The Efficiency of Informality

Quantifying Greenhouse Gas Reductions from Informal Recycling in Bogotá, Colombia

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Summary

The dual challenges of increasing urbanization and consumption are centered in cities in the Global South, where growing waste production threatens public and environmental health. Reuse and recycling are widely recognized to provide broad environmental benefits. Although most industrialized cities replaced their informal recycling sectors with municipally run recycling schemes and have had to build their recycling rates anew, most industrializing cities in the Global South remain centers of recycling and reuse through the work of informal workers. Bogotá, Colombia, is emblematic of many cities in the Global South seeking to modernize their city, in part by formalizing their recycling system. This article asks: What are the greenhouse gas (GHG) emission implications of this modernization? Using interviews and observation in combination with life cycle assessment, we compare GHG emissions resulting from the baseline case (1,200 tonnes per day [t/d] recycled through informal channels; 5,700 t/d landfilled) to three alternative scenarios that formalize the recycling sector: the prohibition of informal recycling; a reduction in informal recycling coupled with a scale-up of formalized recycling; and the replacement of informal recycling with formal recycling. We find that the baseline recycling scenario, dependent on the informal sector only, emits far fewer GHGs than do all formalization scenarios. Three processes drive the results, in order of magnitude: informal textile *reuse* (largest GHG savings); landfilling (largest emitter of GHGs); and metal recycling (GHG savings). A hybrid model could combine the incentives and efficiency of the informal system with the better working conditions of the municipal one.

Introduction

If the sewer is the conscience of a city (Hugo 1884), then garbage is its fingerprint. Waste, "what people have owned—and thrown away—can speak more . . . informatively and truthfully about the lives they lead than they themselves ever may" (Rathje 1992, 54). Waste production reflects cultural preferences and behaviors. Globally, waste production is changing in quantity, composition, and distribution, and cities are the major producers of waste and attendant environmental impacts (Bai 2007; Kennedy et al 2007). Rapid growth in urbanization and consumption has resulted in growing waste production in low- and middle-income cities, which are tasked with managing the waste to protect public and environmental health. How cities choose to do this has important consequences. Taking climate change as one impact, waste management may represent either a net source or sink of greenhouse gases (GHGs) (Bogner et al. 2007). If waste is treated as a resource and recycled or reused, cities can reduce their energy consumption and resource extraction and shift from linear to cyclic metabolisms (Bai 2007). If waste is simply disposed of, or managed inadequately, it places a burden on cities and is a source of GHGs. As cities aim to

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modernize their waste management systems, we ask: What are the environmental services provided by informal waste management systems, and what are the environmental consequences of modernization plans?

Challenges to Growth

Bogotá, Colombia, is experiencing many changes occurring on a global scale. Colombia has rapidly urbanized (Cohen 2004), with 72% of residents living in cities. Its largest city (PAHO 2005), Bogotá, has grown from 0.5 to 7 million people from 1950 to 2010 (Secretaría Distrital de Planeación 2009).

The city's shifting consumption mirrors the world's. What people throw away is a function of income, climate, culture, and technology. As people gain wealth, they tend to throw away more, and their waste grows more complex (Bogner et al. 2007; Johnstone and Labonne 2004; Kinnaman 2009; Zhen-Shan et al. 2009; Gómez et al. 2009). Latin Americans have quickly adopted electronic goods (Silva et al. 2008), and Colombians, as "new consumers," are rapidly increasing their consumption of cars, electricity, and consumer goods as their wealth has increased (Myers and Kent 2003). We estimate that Bogotá generates 0.9 kilograms (kg) per person daily (Vergara 2011)– more than PAHO's estimate (0.71 kg/person-day), which does not factor the diversion of waste from the landfill by informal recyclers.

Along with increasing waste production comes the challenge of managing it effectively; many environmental and social consequences arise from doing so poorly. For instance, open dumping directly pollutes waterways, affecting public and environmental health. Within each element of waste management—generation, handling, collection, transport, transformation, and disposal (Tchobanoglous and Kreith 2002)—lays the potential for environmental improvement or degradation.

Modernizing Waste Management Systems in Developing Cities

Waste management (WM) systems (WMSs) shift in response to changing municipal concerns. Most cities first institutionalize their WMSs to protect public health, and recycling efforts arise from a demand for resource recovery. Concern for environmental protection emerges once waste no longer threatens public health. Climate change has become a driver for improved WM as nations seek ways to reduce GHG emissions from all sectors (Wilson 2007).

An emerging driver in the modernization of waste systems is aesthetic. In developing nations, "the importance of . . . image and municipal pride in keeping streets clear cannot be underestimated" (UNH 2010, 98). Cleanliness and order are necessary components for building a modern city (Thieme 2010; Kaika and Swyngedouw 2000), but these are rarely characteristics of developing nations' waste systems. The vision of the modern city is irreconcilable with informal WM, and this discord plays an important role in municipal efforts to phase out the informal waste sector.

Bogotá's recycling system is emblematic of those across the Global South, where the informal sector plays a central role in managing waste, but faces pressure from modernization plans. The informal sector, here defined as unregulated activities that occur outside of the purview of the state (Mitchell 2008), employs a large segment of the population in cash-poor nations—in Colombia, more than 50% of employment is informal—and 2% of the global urban population works in the waste sector (Medina 2007). Informal waste sector work is varied; whereas in some cities (e.g., Delhi) informal workers participate in primary collection, more often they are involved in recycling as waste buyers, street pickers, dump pickers, sorters, or processors (Wilson et al. 2006; UNH 2010). Informal recyclers respond to market signals, retrieving recyclable goods because of the price they receive for them. In Bogotá, informal collectors remove materials from trash bags destined for landfills and reroute them into the recycling chain. In many cities (e.g., Nairobi), workers toil on the margins of the WMS, removing valuable items from open dumps to resell (UNH 2010). In others, informal workers are integral to the WMS. The Zabbaleen, who collected waste door to door in Cairo for nearly a century in order to benefit from the recycling and reuse of its components, achieved the world's highest waste recycling rate (80%) until the 2009 slaughter of the pigs that were an essential component of their organic waste reuse system (Assaad 1996; Fahmi 2005; Iskandar and Tjell 2009).

The informal waste sector provides cities with essential urban and environmental services, filling gaps in the provision of public goods (Medina 2007; Tripp 1997). "The other private sector" provides 25% of Latin Americans with water services and 50% with sanitation services (Solo 1999). In Bogotá, the informal sector collects virtually all that is recycled from the waste stream, 1200 tonnes per day (t/d) (Vergara 2011). In the United States, as in many industrialized nations, cities prohibited informal recycling, prevalent early in their industrialization (Strasser 1999), and had to rebuild a recycling sector—municipally run and regulated—anew decades later. Many cities in the Global South remain centers of material recovery due to the work of their informal sectors.

As with many other cities, Bogotá is seeking to modernize its waste system as part of a broader modernization effort. Since the 1990s, the municipal government has worked to "[leave] behind the image of chaotic, disorderly city . . . and has become a [model] for other cities [in implementing] 'creative solutions' . . . to urban problems" (Duque Franco 2008, 1). These modernization efforts include building a bus rapid transit system, Transmilenio, whose name and appearance evoke visions of the future, and upgrading the city's dumpsite (Doña Juana), which collapsed catastrophically in 1998, to a state-of-the-art landfill. In the active construction of "Bogotá as a safe, desirable place to do business, to live and to visit" (Berney 2011, 28), the municipal government is overhauling its recycling system, proposing a formalized system, currently at the pilot stage, to eventually replace the informal one.

Though many cities, from Bogotá to Cairo, are currently implementing plans to formalize their WM, no analyses exist of the environmental implications of this transition; no study quantifies the environmental consequences of informal waste recycling. Trade-offs from the formalization of WM must be quantified in order for these cities to transition to socially and environmentally desirable WM plans (McDougall et al. 2001; Gutberlet 2008). This article aims to fill this gap in the literature.

Goal

The aim of this article is to analyze the GHG implications of Bogotá's proposed change to the city's recycling system, from an unregulated, informal system, to a regulated, municipally run system. This work is important for three reasons:

- How cities modernize their waste systems, by including or sidelining informal waste workers (Mitchell 2008), has important consequences.
- Although much qualitative research has explored the functioning of the informal waste sector in various cities (Fahmi 2005; Assaad 1996; Wilson et al. 2006), no study has yet quantified the environmental benefits of informal waste management.
- Assessing the GHG implications of formalizing recycling will allow cities to better understand and reduce their emissions.

Methods

Life cycle assessment (LCA) is used to quantify the GHG implications of the city's proposed modernization scheme. ArcGIS is used to measure the distance traveled by waste vehicles. The following sections detail the LCA model (EASETECH), impact method (IPCC 2007), data used, and scenarios compared in this study.

Life Cycle Assessment and EASETECH

LCA is used to analyze alternative scenarios for WM in Bogotá. LCA can holistically assess the environmental impacts of WMSs, by tracking an item from generation until final disposal, and calculating all energy and materials used in its processing, along with associated emissions and impacts to the environment. The EASETECH model (Clavreul et al. 2014) was used to perform the assessment.

The functional unit for this analysis is the total amount of municipal solid waste generated in Bogotá in 2010.

The following sections describe the modeling and data used; a detailed account is in the Supporting Information (SI) on the *Journal's* website.

Impact Category: Greenhouse Gas Emissions

We focus on the impact of WM decisions on GHG emissions for two reasons. First, climate change poses an urgent threat to the functioning of our biome, and carbon emitted has become an essential metric for decision making. Second, GHGs released under different WM scenarios can function as an indicator of overall environmental impact, given that lower emissions are correlated with lower energy consumption and resource extraction. The characterization factors from IPCC (2007) are used to convert from emissions to carbon dioxide equivalents (CO_2-eq.).

Description of Bogotá's Scenarios and Data Collection

This section describes the data collection methods used as well as the scenarios analyzed.

Data Collection Methods

During 2010 and 2011, the authors used semistructured interviews with key informants and selected players in the recycling chain, document analysis, and the observation of various nodes along the recycling chain to gain an understanding of the functioning of the recycling system in the city (table 1). The data collected served as inputs to the LCA model, and contributed to an understanding of the diversity of arrangements within the informal system. The results from the interviews, observations, and document analysis are presented in the following subsections.

The Recycling Chain in Bogotá

Recycling in Bogotá is a free-market enterprise, involving actors who make a profit from the materials they collect and sell. Informal recyclers remove materials from waste thrown out by consumers. That which they do not recover is collected by truck by municipal waste workers and taken to the landfill. A recyclable item will pass from consumers who generate waste, to recyclers who remove it from the trash, to bodegas that buy it, and to industries that reprocess it into new goods, in a "self organizing symbiosis" (Chertow 2007, 21). Actors in the chain exchange resources (recyclables for money), motivated by profits.

Waste Generation

Most cities do not gather data about "system losses," the material sinks for waste that are outside of the government's control. However, the UAESP (Unidad Administrativa Especial de Servicios Públicos), the municipal government branch that handles WM, keeps data on the quantity and composition of Bogotá's waste reaching the landfill. These data, combined with interviews with waste experts—recyclers, waste consultants, and government officials—allowed us to estimate the quantity and composition of waste generated in Bogotá. The difference between waste generated and waste disposed leaves that which is informally recycled and reused in the city. An overall mass balance for waste generated in Bogotá, along with the composition of waste generated, landfilled, and recycled, is shown in figure 1. We estimate that 9,000 t/d of waste are generated in Bogotá, with almost 1,200 t/d recycled and reused informally, and 2,100 t/d of biogenic waste composted and reapplied to land.

Table 1 Key players in the recycling system in Bogotá, and the methods used to understand their roles

Key player	*Main role*	*Methods used to collect data*
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)

Note: UAESP = Unidad Administrativa Especial de Servicios Públicos.

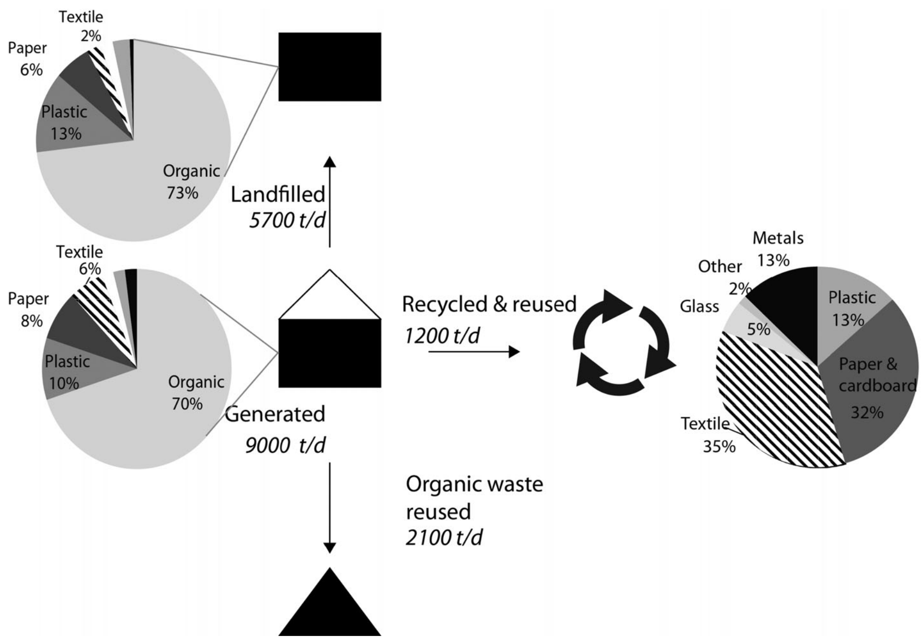

Figure 1 A mass balance on the waste generated in Bogotá, with the composition of waste generated, landfilled, and recycled. Data for this figure come from UAESP (2011) and Gomez (2011). Approximately 9,000 t/d of solid waste are generated in Bogotá; of these, over 2,000 tonnes are processed as compost, 1,200 tonnes recycled and reused, and the remaining 5,700 tonnes disposed of in Bogotá's sanitary landfill. For generated and landfilled waste, the white, gray, and black sections of the pie chart represent "glass," "other," and "metals," respectively. t/d = tonnes per day.

Collection

Informal collection takes many forms in Bogotá. An estimated 20,000 recyclers work in the city (UAESP 2011), differing in their *dedication* to recycling, *means* of recycling, *affiliation*, and *institutional arrangement*. The proportion of total work hours spent recycling is a recycler's dedication; dedication is 100% if he or she only works as a collector of recyclables. A collector's means of recycling—the container used to gather materials—ranges from a burlap sack to a horse-drawn carriage and determines the quantity collected per trip (25 kg to 1 t). The affiliation of a collector—whether he or she is part of a cooperative or works alone—can influence his or her working conditions. Those who are organized tend to find more regular work and wear protective clothing (gloves, boots). Though only 11% of recyclers in Bogotá are affiliated (UAESP 2004), Colombia's recyclers are among the most organized in the world (Medina 2001).

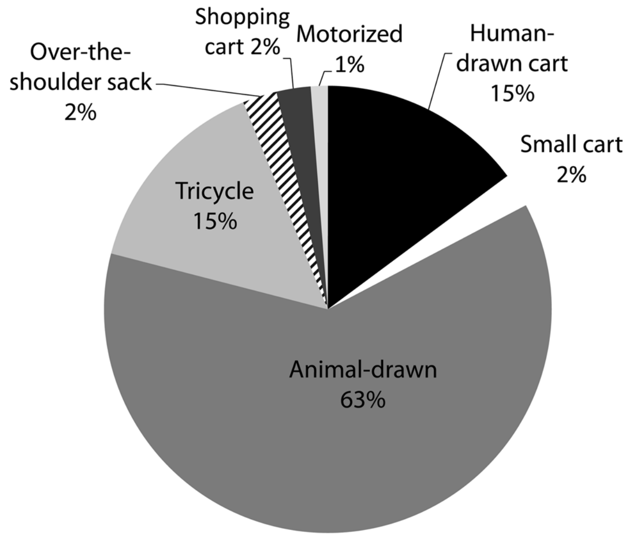

Figure 2 How recyclable materials get collected in Bogotá, by mass of recyclables collected. The majority of recyclable material is diverted from the point of generation by horse-drawn carts. Sources: UAESP (2011), Ruiz Grisales (2010a, 2010b), and D. Martinez (2010).

Institutional arrangements define the relationship between the recycler and the generator. At one end of the spectrum, collectors walk through the streets and occasionally collect recyclables they find. More commonly, recyclers will work negotiated street routes, sorting through garbage bags before the municipal garbage trucks arrive. Some recyclers make arrangements with local residents. Through agreed exchanges, residents and recyclers decide to cooperate; for example, a group of residents gives a recycler their source-separated recyclables in exchange for the recycler cleaning and removing all waste from the front of their house. Through paid exchange, recyclers work for an institution (e.g., university), sorting their recyclables and disposing of their waste, and are paid for their labor in addition to receiving the recyclable material. Finally, a recycler may employ a mixed strategy, combining multiple arrangements. Though a recycler typically sells the materials he collects to a bodega, if he finds books, clothes, or electronics, he will sell these at a flea market for reuse.

Using interviews to determine the mass typically carried per collection vehicle, and the number of recyclers employing each mode of collection (UAESP 2011), we estimate the mass percentage of recyclables collected by collection vehicle (figure 2). Most collection modes are unmotorized, and horse-drawn carriages collect most recyclable material.

Sorting and Storage

After collection, a recycler sells his goods to a bodega, which will pay him for the quantity and market price of the materials he conveys. Usually, materials will travel to multiple bodegas before reaching industry; in the model, we assume they travel 15 kilometers (km) total to three bodegas, by pick-up trucks. The UAESP estimates that there are 3,000 bodegas in Bogotá, but others estimate upward of 6,000 (Espinosa 2011; Gomez 2011). Bodegas profit from the separation and storage of recyclables, and they vary in size, specialization, and institutional arrangements. The smallest bodegas (within trucks or garages) buy materials directly from recyclers, accept a variety of materials, and sell to another bodega. The largest bodegas are most likely to accept only one type of material, to buy materials from other bodegas, and to sell directly to industry.

Transport and Remanufacture

Bodegas sell recyclable materials to industry, which turn the raw materials into new products. We assume that recyclables are processed domestically, traveling from Bogotá in a long-haul truck to the major manufacturer for that material. Plastic, paper, and cardboard travel 420 km to Medellín, glass travels 50 km to Zipaquirá, and metals travel 125 km to Boyacá (Gomez 2011). Colombia has strong domestic markets for all of these products, though some (metals, paper, and plastic) are more competitive than others (glass) (Gomez 2011).

Though product reuse is very common for construction materials, clothing, and books, we consider only textile reuse and assume local reuse. This is a conservative assumption.

Proposed Changes to Recycling: A Pilot Plant

The municipal government wants to formalize recycling. Originally intending to build five pilot recycling plants, the UAESP has built one, La Alquería. The new formal recycling system functions very differently from the unregulated system in place. Serving a small fraction of the city's residents (only in higher-income areas), the new system asks selected residents to separate their recyclables from waste. Trucks take the separated material, 40% of which is nonrecyclable, to the recycling plant (Calderon 2010). Workers at the plant, who are paid by the hour, work regular hours, and receive benefits, separate incoming material by type, and recyclables are baled and sold directly to industry. The pilot plant thus represents a radical break in collection (now motorized), separation and storage (now in one centralized facility, without middlemen), and sale. But the most profound difference lies in the incentive structure. Whereas each node in the unregulated recycling operates as a business, the pilot system offers no incentive to maximize efficiency: Consumers have no incentive to separate their materials, collectors have no incentive to collect only recyclables, and plant workers have no incentive to separate items faster (Vergara 2011).

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

Description of Scenarios

1. *Baseline*: The baseline scenario reflects the current state of WM, against which all other scenarios are measured. The city's recyclables are collected informally, and municipal

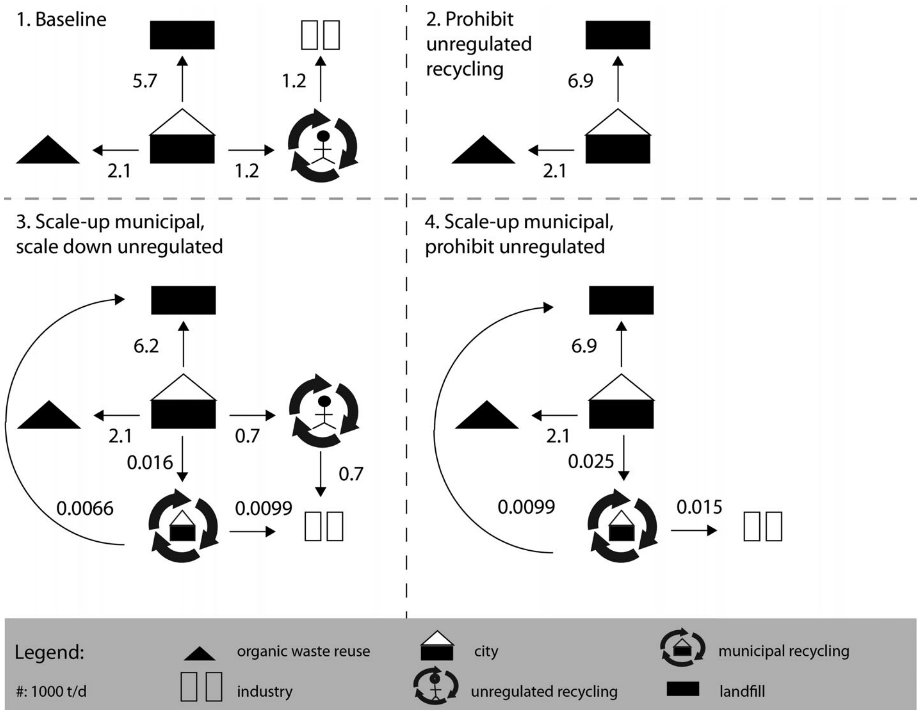

Figure 3 Mass balances showing the fate of wastes for recycling scenarios for the city of Bogotá. All numbers are in thousands of tonnes per day (t/d).

workers transport residual waste to the sanitary landfill. Emissions from energy consumption were modeled using the emission factor for Colombia's grid: 0.36 t CO_2-eq. per megawatt-hour (Esmeral 2011). Methane emissions from horse-drawn collection are taken from Cornejo and Wilkie (2010) and IPCC (2007), and we assume that recyclables travel 15 km from the first to the final bodega. After the collection of recyclables, all transportation is mechanized. All paper is assumed to be recycled into paper and paperboard; all plastic is modeled as polyethylene terephthalate, metal as 50% steel and 50% aluminum, and glass as glass bottles. Data for the recycling processes are based on existing processes in EASETECH and updated with energy production data specific to Colombia. Landfill gas at Doña Juana is flared. We assume a 50% to 80% gas capture rate, varying over time, and a 100% flaring efficiency for the next 45 years. Given that formal recycling represents a small proportion of what is recycled in the city (<1%; J. Martinez 2010), we neglect it in the baseline case. We assume that all textile recycling occurs in the form of reuse and that all textiles can be modeled as cotton t-shirts (after Woolridge et al. 2006). We assume 80% of reused textiles displace the production of cotton t-shirts. These assumptions hold for the following scenarios unless otherwise noted.

2. *"Landfill": Immediate prohibition of unregulated recycling.* If the city suddenly prohibited all informal recycling, then, in the short term, all waste generated would be landfilled. Comparing this scenario with the baseline gives the GHG emissions abated by informal recycling.
3. *"Realistic future": Reduce informal, increase formal.* In the immediate future, horses will be prohibited, and the formal sector will scale up. Here, we assume that informal recycling declines by 63%—recyclers relying on horses will find alternative employment—and that another pilot plant is built, identical to the Alquería in its throughput (5 t/d), sorting efficiency (60% of materials arriving are recycled) and composition.
4. *"Drastic future": Remove informal, scale-up formal.* This scenario assumes the immediate prohibition of informal recycling and an increase in formal recycling through construction of two more pilot recycling plants, identical to the Alquería.

The overall mass balance for each scenario is shown in figure 3 while the percentage of each waste fraction that is reused and recycled for each scenario is shown in the SI.

Though the composition of recycled material changes over time, figure 4 offers a snapshot of the composition of recycled material from the formal recycling plant and from one bodega (part of the informal recycling system) in 2009. The composition of recycled goods differs between the two facilities owing to a difference in the generators (the municipal system collects waste from wealthier neighborhoods only) as well as differing incentive structures. Whereas municipal workers are paid by the hour, informal recyclers are paid according to the quality,

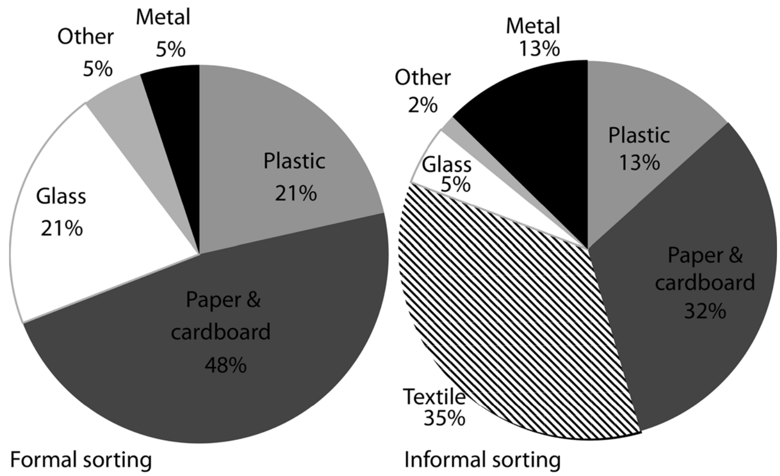

Figure 4 Composition of recycled materials coming out of the municipal plant, the Alquería (left), and from the informal recycling system (right). Though both are dynamic, systematic differences stem from the population served and the incentive structure.

quantity, and composition of recyclables they collect, giving them a strong incentive to collect only goods for which there is a market, and as much of it as possible. Metals have the highest market value; thus, they comprise 13% of material recycled informally, but only 5% of material recycled municipally. Glass has a low market value (and is heavy to carry), and so it constitutes just 5% of the goods recycled informally. Plastic's market value is also low and is so light that large volumes are needed to make significant revenue, so it represents a small proportion of informally collected material. Finally, textiles comprise a large proportion of waste recycled informally. As a raw material, textiles carry a low market price, but as secondhand items, their value is higher. Clothes are sold in flea markets or to industries as rags. Informal actors have access to secondhand markets to which the municipality does not.

Separation occurs at different points in the recycling chain for the informal and municipal systems. In the unregulated system, collectors separate at the point of generation, removing only valuable items from garbage bags, and selling only recyclable goods to bodegas, because that is what they will buy. In the municipal system, bags are taken to the recycling center, opened, and sorted there. Because residents are unaccustomed to separating their recyclables from their waste, the material arriving at the pilot facility is mixed–40% is not recyclable and is landfilled.

Results and Discussion

Life cycle GHG emissions are modeled for each scenario and compared to the baseline scenario. These scenarios reflect probable future events, following the formalization of Bogotá's recycling system. Comparing alternative scenarios shows which elements in the recycling chain have the greatest impact on net GHG emissions.

Greenhouse Gas Emissions

The baseline recycling scenario, dependent on the informal sector only, emits far fewer GHGs than do all the other scenarios (figure 5a). Net GHG savings achieved through the current informal recycling program is calculated by taking the difference in emissions between the baseline scenario and the "all landfill" scenario and amounts to 7.8 million tonnes (Mt) CO_2-eq. The baseline is a larger sink for GHGs than are the modernization scenarios by 5 and 7 Mt CO_2-eq., respectively. Figure 5a also shows that the waste treatment—recycling, reuse, composting, and landfilling—has a far greater impact on GHG emissions than do collection and transportation. This suggests that the most effective way Bogotá can reduce its emissions from waste management is increasing recycling and reuse; improving transportation and collection efficiency would lead to only marginal reductions. Maximizing the collection of recyclable and reusable material with a market value leads to the greatest GHG savings, and the current, unregulated recycling system is the scenario that performs best at this.

Within the treatment phase in all scenarios, three processes have the greatest impact on net GHG emissions: textile reuse (–), landfill gas emissions (+), and aluminum reprocessing (–) (figure 5b; see the SI). The latter two are unsurprising: Landfill gas is the largest emitter of GHGs from WM (Bogner et al. 2007), and aluminum recycling is a significant net sink of GHG emissions because the process requires little energy itself while displacing the high-energy requirements of processing virgin aluminum. But textile reuse overwhelmingly drives the results in the baseline case, with net emissions of −7.9 Mt CO_2-eq. Landfill gas has the next biggest impact, with positive emissions of 1.27 Mt CO_2-eq. Finally, aluminum recycling is also a sink (−0.3 Mt CO_2-eq.). The magnitude of the sink from reusing textiles suggests that informal *reuse* activities may bring even larger environmental benefits than does informal

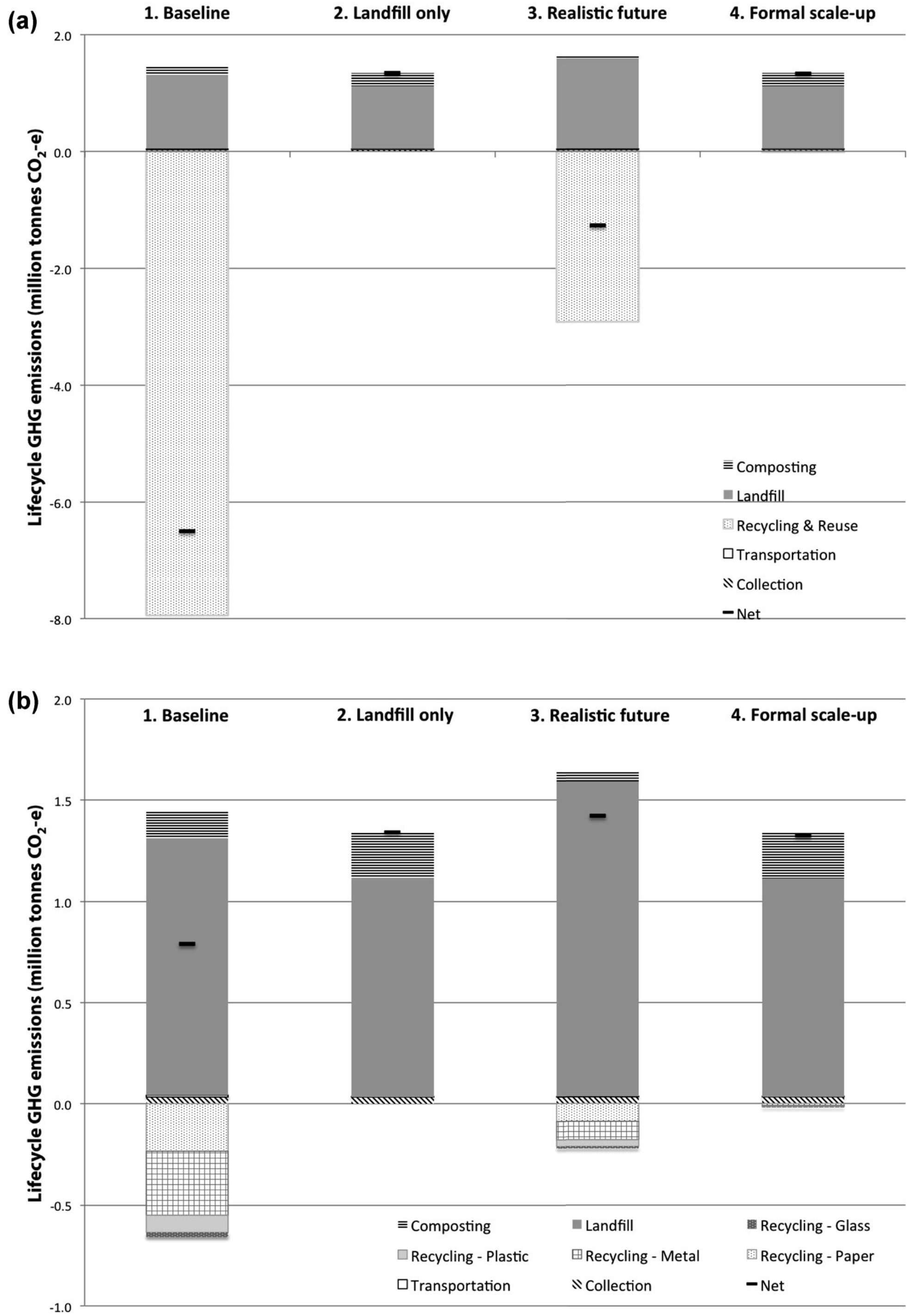

Figure 5 (a) Net life cycle greenhouse gas emissions (million tonnes CO_2-e per year) for the baseline and alternative recycling scenarios for Bogotá's waste. Modeled using EASETECH. Emissions from collection, transportation, recycling and reuse, composting, and landfilling are shown as stacked columns, and the net emissions for each scenario are marked with a dark rectangle. The baseline case has the lowest net emissions. (b) Net life cycle GHG emissions (million tonnes CO_2-e per year) for the baseline and alternative recycling scenarios for Bogotá's waste, with textile reuse removed in order to see the relative contribution of each recycling process. Modeled using EASETECH. Emissions from collection, transport, composting, recycling (metal, plastic, paper, and glass), and landfilling are each shown in a stacked column, and net emissions are marked with a dark dot. The baseline case has the lowest net emissions, because it recycles the most material, even without textile reuse. CO_2-e = carbon dioxide equivalents; GHG = greenhouse gas.

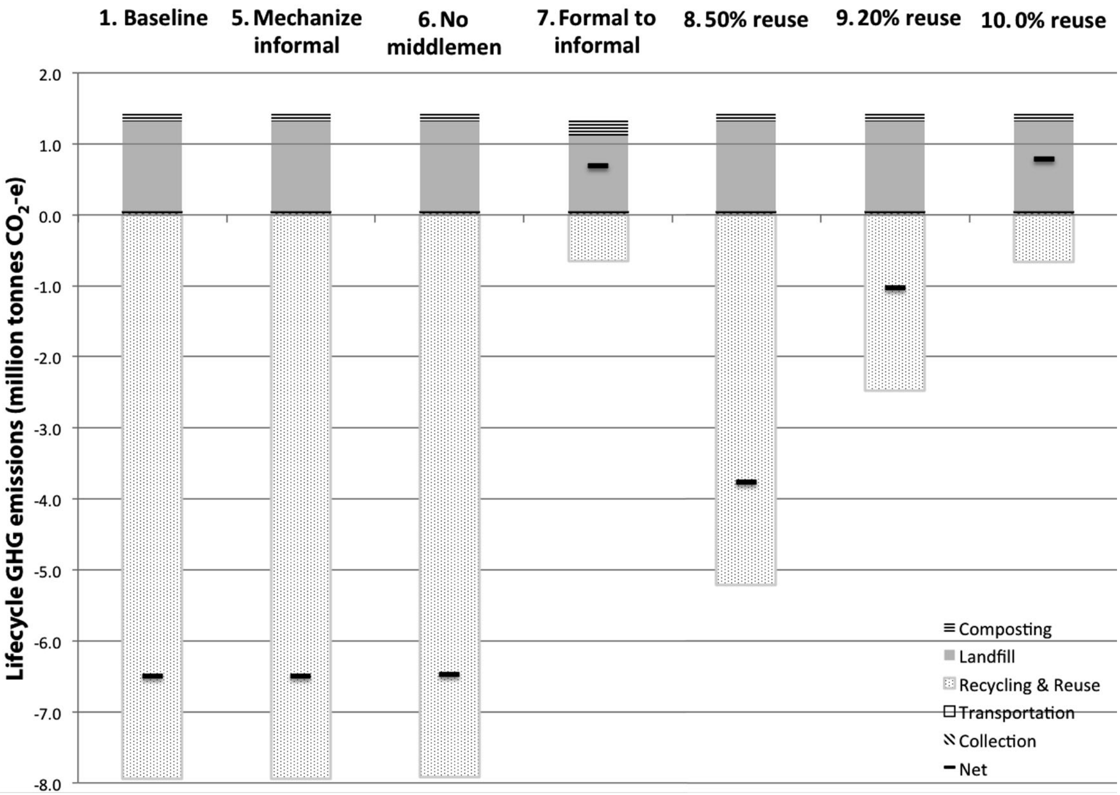

Figure 6 Net life cycle GHG emissions (million tonnes CO2-e per year) for additional recycling scenarios for Bogotá, for the purpose of sensitivity analysis. Modeled using EASETECH. Emissions from collection, transportation, recycling and reuse, composting, and landfilling are each shown; net emissions are marked with a dark rectangle. Two scenarios (5 and 6) change assumptions in the process of informal recycling and have little impact on emissions. Scenarios 8 to 10 change assumptions on the quantity of virgin textile displaced by reused textile and significantly impact the net emissions. CO_2-e = carbon dioxide equivalents; GHG = greenhouse gas.

recycling. Though the informal sector is engaged in a variety of informal reuse activities—spanning electronics, books, and clothing—this analysis conservatively assumes that only textiles are reused, albeit at a high rate of substitution (80%). Thus, the benefit from reuse activities may be even greater than our findings suggest.

Figure 5b shows the resulting GHG emissions without textile reuse, illustrating the dramatic effect of prohibiting informal reuse activities (overall emissions are significantly greater for scenarios 1 and 3 without reuse: +6 and +2 Mt CO_2-eq., respectively) and the relative GHG impact of the other phases of solid WM (collection, transportation, recycling, composting, and landfilling). For the scenarios that feature informal recycling prominently (scenarios 1 and 3), recycling is an important sink for GHG emissions. The baseline scenario still emits fewer GHGs than do the other scenarios, even without reuse activities. The landfill is the biggest contributor to overall emissions across all four scenarios, whereas collection and transportation produce negligible emissions. Composting is a small, positive GHG emitter (0.14 Mt CO_2-eq.) but is responsible for high avoided emissions, if the organic waste were instead landfilled.

Social and Economic Impacts

Carbon emissions are not the only metric needed to determine the most appropriate way to manage waste: Social and economic benefits matter, too. The formalization and centralization of recycling in Bogotá will create steady and healthy jobs, but it will reduce jobs for low-income, unskilled workers who currently make a living by recycling the city's garbage. Where the current, informal recycling system does not incur any direct economic costs to the municipal government, a municipally run recycling program would. These are trade-offs that are beyond the scope of this analysis, but should be considered by the municipality.

Sensitivity Analysis

Six sensitivity analyses highlight the factors driving the results. These additional scenarios show the GHG emissions from: (5) removing middlemen from the informal recycling chain, (6) the mechanization of collecting recyclables, (7) the recycling *process* (municipal versus unregulated), and (8 to 10) the fraction of reused textiles displacing virgin textiles. For these scenarios, assumptions about how materials are reprocessed and disposed of are the same as in the previous scenarios.

5. *Mechanized informal recycling:* As the municipal government banned the use of horses (2012), proposing that these recyclers buy subsidized cars instead, this scenario assumes a mode shift from horses to cars for the quantity of recyclables currently collected by horse.
6. *Informal without middlemen:* This scenario models a more centralized informal recycling system. Here, collectors bring materials to one bodega, which sells them to industry.
7. *Unlikely future: Expand formal recycling to reach current informal recycling levels*: A best case for municipal recycling, this scenario models GHG emissions that would occur if the formalized system were able to recycle as much as its informal counterpart.
8. *Modified textile reuse: Medium (50%)*: In the baseline cases, we assume that 80% of textiles collected displace new shirts. We explore the impact of this assumption by looking at a medium (50%) replacement rate.
9. *Modified textile reuse: Low (20%)*: This scenario assumes a low (20%) displacement rate.
10. *Modified textile reuse: Zero (0%)*: Finally, this scenario assumes 0% displacement, equivalent to the scenario shown in figure 5b.

The results from the sensitivity analyses are reported in figure 6.

The initial sensitivity recycling scenarios show negligible differences relative to the baseline scenario. Mechanizing the informal sector—collectors using pick-up trucks instead of horses—leads to a modest increase in GHG emissions (+0.01 million t CO_2-eq./yr), underscoring the minor role that collection plays in the total GHG emissions from waste management (although it plays an important role in air quality). Cutting out the middlemen in the unregulated recycling chain also has a minimal impact on GHG emissions, but does decrease employment.

Scenario 7, in which the formal sector expands to reach the scale of the informal, is unrealistic but informative. If the municipal recycling system were able to reach the scale and effectiveness of the unregulated recycling sector, it would abate as many GHG emissions through recycling as the baseline, but would not have access to the markets for reusing textiles. This leads to overall higher emissions (+7 Mt CO_2-eq./yr). A potential benefit from this centralization of recycling not included in this analysis is that one facility with access to large volumes of recyclable material might be able to market materials that are rarely sold through unregulated means (e.g., Tetrapak, amber-colored glass). In any case, this scenario relies on two unlikely assumptions. First, it requires an increase in scale that is infeasible. The municipal government's pilot facility has the capacity to receive 20 t of material a day, but as of 2012 was receiving only 5 t. The government has been unable to build the five additional, bigger facilities it wanted because of residents' protests (Vergara 2011). To recycle as much as the informal sector does, the municipal system would need ten recycling facilities, operating at full capacity. Second, it assumes that formal recycling can meet the recycling rates of the informal system. But what makes the unregulated sector so effective is its incentive structure, in which workers get paid for what they collect. Lacking this incentive, the municipal system would likely be unable to collect as much as the current system does. The quantities that municipal workers collect would increase if citizens source-separated their waste, but education and incentives are needed to sustain behavioral change (Rogers 1995).

The final three sensitivity scenarios show the relative impact of how much virgin cotton is displaced by reused textiles. In the baseline case, we assume 80% of reused textiles displace virgin cotton; in the sensitivity scenarios, we look at 50%, 20%, and 0% displacement. Because textile reuse is the biggest sink for GHGs in our scenarios, the results are very sensitive to this assumption; the medium, low, and zero displacement scenarios have increased emissions of 3, 5, and 7 Mt CO_2-eq., respectively. These results highlight that reuse is a powerful sink for GHG emissions from waste. Importantly, even with no displacement, the baseline case of informal recycling still outperforms the formalization scenarios.

Uncertainty

This analysis contains many sources of uncertainty. The informal waste sector is a data-scarce environment; as such, all assumptions are based on personal interviews, observations, and document analysis (see Vergara 2011). Waste generated by a city varies over time, and Bogotá's waste quantities and composition data are measured only at the point of disposal, leaving uncertainty in quantities generated and recycled. The informal waste sector is fluid, adaptive, and dynamic—always shifting to follow economic opportunity. Recycling markets are also dynamic; daily price fluctuations affect the quantity and composition of the materials recycled. Changes in these quantities would affect the results of the analysis. Finally, the modeled processes for recycling and virgin production of material also carry uncertainties, given that there are a large number of value choices to be made when modeling them (Brogaard et al. 2014). Despite inherent uncertainties, the methods and results from analysis should be useful to others seeking to better understand the operation of the informal waste sector.

Conclusion and Policy Recommendations

Informal recycling is an important component of Bogotá's (and many other cities') overall WM program. Understanding how informal actors work in the waste sector is essential to the implementation of integrated WMSs in the Global South (McDougall et al. 2001), yet there are no previous studies that quantify environmental services provided by the informal waste sector (Gutberlet 2008).

To quantify the benefits of these services in Bogotá, we first recognize that its informal sector provides two WM services: recycling and reuse. By diverting waste materials from the landfill and rerouting them to be reprocessed, informal collectors increase the quantity of waste materials that are recycled. But informal collectors also repurpose items in the waste stream for direct reuse. While often overlooked, waste reuse in developing nations is a widespread practice and, as we see in the case of textile reuse in Bogotá, may bring sizeable environmental benefits. The magnitude of the benefits of textile reuse—greater than the abated emissions from recycling and greater than the positive emissions from landfilling—highlights the need for future research on direct waste reuse; no study has yet been published on the practice or its attendant benefits. This article has aimed to address both of these gaps in the literature by exploring the role of the informal waste sector in recycling and reusing Bogotá's waste.

Bogotá's current informal recycling system emits fewer GHGs than does the municipal government's proposed formalized recycling plan. The unregulated system outperforms the municipal one not because of *how* its workers recycle, but *why* they recycle. For informal workers, the incentive to recycle is economic—it is their livelihood, and as such, they work to maximize the quantity and quality of materials collected from waste. Informal recycling is a greater GHG sink than municipal recycling simply because it recycles more. If the city wants to increase recycling, it should note that the informal sector has a broader reach, a larger capacity to recycle, and a strong incentive to do so effectively. The municipal recycling program has no such incentive. As its director put it: "Because it is run by the government, nobody cares. Recycling should be run as a business" (J. Martinez 2010). It already is.

The sector also brings with it social trade-offs. Though waste work provides many (20,000; UAESP 2011) with a source of livelihood, working conditions are not optimal. Informal collectors are exposed to occupational hazards, and many do not use protective equipment while working. However, the "modernization" of recycling through municipal management would result in the loss of many jobs for many people who have a paucity of other options.

So the question remains: How can the two modes of recycling be combined to maximize social and environmental benefits from recycling? Our analysis has shown that the operation of the current informal recycling sector provides greater environmental benefits than does the proposed formal one. However, hybrid models could be pursued: (1) a cleaner, safer informal recycling system; (2) a more efficient formal recycling sector; or (3) an optimized parallel system, in which both formal and informal recycling systems serve the city.

To improve upon the functioning of the informal sector, the municipal government could provide incentives to protect the health of informal workers and maintain the cleanliness of their operations, given that the aesthetics of informality has been a barrier to their acceptance. To improve the efficiency of the formal system, the municipality could establish an incentive structure similar to the informal system's: Workers' earnings are proportional to the quantity of recovered recyclables. But improving the efficiency of the formal system at the exclusion of the informal system would displace jobs from the poor; it would also likely curtail the widespread reuse of textiles, given that this is currently an informal practice. Given that the informal sector provides important social and environmental services free of charge to the municipality, but does not provide recycling coverage to the whole city, a parallel hybrid system may bring the greatest benefits. To combine the best of both systems, the municipality could provide incentives to improve the conditions of the informal workers (as described above) while focusing the attention of the formal sector on collecting materials that are unlikely to be recycled informally owing to lower market prices (e.g., Tetrapak). In doing this, the city would maintain, but improve, the informal sector jobs, provide an additional environmental service to all, and would create new jobs in the waste sector. For the hybrid model (or any model) to be most successful, the municipality should promote source separation of waste in the home. For a new approach on how to do so, we can look to the "agreed exchange" collection arrangement from the informal sector, in which residents separate their recyclables in exchange for complete waste services from their informal provider. This example demonstrates that people are more willing to separate their waste when they receive something in exchange.

This analysis has implications beyond the borders of Bogotá. In studying the informal recycling sector of the city, we see that the informal sector can be a major player in material flows in emerging markets. Because the informal waste sector's work is difficult to characterize—and sometimes even to see—it is often ignored in municipal analyses. Failure to quantify the significant environmental benefits from the informal recycling and reuse sector can lead to suboptimal decisions. Quantifying and characterizing the work of the informal sector in Bogotá reveals an efficient system whose operation could be further improved, but that already provides environmental benefits to the city. Combining the work and benefits of informal and formal recycling sectors could provide even broader environmental and social benefits in Bogotá and in other cities aiming to modernize their WMSs.

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Supporting Information

Additional Supporting Information may be found in the online version of this article at the publisher's web site:

Supporting Information S1: The supporting information describes the data and the scenarios used for modeling in the article. It includes seven alternative waste treatment scenarios and also describes the model assumptions behind the waste management technologies used. These technologies include: landfill, material recycling facilities (MRF), composting, and material recycling and reuse processes for glass, paper, metal, plastic, and textiles.