informal activities, and 2,100 tonnes of biogenic waste are composted or reapplied to land.

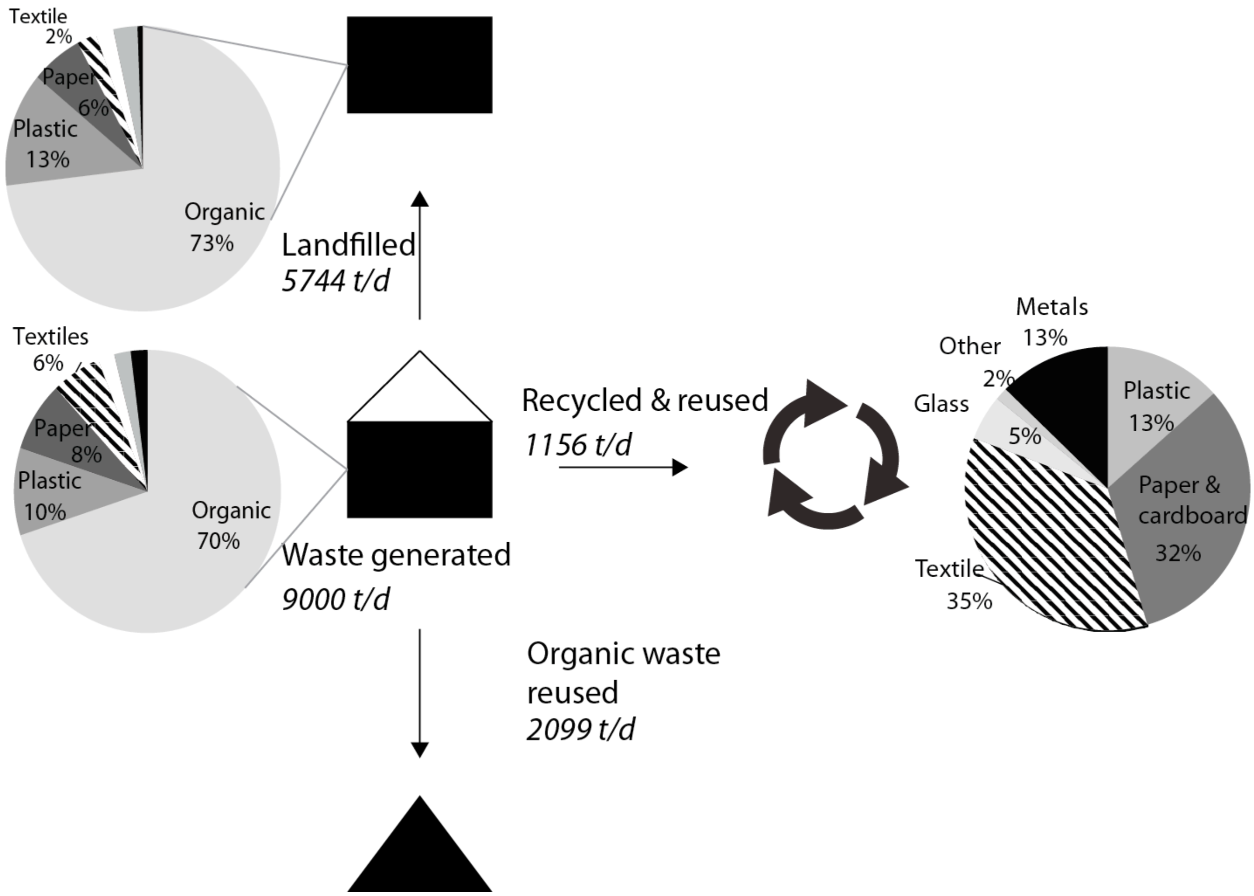


Figure 25: A mass balance on the waste generated in Bogotá, with the composition of waste generated, landfilled, and recycled. Data for this figure come from UAESP (2010) and Gomez (2011).

2.2.1.2. Collection

Informal collection takes many forms in Bogotá. An estimated 20,000 recyclers work in the city (UAESP 2011), and they vary along four variables describing their recycling behavior: *dedication* to recycling, *means* of recycling, *affiliation*, and *institutional arrangement.* Along these four variables, collection has multiple modes of informality. The fraction of work-hours spent recycling is a recycler's dedication; if a person only works as a collector of recyclables, then his dedication is 100%, and if he works a combination of odd jobs, his dedication to recycling will be lower. A collector's means of recycling – the container he uses to gather materials – strongly impacts the quantity that he brings in. Ranging from a burlap sack to a horse-drawn carriage, the means of recycling are varied, and can gather anywhere from 25 kilograms to 1 tonne per trip. The affiliation of a collector – whether he is part of a cooperative or association – can impact the type of institutional arrangement under which he collects materials, and also his working conditions. Those who are organized in some fashion tend to find more regular work, and tend to have uniforms, gloves, and boots to protect themselves from the occupational hazards of their work. Though only 11% of recyclers in Bogotá are affiliated (UAESP 2004), Colombia's recyclers are among the most organized in the world (Medina 2001).

The institutional arrangements of recycling define the relationship between the recycler and the generator. At one end of the spectrum, collectors walk through streets and occasionally collect recyclable material where they see an opportunity to do so. More commonly, recyclers will travel along negotiated *street routes*, aiming to sort through garbage bags between the time they are set out on the street and when the garbage trucks arrive to take the waste to the landfill. Those recyclers who have worked in certain areas for a long enough time may enter into an arrangement with local residents. Through *agreed exchange*, residents and recyclers decide to cooperate; for example, a group of residents gives a recycler access to their source-separated recyclables, if that recycler leaves the area in front of their house clean, swept and free of garbage. Though *paid exchange*, recyclers also work for a particular institution, but they are paid for their labor – not simply given recyclable material. In this arrangement, a university or an office building hires a recycler to work with them, full- or part-time, to manage and sort the organization's waste. The recycler gets to keep the recyclable material, and is charged with properly disposing of garbage. Finally, a recycler may employ a *mixed strategy*, combining multiple institutional arrangements. Though a recycler typically sells the materials he collects to a bodega, he will also sell for reuse. If he happens upon a book, some clothing, or electronic equipment that is in good condition, he will sell these directly at a flea market for reuse.

Using data collected from interviews about the amount typically carried per collection vehicle, as well as data on how many recyclers employ each mode of collection (UAESP 2011), I estimate the mass percentage of recyclable goods that are collected by each collection vehicle (Figure 26). Almost all collection is un-motorized, and the majority of recyclable materials come from recyclers using horse-drawn carriages.

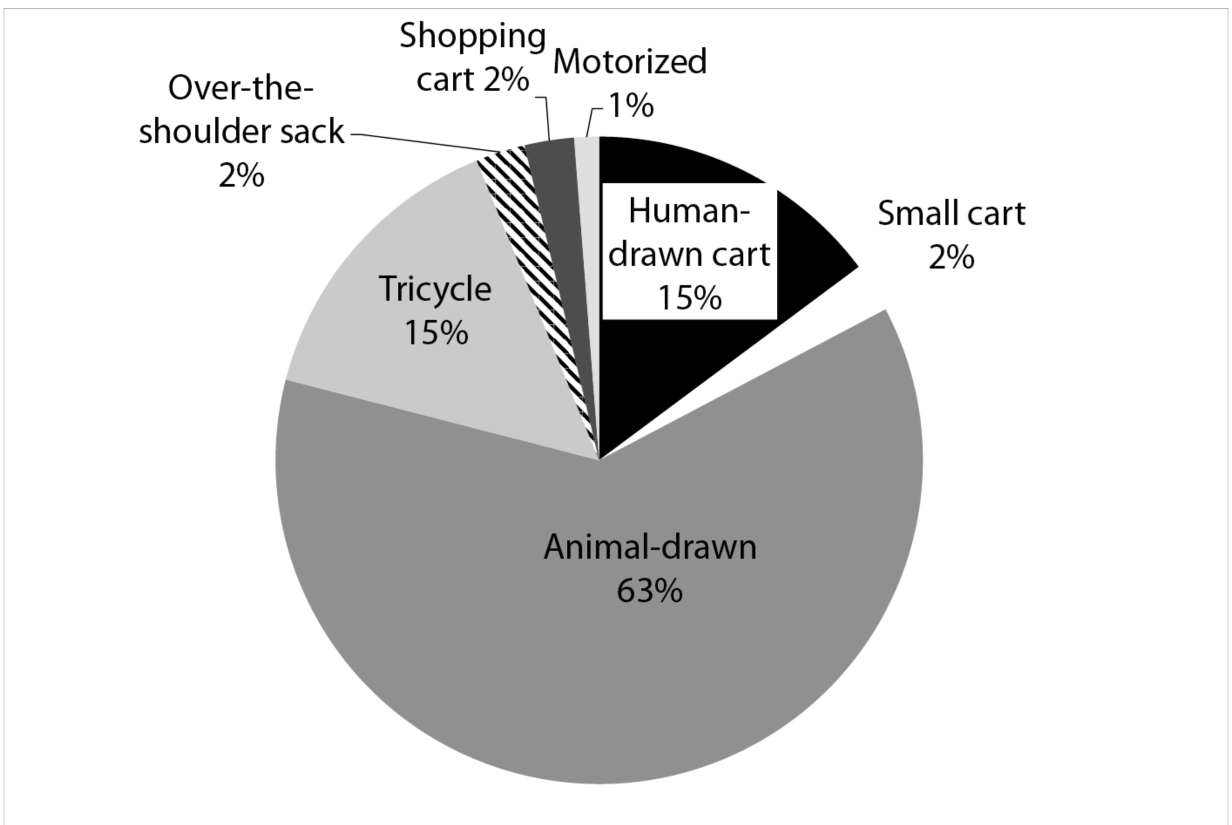


Figure 26: How recyclable materials get collected in Bogotá, by mass of recyclables collected. Data sources: UAESP (2011), Ruiz (2010), Martinez (2010).

2.2.1.3. Sorting and storage

After collection, a recycler will sell his goods to a bodega, which will pay him according to the quantity and market price of the materials he brings. Usually, materials will travel to multiple bodegas before reaching industry; in the model, I assume that materials travel to 3 bodegas, and travel a distance of 15 km between them. The UAESP estimates that there are 3,000 bodegas in Bogotá, but many believe there are at least twice that number (Espinosa 2011; Gomez 2011). Bodegas profit from the separation and storage of recyclable material, and they vary in size, specialization, and in institutional arrangements. The smallest bodegas are mobile units, trucks that buy materials from recyclers, but most small bodegas are housed in shops or garages. These small bodegas are the most likely to buy materials directly from collectors, to accept a variety of materials, and to sell to another bodega. The largest bodegas are most likely to be highly specialized, and only accept one type of material, to buy materials from another smaller bodega, and to sell the materials directly to industry.

2.2.1.4. Transport and re-manufacture

From the bodegas, recyclable materials are sold to industry, where the raw materials are turned into new products. Though the market for many recyclable goods is globalized, so that goods will be sold to the highest bidder and the movement of goods changes over time, Colombia has a number of manufacturing centers and so many recyclable materials remain within the country. For this analysis, I assume that recyclable materials travel to domestic manufacturing centers, where they are processed and converted to new goods.

Each material is assumed to travel from Bogotá in a long-haul truck to the major manufacturing center that uses that material. Plastic, paper and cardboard travel 250 km to Medellin, glass travels 50 km to Zipaquirá, and metals travel 240 km to Boyacá (Gomez 2011). Though product reuse is very common, and evident in construction materials, clothing, and books, I only consider textile reuse, and assume cloth is reused locally.

2.2.2. The proposed changes to recycling: a pilot plant

In an effort to modernize their recycling system, the municipal government wants to formalize the practice of recycling. Originally intending to build five pilot recycling plants, the UAESP has been successful in building one proof-of-concept, a pilot plant called La Alquería. From beginning to end, the newly designed recycling system functions very differently from the current, un-regulated system. Serving a small fraction of the city's residents – and only high-income areas – trucks collect plastic bags (hopefully containing only recyclable material) from homes once a week. Residents are asked to separate their waste – a new behavior – and set recyclables out on one particular day, and their garbage on a different day. The trucks bring the collected material to the recycling plant, which currently receives about 5 tonnes/day on average, 40% of which is non-recyclable material (Calderon 2010). Workers at the plant, who are paid minimum wage, work regular hours, and receive benefits, separate incoming material by type, and materials are baled and sold directly to industry. So the pilot plant represents a radical break in collection (now motorized), separation and storage (now done in one centralized facility, with fewer middlemen), and sale. But perhaps the most profound difference lies in the incentive structure. Where un-regulated recycling operates as a business, each player working to increase their own profits, the pilot plant offers no financial incentives along the recycling chain. Drivers have no incentive to collect only recyclable materials, consumers have no incentive to separate their materials, and plant workers have no incentive to separate faster.

The municipal government wants to scale up this model, such that in the future, recycling in Bogotá will be a modern, formalized business. I look at the implications of such a move by modeling the current recycling scenario against several plausible future scenarios.

2.2.3. Modeling scenarios and assumptions

To explore the GHG implications of the city's proposed changes to recycling, I model the following scenarios using EASEWASTE, a waste LCA software that allows the user to define every aspect of a waste management system, from generation, though collection, transportation, treatment and disposal. ArcGIS is used to calculate the distance traveled by waste collection vehicles.

1. *Baseline*: The current state, against which all other scenarios will be measured. The city's goods are recycled informally, and its waste is landfilled. Emissions from energy consumption were modeled as having an emission factor corresponding to the Colombian grid, 0.35685 t CO_2-e/MWh (Esmeral 2011). Methane emissions from horse-drawn collection are taken from Cornejo and Wilkie (2010) and IPCC (2007), and I assume that recyclable goods travel 15 km from the first to the final bodega. After collection, all transportation is mechanized. All paper is assumed to be recycled into paper and paperboard, all plastic is modeled as PET, all metal as aluminum, and glass recycling is modeled as glass bottle recycling, following the modules in EASEWASTE and updated with energy use specific to Colombia. Though the landfill, Doña Juana, will soon collect and combust its landfill gas, it is currently being flared. The landfill is assumed to have a 50-80% gas capture rate, and a 100% flaring efficiency for the next 45 years of operation. Because regulated recycling is a small fraction of what is recycled in the city (<1%; J. Martinez 2010), I neglect it in the baseline case. I assume that all textile recycling occurs in the form of reuse, and assume all textiles can be modeled as a cotton t-shirt (after Woolridge et al. 2006). These assumptions hold for the following scenarios except where noted.
2. *Immediate prohibition of un-regulated recycling:* If the city immediately prohibited all informal recycling, then in the short term, all waste generated would be landfilled. This scenario's comparison with the baseline gives the GHG emissions abated from informal recycling.
3. *Realistic future: reduce informal, increase formal*. In the realistic, immediate future, the use of horses will be prohibited, and the formal sector will scale-up. In this scenario it is assumed that informal recycling will decline by 63% – recyclers who rely on horses will have found alternative employment – and that another pilot plant will be built, identical to the Alquería. I assume that the current quantity (5 tonnes/day) and sorting efficiency (60% of materials that arrive are recycled) hold constant for each plant, and that the composition of recycled materials also holds constant. The composition of recycled materials in the Alquería in 2009, as compared to the composition of overall recycled materials in Bogotá, is shown in Figure 27.

4. *Drastic future: remove informal, scale-up formal.* This scenario reflects an immediate prohibition of informal recycling with an increase in formal recycling through the construction of two more pilot recycling plants, identical to the Alquería.

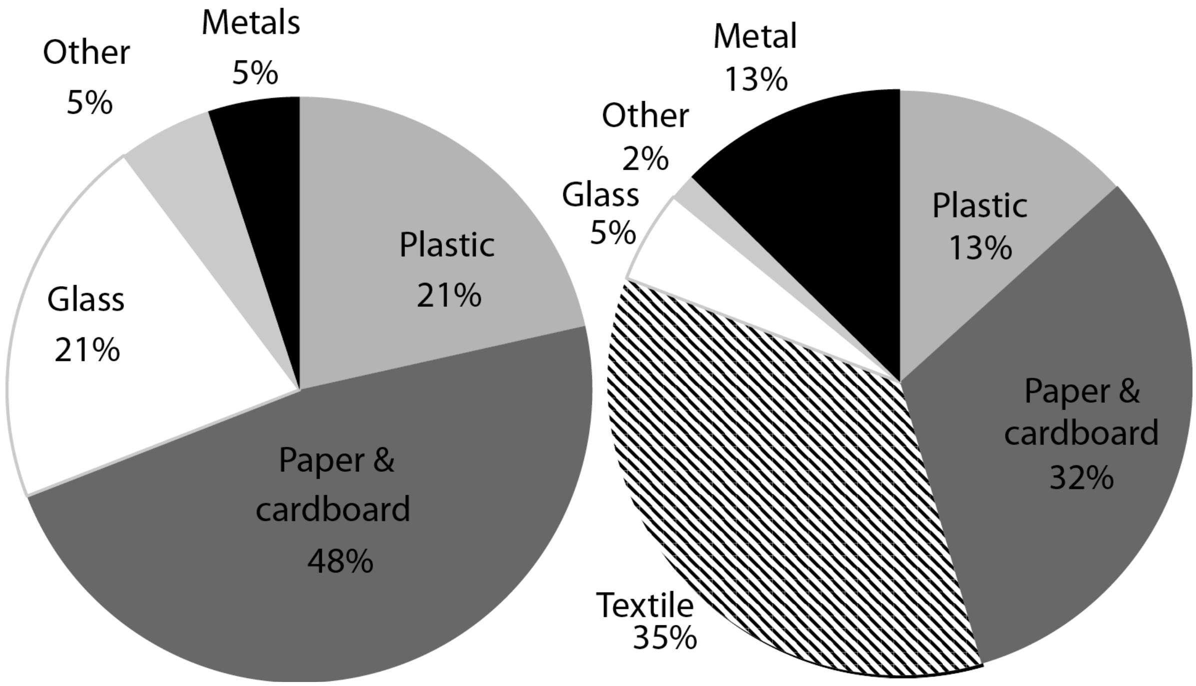


Figure 27: Composition of recycled materials coming out of the municipal plant, the Alquería (left), and from the informal recycling system (right). Though both are dynamic, systematic differences stem from the population served and the incentive structure.

The composition of recycled goods from municipal and unregulated recycling systems change over time, so Figure 27 offers a snapshot of what was recycled from each system in the year 2009. The composition of recycled goods differs between the two systems for a number of reasons. First, the population of generators is different: where the unregulated system is dispersed throughout the city, the municipal recycling program only collects waste from a subset of middle and upper-class neighborhoods, whose waste composition differs from the average. But more important than this difference is the incentive structures affecting each system. Where municipal workers – drivers, sorters, administrators – are paid by the hour regardless of the quality, quantity, or composition of recyclable material that they bring, informal recyclers are paid according to the quality, quantity and composition of the materials they collect. There exists a very strong incentive for informal recyclers to collect only goods for which there is a market, and as much of it as possible. Metals tend to have the highest market value, and for this reason, it makes us 13% of what is recycled informally, compared to only 5% of what is recycled in the municipal facility. Glass has a low market value (and is heavy to carry around), and so constitutes 5% of the goods recycled in the unregulated system. Plastic has a relatively low value and is light enough that one has to collect quite a bit before making any significant revenue, so it is also a small fraction of what is collected by the informal waste sector. Finally, a big proportion of waste 'recycled' informally is textile. As a raw material, textiles carry a low market price. But as a second-hand item, clothing is easily and often sold in flea markets in Bogotá. Informal actors have access to these markets – they know where, when, and to whom they can sell second-hand clothes – in a way that the municipality does not.

Another important difference between the goods recycled informally and municipally is when separation occurs in the recycling chain. In the unregulated system, collectors separate at the point of generation; they remove valuable items from garbage bags and carry them away, so that 100% of what arrives to the bodega is recyclable. If it weren't, then they would be carrying around goods for which they will not be paid, and which the bodegas will not accept. In the municipal system, full bags are taken to the recycling center, and they are opened and sorted within the facility. Because residents do not have a habit of separating their waste into recyclable and non-recyclable components, 40% of the material that arrives to the pilot recycling facility is not recyclable, and is sent to the landfill.

The scenarios are depicted in Figure 28. The scale of municipal recycling, presently, and for the near future, is two orders of magnitude smaller than the scale of unregulated recycling. So is the scale of employees who make a living in each system.

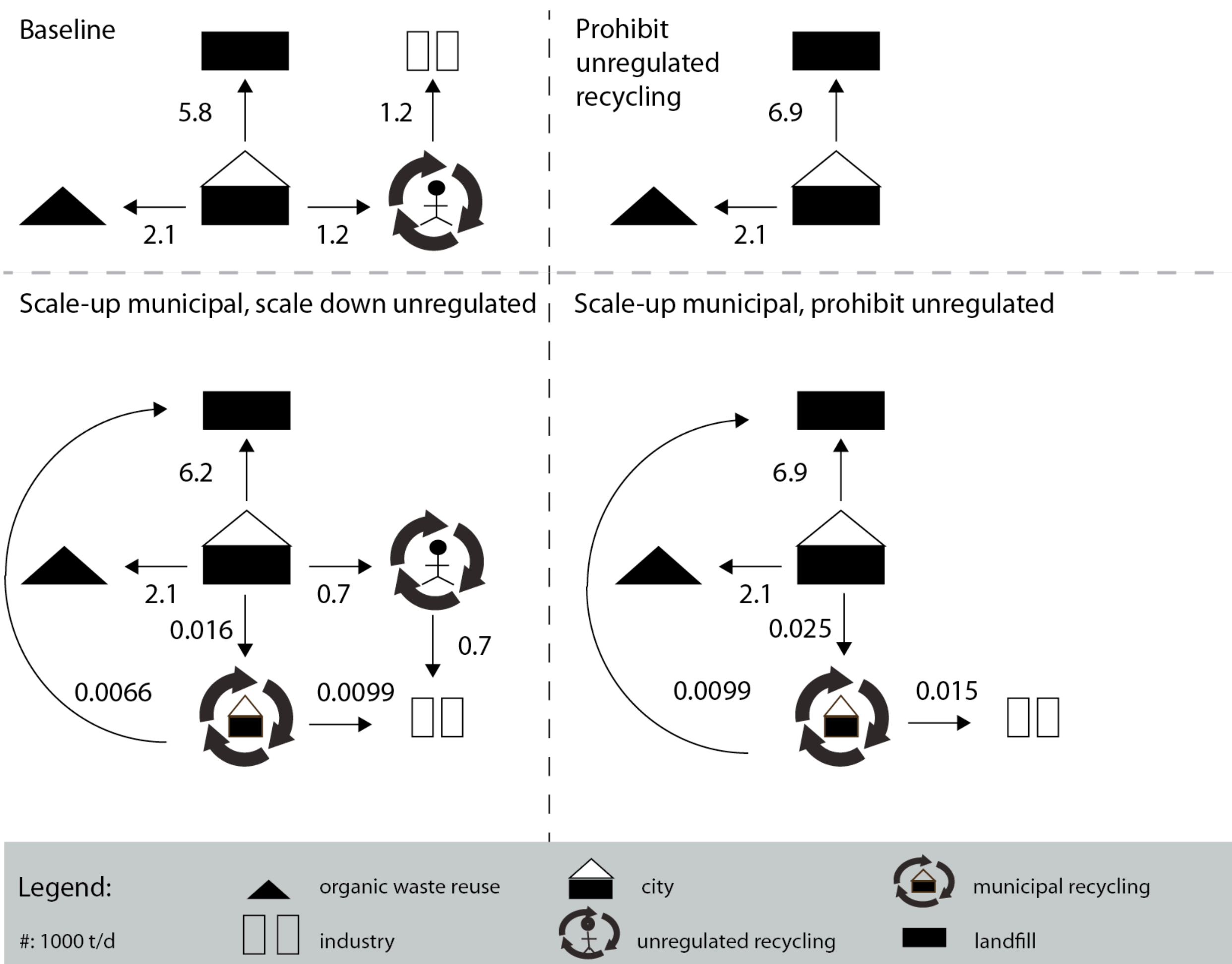


Figure 28: Recycling scenarios for the city of Bogotá. All numbers are in thousands of tonnes per day.

3. Results and discussion

The life-cycle greenhouse gas emissions are modeled for each scenario and compared to the baseline scenario. These scenarios reflect probable futures, given that the municipality would like to formalize the recycling system. Comparing alternative scenarios allows us to see which elements of recycling chain that have the largest impact on net GHG emissions.

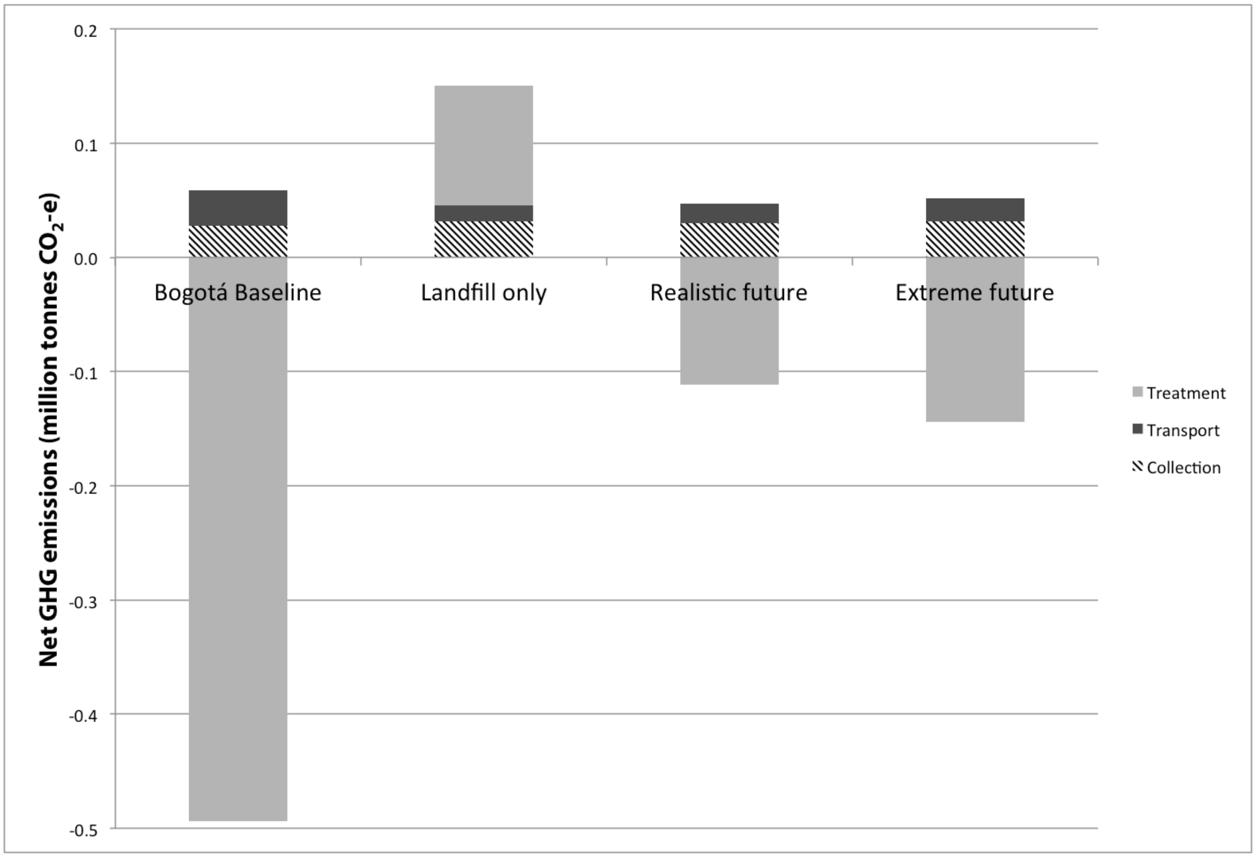


Figure 29: Net lifecycle GHG emissions for the baseline and alternate recycling scenarios for Bogotá. Modeled using EASEWASTE.

3.1. Emissions

The baseline recycling scenario out-performs the other scenarios by a wide margin. The difference between the baseline scenario and the landfill scenario's emissions gives the GHG savings achieved through the current recycling program (0.57 Mt CO_2-e). Comparing the baseline with the two possible future scenarios, we see that the baseline is a larger sink for GHGs than are these modernization scenarios (by ~ 0.35 Mt CO_2-e) and there is little difference between the two). Figure 29 also shows that the treatment phase dwarfs the collection and transportation phases of waste management, in terms of net GHG emissions. A corollary to that is that the most important way that Bogotá can reduce its emissions through improvements to their waste management program is by recycling more – the city can only marginally reduce emissions by improving transportation and collection efficiency. Maximizing the collection of recyclable material that has a market value – so that it is actually re-processed into a new item – leads to the largest GHG savings, and the scenario that performs best is the current, unregulated recycling system.

3.2. Social and other impacts

Carbon is not the only measure that is important. The formalization and centralization of recycling in a city like Bogotá will result in the creation of steady jobs with good working conditions, but it will also take work away from low-income, unskilled workers who currently make a living by recycling Bogotá's garbage. These are trade-offs that should be considered by the municipal government.

3.3. Sensitivity analyses

Three sensitivity analyses are performed in order to understand the contributing factors leading to the previous results. One shows the relative impact that middlemen (bodegas) have on the GHG emissions from unregulated recycling, another gives the relative impact of the mechanization of collection of recyclables, and the third analyzes how the municipal recycling *process* (not outcome) compares to the unregulated one. These additional scenarios are:

5. *Informal without middlemen:* This models a more centralized variation on informal recycling. Collectors bring materials directly to one bodega, which sells the recyclables to industry.
6. *Mechanized informal recycling*: Because the municipal government has banned the use of horse-drawn carriages in Bogotá starting in 2012 (and has suggested that these recyclers instead buy cars), this scenario assumes a mode shift from horses to cars for the fraction of recyclables that are currently collected by horse.
7. *Unrealistic future: expand formal recycling to reach recycling levels now seen by informal.* A best-case scenario for municipal recycling, this scenario models the GHG emissions that would occur if the formalized system were able to recycle as much as the informal does now.

The results from the sensitivity analyses are reported in Figure 30 below.

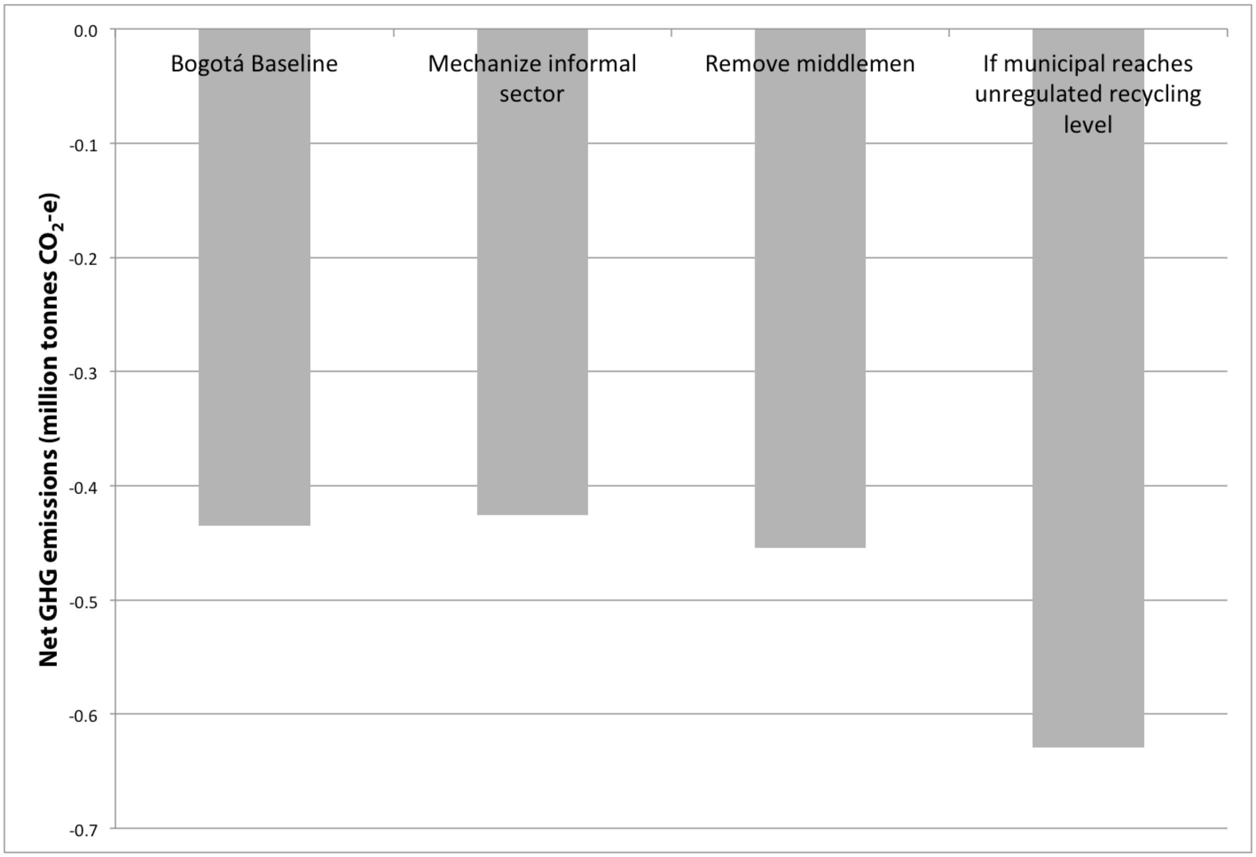


Figure 30: Sensitivity analyses on recycling scenarios for Bogotá. Performed using EASEWASTE.

In contrast to the likely scenarios that were initially modeled (and shown in Figure 29), these alternative recycling scenarios are as good or better greenhouse gas sinks than the baseline recycling scenario. Mechanizing the informal sector, by having collectors drive pick-up trucks instead of horses, leads to a modest increase in GHG emissions. Cutting out middle-men, meaning that recyclable materials would pass through only one bodega before reaching industry, leads to a modest decrease in GHG emissions (though also would lead to a decrease in employment). The final scenario is unrealistic but informative. If the municipal recycling system were able to reach the scale and effectiveness of the unregulated recycling sector, it would be an even larger greenhouse gas sink than the baseline scenario. That the large-scale municipal recycling system would be a larger GHG sink than the unregulated one is may be due to economies of scale – fewer larger trucks are needed to transport material, and material travels a shorter distance to reach a centralized recycling facility. Though the benefits of the economies of scale are not modeled in this analysis, in actuality, if one facility has access to large volumes of recyclable material, it is also possible that they would be able to market and sell some materials that are rarely sold through unregulated means (e.g., Tetrapak, amber-colored glass, etc.). It is worth noting why this scenario is unrealistic. First, it requires an increase in scale that is infeasible. The municipal government's pilot facility has a capacity to receive 12 tonnes of material a day, but presently receives only 5. The government wanted to build 5 such facilities, but residents protested whenever another potential site was suggested. To recycle as much as the informal sector does, the municipal recycling system would need 10 such facilities, operating at full capacity. Secondly, what makes the unregulated sector work is the financial incentive.

Workers get paid for what they bring in. No such financial incentive exists in the municipal system, and for that reason, is unlikely to collect orders of magnitude more goods than they do now.

3.4. Uncertainty

There are many sources of uncertainty in this analysis. The informal waste sector is a data-scarce environment, and as such, all assumptions are based on personal interviews, observation, and the data collected. The waste generated by a city is variable – it responds to cultural, climatic, and economic trends – and the data on waste quantities and composition are collected only at the point of disposal. Thus, data on waste generated and recycled are uncertain. The informal waste sector is fluid, adaptive, and dynamic, changing where there is economic opportunity to do so. Finally, recycling markets are also dynamic, with daily price fluctuations that affect the quantity and composition of materials recycled. Changes in these quantities would affect the results of the analysis. My hope is that this research will help others conduct research on this neglected actor in waste system: the informal sector.

4. Conclusions and policy recommendations

Informal recycling is an important component to Bogotá's (and to many other city's) overall waste management. Understanding informal actors' work in the waste sector has been identified as one of the key barriers facing the implementation of Integrated Waste Management Systems in the Global South (McDougall 2001), yet there are as of yet no studies that quantify the environmental services from the informal waste sector (Gutberlet 2008). Waste reuse is another sink waste management systems in developing nations that is often overlooked, but carries with it great environmental benefits. These chapters address both of these gaps in the literature by exploring the role of the informal waste sector in recycling Bogotá's waste.

The central conclusion from this chapter is that the current system abates more greenhouse gases than do the municipal government's proposed modernization plans for the recycling system. The reason the unregulated system outshines the municipal one is not how they recycle – it is *why* they recycle. For informal workers, the incentive to recycle is financial – it is their livelihood. As such, they work to maximize the quantity and quality of materials collected from waste. Informal recycling is a better greenhouse gas sink than is municipal recycling simply because it recycles more. If the city is serious about wanting to recycle, it would be prudent to note that the informal sector has a broader reach, a much larger capacity to recycle, and a strong incentive to do so well. The municipal recycling program has no such incentive. As the director of the recycling program put it: "Because it is run by the government, nobody cares. Recycling should be run as a business" (J. Martinez 2010).

The sector also brings with it social trade-offs. While waste work provides many – UAESP (2011) estimates about 20,000 – with a source of livelihood, the conditions under which it does so are not optimal. Informal collectors are exposed to disease and other occupational hazards, and many do not use any protective equipment while working. However, the 'modernization' of recycling, either through municipal management, or a slow erosion of informal workers' right to collect waste, would result in the loss of many jobs, to many people who have few other options.

The municipal government of Bogotá should work on improving the social conditions of waste workers, rather than prohibiting their work. They provide a service that would be difficult to match, free of charge to the municipality. Instead, the municipal government should focus on protecting the health of informal workers, and on expanding the recycling program. In its expansion, the city could focus on collecting Type 2,3, and 4 recyclable materials, materials that are unlikely to be recycled for the financial incentive to do so is lacking. If the city were to recycle materials that are not currently collected, it would provide an environmental service to all, and would add new jobs to the waste sector. To collect these materials more effectively from the waste stream, future work should focus on source separation of waste at the home. For a new approach on how to do so, we can look to the "agreed exchange" collection arrangement from the informal sector, which shows us that people are more willing to separate their waste when they get something in exchange.

Conclusions

In these four chapters, I take a broad look at waste management in the world to understand the important ways in which waste impacts social and environmental health, with a focus on climate change. The first chapter's analysis reveals a general tendency for waste to be managed at an increasing scale; where 'waste' was managed at the household-level for most of history, cities began to manage it as populations urbanized, and now many places, especially those which have invested in advanced waste treatment technologies, are managing waste at a regional scale. Concurrent with the change in scale of waste management, cities have also moved towards formalizing their waste systems. These trends have contributed to a separation between people and their waste, and with that, we have seen a decline in cultures of reuse. Because various modes of reuse bring important environmental benefits, including greenhouse gas emission reductions, my work looks at waste reuse at multiple scales – the household, the city, and the region – to quantify the benefits of reuse as a waste management strategy.

I use carbon as the primary metric with which to analyze the benefits of reuse as a waste management strategy. Carbon emissions are an effective metric for a few reasons: climate change is an urgent crisis that must be averted, carbon emissions are good indicators of the environmental impact of a system, and they allow for easy comparison with other systems. Additionally, waste management's contribution to climate change is highly variable and uncertain (Bogner et al. 2007); it can act as a net source or sink of greenhouse gas emissions. Because forms of waste reuse – the use of waste as a resource – can have important environmental benefits, and these are not well quantified, this analysis focuses on waste reuse potential in two locales, with different waste challenges. The second chapter looks at California, a very high waste producing state with access to high levels of technology and political will, and asks how emissions from waste management can be reduced. The third and fourth chapters focus on a city faced with the need to expand urban waste services to a population that is growing in number and in waste generation. Bogotá, Colombia, is illustrative of many cities in the Global South that are grappling with how to include (or exclude) its informal sector. The fundamental question is: what are the environmental implications of the city's plan to formalize the unregulated recycling sector?

In California, I use life-cycle assessment to analyze a number of alternative waste management plans, and find two effective means of reducing GHGs from the waste sector. The most robust method is to reduce waste production, through waste reuse or a decrease in consumption at the household level. Though this requires citizens to change their behaviors – and this is not easily achieved – source reduction leads to environmental benefits throughout the waste management system, including a large reduction in greenhouse gas emissions. The second scenario that could deliver sizeable environmental and climate benefits is the anaerobic digestion of California's MSW. In separating biogenic waste, digesting it, and creating electricity, California would change its biogenic waste's destination from a landfill, where it will slowly degrade and produce methane (some of which is captured), to a digester, which is designed to maximize and capture methane produced.

Another key result of the California analysis is methodological. Waste LCA models are very sensitive to assumptions, and as such, the magnitude of the climate benefits from implementing alternative waste treatment depends strongly on a number of model assumptions: the type of electricity displaced by waste-derived energy, how biogenic carbon is counted as a contributor to atmospheric carbon stocks, the landfill gas collection rate, and the waste LCA model used. This sensitivity leads to two conclusions: (1) waste modelers must explicitly state their assumptions, and should perform sensitivity analyses as part of policy recommendations; and (2) because waste reduction is the scenario that is least sensitive to other system changes, it is the most robust method to reduce emissions from California's waste management.

In Bogotá, the waste management challenges are very different. Rather than asking which of a suite of waste technologies should be more broadly deployed, I focus on the municipal government's plan to replace the unregulated recycling system with a formalized one. This is a broader trend in developing cities, and is tangibly felt in Bogotá, where the district courts are regularly mediating conflicts between the municipal government and the recyclers' associations, who are battling for the right to recycle Bogotá's waste. To analyze the city's recycling options, a variety of social science and engineering methods have been employed; this interdisciplinary lens is necessary to understand the functioning and the quantitative benefits of the systems.

From this mixed-methods study, I find that building a modern city is an important driver for waste management systems in developing nations, in addition to the other drivers identified by Wilson (2007). Municipalities seek to implement modern qualities – aesthetics, cleanliness, universality, and invisible connections – in creating new waste management systems to displace their current, "backward" (Mitchell 2008) ones. Bogotá's unregulated recycling system is dispersed and effective, recycling about 1000 tonnes of waste per day that would otherwise go to the landfill – but it is not aesthetic. It is unpredictable, messy, adapted to local conditions, and it makes very visible the business of waste. In Bogotá, the battle over who will recycle waste is also a battle for the image of the city.

But the question of how Bogotá's waste will be recycled is not dichotomous. It is not simply a battle between formal and informal, because both the municipal and the unregulated recycling systems have elements of formality and informality, and the current system is (and likely the future system will be) a co-existence of multiple modes of recycling. Concretely, Chapters 3 and 4 analyzed the social and environmental implications of the municipal plan to take over the recycling system. In analyzing the differences between the two systems – the unregulated on, and the municipally-managed one – I used four metrics identified by the government's District Recycling Plan: economic sustainability, environmental sustainability, social inclusion, and modernization.

The economics of the two systems are diametrically opposed; one is a free-market system, and one is a subsidized system, operating by mandate. The first (surprising) finding is that the 'informal' waste recycling system is more expensive than the municipal recycling plan; more money is spent overall on the functioning of the unregulated system (per tonne of recyclable waste). However, these costs are borne by individual nodes on the recycling chain, and each still each makes a profit, since each node operates as a business, and revenues must exceed costs. Though the municipal plan is overall less expensive, it is losing money, and is financed by the government and international donors. So while it costs less, its revenues are lower still than its costs. So the unregulated system is more financially sustainable.

In terms of social inclusion, the unregulated system employs more people per tonne of waste (and these people are lower-income, and face low opportunities for employment alternatives). However, the modes of employment are very different. Municipal recycling jobs are steady, they provide benefits, and they provide protecting equipment and clothing to its workers. Informal recyclers, in contrast, choose their own hours – working less when there is abundant material, and more when it is scarce – they do not have benefits (and so face an uncertain future), and they are exposed to health and occupational hazards.

In comparing the modernity of the two types of recycling systems, the municipal system far out-performs the unregulated system. The municipal recycling plan is clean, predictable, universal, and it hides the business of waste from the citizens of the city. Unregulated recycling, on the other hand, is sporadic, messy, and highly attuned to local conditions.

The central finding in terms of environmental outcomes is that, under current and likely future conditions, the informal sector abates orders of magnitude more GHGs via their recycling. The key difference between the two systems is their incentive structure. Where the unregulated system is governed by the free-market, and all actors within it maximize their returns to recycling (by collecting high quantities of valuable material), the municipal recycling program has no such incentives. The lack of incentives in the municipal system results in the collection of small quantities of low quality material. The climate benefit of the unregulated recycling system derives from the informal sector's ability to recycle a much greater quantity than the municipal recycling system. It is unlikely that the municipal system, currently recycling almost 5 tonnes/day, will be able to reach the levels of the unregulated system, currently recycling 1000 tonnes/day, in the near future.

That informal recycling can provide large climate benefits – larger even than municipal programs – is a big lesson for cities in the Global South. Cities should aim to first understand how their informal waste sector operates, and then understand the environmental services it is providing. The municipal governments should aim to improve upon, collaborate with, and add to the existing systems, rather than entirely replacing them. Cities would do well to focus on wastes that are hard to manage, or have low or negative values. Though hybrid waste management models exist in practice – the informal systems usually live in the interstices of the formal – they are rarely considered as institutional models. Effective hybrid models could combine the best of the unregulated sector – their efficiency at collected waste materials that have resale value, their flexible employment opportunities – and the regulated sector – they uphold basic health and environmental standards. Hybrid models like those institutional arrangements between homes and recyclers observed in Bogotá – in which households separate their waste and give it to a particular recycler in exchange for waste management services and a clean sidewalk – could be a way of the future. Cities should aim to maximize the environmental benefit of reuse programs and the working conditions of employees.

In both studies, in different contexts, waste reuse provides large environmental benefits – here illustrated by GHG reductions. Though historical waste management relied exclusively on reuse, increased consumption, urbanization, and growing waste complexity has made waste reuse challenging. Global focus on landfilling as the most important step with which to provide environmentally and socially acceptable waste management (McDougall 2001) to citizens precludes effective reuse of waste. Reuse-centered strategies focus on maximizing beneficial reuse before safely disposing; landfill-centered policies aim to contain wastes from the environment.

Reuse on a large scale is still possible, and our central recommendation is that cities should be thinking about how to maximize their use of waste as a resource – as homes used to – not just aim to maximize waste containment. Waste reuse is still evident in many places – large-scale composting in California, city-wide recycling (and reuse) in Bogotá, and voluntary simplicity within the home. In some ways, waste management trends have come full-circle. Cultures of reuse, and household-centered waste practices were the focus of historical waste management, and will be the focus of future waste management. Where waste management has been centered in the home, the city, and the state, perhaps we are seeing a return to the home. Household consumption behaviors have the power to tremendously improve environmental outcomes associated with waste management. Transforming trash – by both re-thinking its definition, so that it may at once be discarded and a resource, and by changing its composition through reuse – is an effective waste management and climate mitigation strategy.

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