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Good News From the Dump

Methane Emissions from Solid Waste: Current Conditions and Future Prospects

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DECEMBER 2012

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Founded in 1996, the Clean Air Task Force is a nonprofit organization dedicated to restoring clean air and healthy environments through scientific research, public education, and legal advocacy.

This paper was written by Elaine Matthews, a consultant to the Clean Air Task Force, following a joint project between CATF and NASA's Goddard Institute for Space Studies (GISS). Elaine has worked at GISS since the early 1980s, and began research on the global methane cycle in the mid-1980s estimating global methane emissions from anthropogenic and natural sources including fossil fuel production, processing and consumption, rice cultivation, ruminant animal husbandry, termites and natural wetlands. Her recent work has focused on future methane emissions and mitigation strategies and plausible projections appropriate for policy studies.

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Executive Summary

Overview

Estimates of recent historical and future methane emissions from solid waste rely primarily on one of the methodologies promoted by the Intergovernmental Panel of Climate Change (IPCC). One approach is a First Order Decay (FOD) model appropriate for individual landfills as well as whole countries but that requires substantial multi-decadal landfill data including amount of waste in place, management and waste composition. The more commonly used is a simpler approach initially outlined in IPCC (1996) that relies on country-specific or default values for a series of variables to calculate solid waste produced, landfilling and anaerobic landfilling rates, carbon content of waste, methane fraction of gas produced, and methane capture, oxidation and emission. Studies based on the latter IPCC approach report global methane emissions from landfills to be ~35 Tg (10^{12}g) CH_4/year although several researchers report values as low as ~10 Tg CH_4/yr as well as methodological and data-based explanations why the higher values may be overestimates.

Studies that predict future methane emissions from solid waste universally indicate that emissions from developing countries will rise dramatically (by a factor of 3-4 by 2030) due to: 1) large population increases, especially in cities with higher per capita waste production than rural areas; 2) increases in per capita waste generation due to economic growth and greater overall consumption; 3) increased landfilling rates; and 4) construction of landfills to replace open dumps, thereby favoring anaerobic conditions and methane production.

However, there are many current factors and dynamics suggesting that future trends may not rise so rapidly. Much of the world does not currently have managed landfills for disposal of waste after collection. In fact, much of the world does not have standard procedures for waste collection and management although municipalities throughout the developing world are officially responsible for waste management. The 'informal' sector (i.e., scavengers, wastepickers, recyclers) play a major role in removal, recycling and reuse of discarded items in all developing countries, as well as in some industrialized countries (Chikarmane and Narayan, 2009). Although information about activities and impacts of the informal sector is mostly qualitative and anecdotal, most agree they play a substantial role. The impact of informal waste pickers was shown over the last decade in Cairo, Egypt when an established community of pickers - the Zabaleen - was partially eliminated from the waste-management process when European and Egyptian companies were hired to collect and dispose of Cairo's waste. Recycling and reuse plummeted, costs rose, more space for disposal was needed and Cairo, like many other cities, is now attempting to develop a management system that explicitly includes the informal sector (Fahmi et al., 2010).

Industrialized countries are generally reducing the fraction of waste disposed of in managed landfills although the US still landfills >60% of municipal solid waste (MSW). EU countries have lowered this fraction substantially. The Netherlands has achieved an extraordinarily low landfilling rate equal to 3% of produced MSW by volume, and that consists largely of ash from incineration. As of 1999, no new landfills can be constructed in the EU so coordinated local and regional efforts are operating and in development to recycle, reuse, and compost waste.

In developing countries, much of the solid waste that is not recycled or reused is disposed of at open dumps; some are official while the majority appears to be unofficial or illegal. Shallow open dumps are often aerobic but large sites, located mostly around rapidly growing cities, can be deep enough that lower layers of waste are anaerobic. Moreover, dumps often grow in low-lying areas that encompass ponds, streams or rivers, and may be inundated in rainy seasons. Some of these dumps are decades old and tens of meters deep. Organics, especially fresh material such as food waste, decompose aerobically to CO_2 in shallow open dumps, especially in dry climates. However, organics produce both methane and CO_2 when they degrade anaerobically in deep and/or saturated dump sites and in sanitary landfills.

Current and Prospective Waste Disposal Approaches

1. Composting

In some developing countries, food waste is separated before disposal and applied to farmland as nutrient supplements and soil amendments, or fed to animals. In some cases (e.g., Beijing), animals feed directly on organic waste in dumps. However, source separation is not widely practiced and is crucial to successful composting.

The high organic content (50-80% of wet weight) of solid waste in developing countries, together with the scarcity of space for waste disposal near large cities and the need for fertilizers and soil amendments for farms and urban gardens, makes composting an excellent option to include in solid-waste management. Nevertheless, composting is currently a little used approach especially in developing countries despite high organic content of waste. In some cases, composting facilities were constructed but stopped operating after a short time. Problems included: a) failure to achieve a high quality product due to lack of source separation and subsequent contamination of compost with, e.g., heavy metals; b) lack of spare parts and technical expertise for compost facilities equipped with heavy equipment; c) lack of markets for compost (expectations often involve municipalities as the major consumer of the product); d) lack of companies to operate facilities due to risk of failure and e) problems with transporting organics to facilities. Another probable explanation for low composting rates in developing countries is that more income may be made in collecting and transporting waste to landfills and dumps. There are however successful composing facilities, e.g., Brazil. Composting not only represents a good fit to waste composition and funding limitations in developing countries but it is an effective strategy to mitigate methane emissions from solid waste disposed of in landfills. Estimates of potential mitigation of methane emission for 2000-2030 reported here indicate that plausible expansion of composting may reduce emissions by ~25% compared to a baseline emission projection.

2. Thermal processing

Incineration of waste (not including open burning) with energy recovery is relatively scarce in developing countries except in China which now has >100 waste-to-energy plants. Reasons include very high costs of construction and maintenance, and dependence on foreign suppliers for construction, replacement parts and expertise. Incineration without source separation of organics is not economically or technically feasible since high organic and water contents of waste require potentially expensive preprocessing and often auxiliary fuel as well. Another obstacle is poor infrastructure (human, mechanical, institutional) for incineration plants.

China is atypical in the waste-to-energy arena. Extremely high economic growth rates in China over the last few decades has produced massive growth of cities, competition for peri-urban space, and increased per capita consumption of products (and waste). These trends conflate to produce wealth to pay for expensive incineration technology and production of enormous amounts of MSW requiring disposal. While this trend is likely to continue in China, and some fast-growing cities in India may take a similar route, is it highly unlikely that the number of waste-to-energy plants in developing countries will rise rapidly in coming decades.

Open burning of waste, both informally and as a disposal strategy, remains very uncertain with respect to amount, composition and process. Data on waste-collection rates compiled for this study (Table 2) indicate that globally, maybe 75% of generated waste is collected leaving the remaining 25% unaccounted for, and possibly disposed of through informal burning.

3. Anaerobic digestion

The series of stages in anaerobic digestion converts organic material (most often sewage sludge but also organics from the solid waste stream) into gas (methane and CO_2), digestate, and water. Anaerobic digestion has been promoted primarily as a producer of fuel rather than as a waste-management option. While systems can be relatively simple (i.e., single-stage digestion), they still require, at a minimum, dedicated equipment, temperature control, and pre-treatment of the feedstock (shredding, pulping etc.). Large facilities further require mechanisms to transport methane to consumers. Small-scale, domestic anaerobic digestion has been introduced in China in part because China has a long history of domestic maintenance of biogas pits but the cost, and need for constant supply of feedstock indicates that this anaerobic digestion will not experience major growth in developing countries, and will likely continue to be used to process manure from industrial farms and sludge from wastewater treatment.

4. Landfills and dumps

Waste disposal in developing countries (especially in cities) is overwhelmingly in open, peri-urban dumps even if regulations exist requiring construction and maintenance of landfills. Dumps are located convenient to collection vehicles and often pose environmental and health risks to resources and to residents living nearby or in the dumps (Ray et al., 2005). Disposal sites in developing countries, including landfills, are rarely lined allowing leachate to contaminate soil and surface and ground water. Lack of security permits uncontrolled dumping of toxic and other materials. In contrast to sanitary landfills, waste is not compacted nor frequently covered with clean soil. Waste pickers are a common feature at landfills and their activities depend on the composition of waste arriving at the landfill. Substantial, although mostly unquantified, diversion of products via recycling and reuse occurs prior to and following disposal at dumpsites and landfills. Sanitary, engineered landfills provide the anaerobic conditions required for methane production through decomposition. Many landfills are not equipped with the equipment to capture landfill gas allowing a substantial fraction to migrate to the surface and emitted to the atmosphere. Even in instrumented landfills, gas collection is delayed until cells are closed during allowing generated methane to escape. As a result capture rates are likely ~50-60% of generated methane over the lifetime of the landfill. Moreover, in countries where disposal is relatively free (i.e., open dumping), constructing landfills represents a new cost.

5. Integrated management

As demand rises for valuable and increasingly rare materials (e.g., metals and rare earths), reclamation of these products is being formalized at disposal sites in developing countries. Many countries and cities are attempting to upgrade existing dump sites to control waste input, institute leachate treatment, and provide facilities for composting, recycling, and reclamation. These approaches are often quasi-local efforts, which means they are likely to continue in spite of political changes that would threaten government-funded projects. They are also likely to provide more jobs than more mechanized or high technology approaches.

Prospects for Methane Emission From Solid Waste

Current methane emissions from landfills are likely ~10-15 Tg (1 Tg=10^{12} g) CH_4/yr rather than ~35 Tg as reported in most studies relying on IPCC-based methodology. While developing countries will account for the majority of population growth in coming decades, including disproportionate growth of urban populations, methane emission from solid waste is unlikely to grow at the high rates predicted for population and economic growth. Developing countries are not on the same trajectory as that historically followed by industrialized countries that relied on landfills as the dominant approach to waste disposal. Developing countries are not expected to follow this trend for the following reasons:

- There is a well-established culture (and increasing need) for recycling, reuse and materials recovery in developing countries.
- Rapid growth of large cities is competing for peri-urban space where waste has historically been deposited.
- Chronic lack of funds for waste management and other services in poor countries, together with space limitations, suggests that constructing methane-producing sanitary landfills will not be the primary solution to managing municipal waste in these countries.
- High organic content of waste in developing countries (50-80% of wet weight), together with emerging plans for source separation and collection of waste, suggests that the role of aerobic composting will rise in coming decades if problems of marketability, source separation and product quality can be solved.

The more recent growth of incineration in industrialized countries and China is also unlikely to play a major role in waste management of developing countries for multiple reasons including high organic and water content of waste and high capital costs for plants.

Reduction in waste requiring disposal at dumps or landfills—particularly of organics that contribute most to methane production and emission—will further decouple growth in population and GDP from growth in landfilling and methane emissions in developing countries. This trend is already in evidence in most of Europe as a result of aggressive efforts to reduce waste generation (e.g., packaging legislation), recycle paper, glass, metal and many plastics, and divert organics to compost plants (World Bank, 2005).

Composting offers the best option for addressing multiple solid-waste problems including methane emission including:

- Well adapted to high-organic waste characteristics of all developing countries
- Provides a low-technology, and relatively low cost, alternative to incineration and landfills
- Emits low-to-no methane
- Requires less land, and longer lifetime, than landfills
- Provides useful soil amendment and fertilizer
- Reduces health and pollution impacts by minimizing leachate production at disposal sites

Low current methane emissions associated with solid waste management, and future modest emission growth, imply that mitigation of waste-related CH4 emissions, including Clean Mechanism Projects, is a poor candidate for limiting climate change.

1. Introduction

Landfills are currently estimated to emit ~10-35 Tg (10^{12}g) methane annually out of the anthropogenic emission total of ~600 Tg. The production and emission of methane in landfills and other waste-disposal sites is controlled by a suite of processes and characteristics that vary over time and space. Primary drivers include:

1. Size, living standard and urbanization of human populations.
2. Amount and composition of waste generated (e.g., organic content, recyclables).
3. Collection and disposition of waste (e.g., extent of collection services, recycling, incineration, composting, unregulated dumping, landfilling).
4. Presence, type and efficiency of gas-capture in landfills (e.g., active or passive capture).
5. Disposition of captured methane (vented, flared, used as energy source).
6. Methane oxidation in landfill covers.

The local nature of waste generation and management means that information on amount, composition and disposition of waste is typically scarce, particularly for developing countries although statistics for industrialized countries are available. Regional review papers and studies for large cities in developing countries have been published but suffer from uncertainties due to data gaps and/or generic assumptions in the absence of reliable data. For example, waste studies reporting daily per capita waste generation may reflect only residential waste, or the latter plus industrial and commercial waste; construction and demolition (C&D) waste is typically not included but may double waste generation for the former three categories. The prevalence of unofficial settlements in cities makes reliable population counts almost impossible. Illegal dumping and burning of waste is not reported and rarely estimated.

In developing countries, all waste streams, including medical and other toxic materials, are often disposed of at the same sites. Because most dumps and uncontrolled landfills are illegal, quantification and analysis of composition and amount in place is very difficult. The anaerobic conditions required for methane production may or may not be supported in uncontrolled dumps depending upon composition, depth and aeration of waste, climate, local topography, and management, if any.

Recycling is primarily carried out by informal sectors, making this component of waste dynamics extremely difficult to quantify. Because waste-collection rates are notoriously low in poor, peri-urban and unofficial settlements in cities of the developing world, it is critical to account for the gap between generated and collected waste when estimating emissions. While methane dynamics at sanitary, engineered landfills are complex, data on waste production, composition, recycling and landfilling rate, as well as the existence and location of landfills, are more available in industrialized countries where these disposal sites dominate. However, these are also the countries that will contribute modestly to future trends in waste generation. Therefore, reducing uncertainties in future emission estimates requires closing data gaps in developing countries.

The Intergovernmental Panel of Climate Change (IPCC) has published methodologies for estimating methane emissions from landfills and other sources. Initial methods (IPCC, 1996) rely on calculations including*, inter alia,* daily per capita waste production, landfilling and anaerobic landfilling rates, organic content of waste and other variables to estimate methane generation and emission from landfills (Tier I approach). The methodology provides default values for parameters when country-specific values are not available. The Tier I method, including default values, is still frequently used to estimate methane emissions associated with solid waste, particularly for developing countries where region specific data are more difficult to obtain. Subsequently IPCC (2000) outlined good practice approaches if data are available but the essence of the Tier I method remains. IPCC's Good Practice document (2000) offers guidance for characterizing carbon contents of individual waste components to improve estimates of methane-producing potential, but fails to adapt the basic method to reflect emerging data and information about solid waste management in developing countries. The most recent inventory guidelines (IPCC, 2006) rely heavily the existing methodology with some additions that are only applicable with substantial amounts of data that are often lacking for poor countries. For example, although IPCC (1996, 2006) methodologies supply methane correction factors (MC_f) to reflect methane-generating potential of different types of disposal sites, introduction of a generic disposal category —Solid Waste Disposal Site (SWDS) — lessens the reliable application of MC_fs that are linked to type of disposal site.

The goals of this study are to:

1. summarize fundamental processes associated with methane production from solid waste
2. provide an overview of current conditions, practices and characteristics of waste management as related to methane emission for countries and regions
3. present recent historical and future projections of waste generation and management, and resultant methane production and emission, to bracket the role of plausible mitigation strategies on future methane concentrations.
4. summarize remaining uncertainties and their potential impact on estimates of current and future methane emissions from solid waste.
5. offer approaches to reducing uncertainties in estimating methane emissions from solid waste for current and future periods

2. Overview of processes and conditions related to solid waste and methane emission

2.1 Waste generation

Municipal solid waste (MSW) is typically understood to mean household, commercial and industrial waste. In some studies, it also includes waste from construction and demolition (C&D). Per capita waste-generation rates are reported for many cities but rarely for rural areas. These studies focus on household, commercial, and industrial waste; C&D waste is less often reported although it may be equal to 75% or more of MSW.

Per capita waste-generation rates are arrived at in several ways. They can be calculated from an estimate of total waste generation and population statistics. Alternatively, total waste generation can be calculated using per capita generation rates and population statistics. Per capita rates can also be built up from field observations of household, industrial and commercial waste generation in specific cities. Because per capita values are very sensitive to population data, which are often unreliable particularly in megacities with substantial unofficial populations, it isn't productive to analyze these numbers in detail. However, general patterns in per capita waste-generation rates reflect, *inter alia,* level of economic development (more waste with higher economic development and income), size of city (more per capita waste in larger, growing cities) and urbanization (more per capita waste in cities than in villages and rural areas). A universally robust pattern is that people in poor, less developed countries typically generate ≤0.6 kg/capita/day on a wet weight basis (CalRecovery and UNEP, 2005) equal to ~25-30% that for most industrialized countries. However, the composition of waste generated by the poor is dominated by food with high water content (Staley and Barlaz, 2009) meaning that, e.g., 0.6 kg of mostly food waste represents substantially less volume than 0.6 kg waste generated by wealthier people which has higher fractions of low density paper and plastics. It is volume, and its reduction, that plays a defining role in planning for waste disposal whereas weight may determine what fraction of waste is collected and the cost of doing so.

Cities in low-income Asian countries exhibit generally low rates although per capita generation for the majority of Indian States (Gidde et al., 2008) is <0.4 kg/capita/day. The World Bank (1999b) reports a mean of 0.73 kg/capita/day for middle-income Asian cities based on the following city rates: Indonesia (0.76 kg/capita/day), Philippines (0.52), Thailand (1.10), and Malaysia (0.81). Residents of high-income Asian cities are estimated to generate an average of 1.64 kg/capita/day relying on statistics from the Republic of Korea (1.59) Singapore (1.10) and Japan (1.47). Differences among cities of varying size and economic activity are apparent within individual countries such as Vietnam: Ho Chi Minh City (1.3 kg/capita/day), Hanoi (1 kg) and Danang (0.9 kg) (Nguyen, 2005). Similarly the average for Vietnam cities, which encompass ~50% of the population, is 0.7 kg/capita/day whereas rural populations are reported to generate only 0.3 kg/capita/day (Nguyen, 2005). Households in small communities in Central and South America and the Caribbean typically generate 0.25-0.5 kg/capita/day whereas households in large cities (>500,000 residents) generate ~0.75 kg/capita/day (Espinoza et al., 2010). Unlike household generation rates, non-household waste accounts for ~0.3 kg/capita/day in settlements of all sizes. Staley and Barlaz (2009) report per capita waste generation in the US to be 1.9 kg/person/day, which is bracketed with two other recent studies reporting 1.44 (EPA, 2007) and 2.36 kg/person/day (Simmons et al., 2006) for the US. European countries show similar generation rates although some have recently achieved reductions in absolute per capita waste generation primarily through packaging regulations.

2.2 Waste composition

Table 1 provides a representative sample of waste-composition studies. Income often determines the amount and composition of generated waste, among countries as well as among cities within individual countries and even among neighborhoods within cities. In developing countries, composition studies are typically confined to major cities because the information is crucial to evaluating options for waste management. Minimal effort is devoted to rural waste although much of that is fed to animals and/or spread on fields.

Studies that rely on analyzing waste samples can be difficult to compare (Staley and Barlaz, 2009). Samples may be taken at the generation source (e.g., household, factory), at collection sites (community bins, transfer stations), or at disposal sites (Kumar et al., 2009; Mor et al., 2006; UNEP, 2009a,). Recycling, activities of waste pickers and collection rates can substantially alter waste composition, especially recyclables and organics, at these different locations. In developing countries, reported waste composition follows some general patterns (Table 1). Recyclables including plastic, glass and metals generally total <10% of waste by wet weight while paper and cardboard account for 10-15%. A universal feature of waste in developing countries is the high fraction of organic matter (food, yard waste) that accounts for 40-80% of the total. It appears waste generated in African cities contains the highest organic fractions while cities in south Asia may be in the lower range (40-45%) although there is substantial variation even for the same country or city from different authors (Table 1). The mean compostable waste fraction for 23 cities studied by Sharholy et al. (2008) is ~42%. India is unusual in that inert materials, such ash and dust from street sweeping, often account for 30-50% of total waste; the mean inert fraction is 40% for 23 Indian cities.

Waste densities in developing countries are ~200 to >500 kg/m^3 because of the high water content of organics whereas densities, even of compacted waste, in industrialized countries are 30-50% those in developing countries. As noted above, high density poses major challenges to collection; it appears that a substantial fraction of these organic wastes may go uncollected.

Paper and plastic fractions also show wide ranges although interpretation is complicated because these materials are often recycled and it is usually impossible to determine if reported composition reflects pre- or post-recycling.

2.3 Collection

Collection rates (Table 2) reflect either the fraction of the population with waste-collection services or the fraction of generated waste that is collected. Although collection and transport of waste accounts for the majority of funds targeted for solid waste management in poor countries, collection rates (either curbside or from community bins) are especially low in poor, peri-urban and unofficial settlements in cities of the developing world whereas collection service is scarce or absent in rural areas and smaller cities. In a study of 59 Asian cities, Kumar et al. (2009) report collection rates of 50-70% but even these are not evenly distributed among neighborhoods. Low income, unofficial, and/or squatter settlements receive little or no collection services while wealthier areas are well serviced. Only seven of the 59 cities provided house-to-house collection while the remainder provided community bins for residents to deposit their trash. Eleven of the cities employed private companies, in part or in full, for collection services. While only 15 of 59 cities had active waste-processing facilities, 2/3 of these were composting facilities. Visvanathan and Glawe (2006) report the following minimum and maximum collection rates (as % of population) for Asian countries: Afghanistan (0-22%), Pakistan (0-60%), Bangladesh (40-90%), India (50-90%) and Sri Lanka (10-40%). Hazra and Goel's (2009) study of Calcutta, India concludes that ~61% of the population receives some type of collection service (door-to-door or community trash bins). More specifically, 57% of people in 'standard' residential areas receive door-to-door collection service, whereas 67% of people in registered slums and only 13% of those in unregistered slums have any form of collection services. Sharholy et al. (2008) observe that collection rates are higher where private companies and NGOs are responsible for collection but private companies charge fees and thus are more likely to operate in wealthier areas (Vin et al., 2007). Nguyen (2005) reports relationships between collection service and income in and among Vietnamese cities. Yousef and Rahman (2007) estimate that ~50% of the all waste generated in Dhaka, Bangladesh is collected. Gamarra and Salhofer (2007) report urban waste-collection rates in Central and South America ranging from of 20% in Honduras to 81% in Ecuador (Table 2). However, large unexplained differences in collection rates are apparent for the same country from different authors: collection rates are reported for Honduras as 20% and 65% (Table 2). It is beyond the scope of this study to reconcile these inconsistencies. Blight and Mussane (2007) studied collection rates in the municipality of the Eastern Cape, South Africa whose population distribution is ~22% in formal and informal urban areas and 78% in dense rural villages; they conclude that only 19% of the population receives any form of waste-removal services. About 75% of generated waste is collected in Eastern Europe (Gamarra and Salhofer, 2007) while in the US and Western Europe close to 100% is collected; lower collection rates in rural areas of the US occur where residents are required to bring their waste to designated locations.

Systems for waste collection in major cities in developing countries rely primarily on labor intensive techniques such as animal- or human-powered carts; trucks and compactor trucks are less common in part because of high cost for purchase and maintenance as well as because compaction of wet organic waste produces large volumes of leachate that also requires disposal. In some urban areas with no direct collection service, pre-collection is carried out by community groups thus providing more opportunities for recycling and reuse. A special case is that of the Zabaleen in Cairo, Egypt (Fahmi et al., 2010). The city, with a population of 8-10 million, relied entirely on the Zabaleen to collect and manage solid waste for decades. With no government participation, cooperation or pay, the Zabaleen collected waste – directly from outside the doors of apartments, houses and stores – and brought it to their own neighborhood for sorting and recycling. Estimates are that ~80% of the trash was recycled, leaving about 20% to be disposed of at landfills or dumpsites. Specialists among the Zabaleen focused on plastic bottles, metal, and paper. Organics, accounting for about half of Cairo's waste, supported the Zabaleen's substantial pig population that provided additional income and protein to the community. In 2009, all the pigs were slaughtered by the government as a preventive measure against swine flu. With no use for organic material, the Zabaleen no longer collect this putrescent portion of Cairo's waste. The Cairo government, without consultation with the Zabaleen whose livelihood relied exclusively on waste, decided to modernize and formalize trash collection and disposal in the city. They contracted with European and Egyptian companies to collect and dispose of Cairo's trash, which proved to be expensive and short-lived. While the effort provided employment for some, the number was far less than the previous system; the Zabaleen were edged closer to extreme poverty; minimal recycling by the new companies meant increased demand for disposal space near the city and/or disposal of the trash by burning. Cairo is now attempting to develop a new integrated waste-management that includes the Zabaleen although they are being pressured to move outside of the city, sharply increasing the time and effort required to transport waste collected in the city to sorting areas. This approach of officially recognizing the traditional informal sectors in waste management is echoed is many current plans for waste management in developing cities although actual implementation lags behind the plans.

Wide ranges in collection rates summarized here can exert a substantial influence on estimates of methane emission from solid waste management if estimates assume that all generated waste is collected - which is the standard approach. Assuming that waste generated—minus that composted, incinerated and recycled—is collected and transported to disposal sites that may produce methane is not consistent with data for developing countries, and boosts estimates of methane emission from solid waste for these countries.

2.4 Disposal

2.4.1 Recycling, reuse, and materials recovery

These terms are not universally agreed upon but generally refer to removal of materials from initial waste streams for purposes including recycling for processing and/or sale (plastic, glass, paper, gypsum), repair of products for resale/reuse (furniture, electronics) and materials recovery (precious metal from electronics) although the latter leaves the bulk of diverted products to be disposed of. Data on recycling are often lacking in developing countries primarily due to the dominant role of the informal waste-management sector, in addition to uncertainties in amounts of generated recyclables. Estimates of recycling rates and/or amounts are derived by calculating the difference between generated and disposed of quantities of recyclable materials or by sampling differences in waste composition at the source (e.g., households, offices) and at temporary or permanent disposal sites (collection centers, landfills). Most studies of waste in developing countries acknowledge both the importance of the informal sector in recycling and materials recovery, and the difficulty of quantification. However, several authors estimate that 10-25% of MSW is removed from the waste stream mostly by informal sectors (Table 3). An alternative approach is to estimate total recycled amounts from waste generation and composition, which is similarly hampered by scarcity of reliable data.

Recovery and reuse of waste products is overwhelmingly via informal processes in developing countries because these activities provide needed products and income to large numbers of people and because funds for such services are lacking in poor countries. In Africa, low-income households reuse and recycle products themselves whereas domestic servants may recover and sell items in higher income households. Waste pickers respond to volatile markets focusing on materials for which there is a market and a reasonable resale price. Some pickers carry out basic processing including pelletizing plastics or shredding or cleaning textiles. Recycling rates are high where deposit systems are in place, which applies almost universally to glass, and to tin and aluminum cans in some countries. Commercial recycling operations are found in large African and Asian cities. In some East Asian cities, waste reduction efforts rely in part on volume-based fees and source separation. Such efforts reduced wastes requiring disposal by 20-30% in South Korean cities after implementation in 1995 (UNEP, 2004). In wealthier cities such as Singapore, commercial waste-trading companies recycle ~40% of all generated waste (mostly industrial and commercial) although recycling is also encouraged in designated locations at landfills. In many regions of the developing world, individual street peddlers buy recyclables from households and sell to dealers and/or wholesalers. Multiple levels of middlemen expand the income differential between collectors and final purchasers (Agarwal et al., 2005). In poorer cities, traditional collection, recycling, repair, processing and reuse continue on an informal basis. In contrast, several large industrial parks have recently been built in China to host commercial recycling and reprocessing companies. However, the raw products are overwhelming imported from other countries. Neighborhood centers, where individuals sell glass, paper and textiles were established by the Chinese government but use has declined as trade in more valuable materials such as metals is preferred and supported. Recycling and recovery in large cities in Vietnam is often carried out by family businesses, while small-scale collectors and peddlers are still common in African countries.

2.4.2 Composting

A large suite of microorganisms (chemical decomposers), including bacteria and fungi account for most naturally occurring and managed decomposition of organic materials. Aerobic bacteria are the most important chemical decomposers because they eat almost anything and are the most abundant. Oxidation of carbon in waste supplies energy to bacteria and is responsible for heating up compost, whereas nitrogen provides protein to build body mass and aid in reproduction. In the process of consuming plant material, organisms release nutrients such as nitrogen, phosphorus and magnesium in a form available for plant eventual uptake. If oxygen drops below 5%, populations and activity of anaerobic bacteria rise but produce unavailable nitrogen, and gases such has hydrogen sulfide, cadaverine, and putrescine that are responsible for the odor of rotting trash.

Groups of aerobic bacteria operate at different temperature optima (Table 4). Psychrophilic bacteria are most active in the range of 10-21˚C. The modest heat they produce improves conditions for the very active mesophilic bacteria that operate best between 21 and 38˚C. Above 38˚, mesophilic organisms either die or migrate to the outer, cooler parts of the compost. Thermophilic bacteria operate at 38-71˚C, raising the compost temperature to 54-51˚C where it stabilizes. Addition of new materials is crucial to maintain these bacteria because they rapidly use up degradable materials. If the compost cools down, the mesophilics resurge and finish off the biological process. While temperatures >60˚C typically kill pathogenic organisms - an advantage for compost that will be applied to crops - such high temperatures are not necessary to complete the composting process.

A carbon-to-nitrogen (C:N) ratio of 25-30 is optimum for rapid decomposition (Table 5). At ratios >30, heat production declines and decomposition slows whereas higher nitrogen content (lower C:N) can release ammonia and can boost pH which may become toxic to some of the decomposers. Moisture for efficient decomposition is typically between 40 and 60%. Above that, anaerobic conditions prevail which slows decomposition and increases production of noxious gases such as hydrogen sulfide. Below ~40%, bacteria slow down or stop activity. Aeration of compost is crucial to maintaining conditions conducive to fast decomposition that releases nutrients available for plant uptake. Aeration is maintained by turning compost, either mechanically or manually, including coarse material, and/or inserting ventilator stacks. In late stage composting, Actinomycetes—higher bacteria similar to fungi and molds—decompose the more recalcitrant materials including lignin, cellulose, starches, and proteins.

Although aerobic composting can be carried out in local, low-technology ways, success depends on a suite of inputs and management steps to ensure the rapid completion of biological processes required to produce good compost. Lack of knowledge about the biology of composting is one of the tractable problems preventing more widespread implementation of the technique. The most crucial step in successful composting, whether centralized or small scale, is source separation of waste.

In a small number of countries, food waste is separated before disposal and applied to farmland as nutrient supplements and soil amendments, or fed to animals (CalRecovery and UNEP, 2005). The high organic content of solid waste in developing countries (Table 1), together with the scarcity of space for waste disposal near large cities and the need for soil amendments for farms and urban gardens, makes composting a good option to include in solid-waste management.

Nevertheless, composing is a little used approach in both developing and developed countries (Table 3) with a few exceptions. While 58% of yard trimmings was composted in the US in 2010, only ~3% of food waste was composted in the same year although the country had ~2300 composting facilities (http://www.epa.gov/osw/conserve/rrr/composting/basic.htm).

In some cases, composting facilities were constructed in developing countries but stopped operating after a short time. The Indian government promoted composting via funding and pilot programs starting in the 1970s and high-capacity mechanical plants were constructed in large cities including Calcutta, Mumbai, Indore, and Bangalore (Shekdar, 1999, 2009; Sharholy et al. (2008) report that composting continues to grow in India. The Pan American Health Organization (PAHO, 2010) reviewed the fate of ~30 mechanized composting plants purchased but never installed in South and Central America, and identified the major reason for failure as lack of technical expertise. Several authors note the perception that compost produced from 'garbage' is not clean enough for use on food crops which may explain why vermicompost (produced from worms feeding exclusively on food waste) has been more successful in some regions (CalRecovery and UNEP, 2005). Problems with composting in developing countries include: a) failure to achieve a high quality product due to lack of source separation and subsequent contamination of compost with, e.g., heavy metals; b) over-emphasis on mechanized processes rather than labor intensive operations; c) lack of expertise in biological process requirements; d) lack of markets for compost (expectations often involve municipalities as the major consumer of the product); e) dearth of companies willing to operate facilities due to risk of failure and/or low return; and f) problems with transporting organics to facilities (World Bank, 1999b). Another possible explanation is that more income can be made by private companies in collecting and transporting MSW to landfills and dumps than in composting. The World Bank (1999b) identifies what they term 'perverse incentives', e.g., government funding may subsidize the purchase of chemical fertilizers rather than support composting, or emphasize capital intensive projects where less costly, labor-intensive facilities may be more appropriate and sustainable. Financial barriers to success include difficulties in securing financing since the revenue generated by compost sales rarely covers costs. Some researchers claim that composting will never pay entirely for itself and should be considered a cost-reduction strategy rather than as an income producer. However, waste is dumped freely in many countries such that composting may represent a new cost. The reality of limited funds, especially in poor countries, suggests that successful composting efforts will have to produce some income although subsidies will most likely be required to maintain programs. A consistent theme in the waste literature is that large-scale composting facilities, requiring mechanization, have not been successful in cities of developing countries and that future efforts are likely to take the form of smaller efforts, organized by NGOs and community groups.

2.4.3 Thermal treatments

The Tanner Triangle (Figure 1) is used for rapid, initial assessments of waste combustibility. The shaded area in Figure 1 indicates the limits for combustibles, moisture and ash (inerts) within which materials can burn without auxiliary fuel. While organics are not explicitly assessed in the method, moisture is a reasonable indicator of organic content.

Thermal treatment of solid wastes can involve simple burning of waste that is notoriously difficult to quantify. Set and accidental fires occur in backyards, streets and dump sites. Because the fuel is usually mixed waste, temperatures are relatively low, combustion is incomplete, and pollutants such as black carbon, NOx, CO and toxics are released from these fires. Planned thermal treatment, with the combined goal of reducing waste and producing energy, comprises incineration, pyrolysis, and gasification, each of which operate at different temperatures and produce different types of byproducts.

The optimal feedstock for incineration with energy recovery (Waste-to-Energy) is materials of high calorific value such as plastics and paper (Table 6) (Staley and Barlaz, 2009); the process occurs at 750-1000˚C and energy recovery takes the form of steam, heat or electricity.

Alternatively, mass incineration plants are designed for mixed waste feedstocks with no pre-treatment or sorting and thus require auxiliary fuel to operate. The minimum weighted calorific value for waste to burn without supporting fuel is

~3400 kcal/kg waste. Table 4 shows representative calorific values for individual fuels (Staley and Barlaz, 2009). Food waste is lowest at ~1300 kcal/kg whereas plastics are all 5000->9000 kcal/kg. Ranges for calorific values for municipal solid waste exhibit an interesting pattern before and after recycling. Values at the low end of the range rise after recycling, probably reflecting the removal of low CV inerts like glass and metal. However, the upper value declines with recycling, reflecting removal of high CV materials such as plastics and cardboard.

Pyrolysis, or indirect gasification, involves heating materials in an anaerobic environment to produce solid, liquid or gaseous fuels. Conventional or slow pyrolysis is most often used in charcoal production, and produces solid, liquid and gaseous fuels in approximately equal amounts. Fast pyrolysis (thermolysis) requires rapid heating of biomass feedstock to high temperatures in the absence of oxygen

Contained incineration of waste with energy recovery is extremely rare in developing countries with the exception of China which now has >100 waste-to-energy plants. Reasons include very high capital and maintenance costs, high organic and moisture content of waste, and dependence on foreign suppliers for construction, replacement parts and expertise. Another obstacle is poor quality of the infrastructure that is required to guarantee usable feedstock and its delivery. High organics and high moisture, together with current weakness in source separation, mean that WtE plants are only economically and technically feasible in wealthier and economically growing regions.

China is atypical in the waste-to-energy arena. Extremely high economic growth rates in China over the last few decades has produced massive growth of cities, competition for peri-urban space, and increased per capita consumption of products (and waste generation). These trends conflate to produce wealth to pay for expensive incineration technology and production of enormous amounts of MSW requiring disposal. While this trend is likely to continue in China, and some fast-growing cities in India may take a similar route, is it highly unlikely that the number of waste-to-energy plants in developing countries will rise rapidly in coming decades.

2.4.4 Anaerobic digestion

The series of stages in anaerobic digestion (AD) converts organic material (most often sewage sludge but also organics from the solid waste stream) into biogas (methane and CO_2), digestate, and water. Anaerobic digestion has been promoted primarily as a supplier of fuel and secondarily as a waste-management option. While systems can be relatively simple (i.e., single-stage digestion), they still require, at a minimum, dedicated equipment, temperature control, and pre-treatment of the feedstock (shredding, pulping etc.). Small-scale, domestic anaerobic digestion has been introduced in China in part because China has a long history of domestic maintenance of biogas pits but the cost and need for substantial feedstock indicates that this anaerobic digestion will not experience major growth in developing countries, and will likely continue to be used to process manure from industrial farms and sludge from wastewater treatment. UN Habitat (2010) refers to the spread of biodigesters in developing countries, except for China, India, Bangladesh and Nepal, as 'disappointing' noting many of the same problems that plague composting efforts: poor quality of feedstock, low temperatures, and lack of technical competence and of incentives. The report also highlights that large AD systems (such as those used on commercial dairy farms) have been the focus of research but minimal attention has been devoted to small digesters that are the only likely candidates for large scale use in the developing world. As with composting, the ecological process is relatively simple, as are management requirements, but systems must maintain these fundamental requirements to succeed in producing fuel. Again similar to composting, large centralized AD facilities require costly mechanization as well as separation and transport of appropriate feedstock.

As an option to dispose of organic waste and produce a needed product (methane fuel in this case), anaerobic digestion may be considered as an alternative or addition to composting. However, it is less likely that AD will be implemented more widely than composting: there is less tradition supporting the technique than with composting, and technical requirements (equipment and management) are more difficult to achieve (UN Habitat, 2010).

2.4.5 Landfills and dumps

Waste disposal in developing countries (especially in cities) is overwhelmingly in open, peri-urban dumps even when regulations require construction and maintenance of landfills. Dumps are located convenient to collection vehicles and often pose environmental and health risks to resources and to residents living nearby or in the dumps. Disposal sites are not lined, allowing leachate to contaminate soil and water. Lack of security at sites permits uncontrolled dumping of toxic and other materials. In contrast to sanitary landfills, compaction and daily covers of clean soil do not accompany trash placement. Waste pickers are a common feature at dumps and landfills in developing countries and their activities depend on the composition of waste arriving at the landfill and prices for recyclables. Substantial, although mostly unquantified, diversion of products via recycling and reuse occurs prior to disposal at dumpsites and landfills.

Methane capture at landfills with installed equipment is usually not enabled until cells are closed and capped but sloping edges of cells are sometimes uncovered until final capping of the landfill. Consequently, capture efficiency can reflect either instantaneous rates or the rate over the lifetime of the landfill, the latter being much lower than the former. Moreover, biogas capture efficiency at engineered landfills is not a simple measurement but rather is calculated as the difference between methane generation (modeled or estimated) and the sum of gas captured (measured), oxidized (estimated or modeled) and emitted (estimated or modeled). Kohler et al. (2011) reports instantaneous capture rates of 50-75% for the UK, suggesting that reported rates as high as 85% can only be achieved at closed facilities with very low pipe leakage, and lifetime rates of 60-70% might be possible but only at landfills with very stringent controls. They conclude that 50% may be more representative of instantaneous efficiency and 25% for lifetime efficiency. These capture rates are similar to those measured by Amini and Reinhart (2011) for closed and active landfills. Dever et al. (2011) used several methods to derive capture efficiency at an Australian landfill. The uncalibrated IPCC first order decay (FOD) model resulted in CH_4 generation that was less than CH_4 capture measured at the site but a site-specific calibration of the model indicated that instantaneous capture efficiency could be quite high (~85%) and that emission accounted for ~20% of generated methane. However, the high data requirements, as well as site calibration of the FOD model, seriously limit its application to many sanitary landfills in developed countries, and make it impossible to use for uncontrolled dump sites everywhere else.

2.5 Integrated management

As demand and production costs rise for valuable and/or increasingly rare materials (e.g., metals and rare earths), reclamation of these products is being formalized at disposal sites in developing countries.

Many countries and cities are attempting to upgrade existing dump sites to control waste input, institute leachate treatment, and provide facilities for composting, recycling, and reclamation. These approaches are often quasi-local efforts meaning that they are likely to continue in spite of political changes that threaten government-funded projects. They are also likely to provide more jobs than more mechanized or high-technology approaches.

The literature indicates that similar waste management plans and practices are arising internally in developing countries. These include: 1) less reliance on high-tech and expensive projects funded and built by foreign countries and banks like the World Bank or European Investment Bank. 2) developing strategies to manage, upgrade and control existing open dumps including compaction, leachate collection, onsite recycling, composting and legitimization and integration of traditional informal waste pickers into management systems, 3) encouragement of source separation to achieve a high-quality organic stream for composting; 4) moving toward community management of composting and recycling (cities) and working toward locally controlled systems with costs and management shared by multiple towns (rural areas).

3. Processes and dynamics of methane emission from solid waste

3.1 Methodology - how are estimates done?

Early estimates of emission from landfills ranged from 7-70 Tg CH_4/yr based on a very sparse data set of measured or estimated national solid waste generation, fractions of MSW landfilled and anaerobically landfilled, DOC content, fraction of DOC and methane content of the landfill biogas.

The IPCC (1996) proposed methodologies to estimate emissions from multiple sources of methane and other climate-relevant constituents. The following is the approach for estimating methane emission from solid waste.

Methane emitted (Tg) = $\{[MSW_t * MSW_f * MC_f * DOC * DOC_f * F * (16/12)] - R\} * (1- OX)$ (1)

where:

MSW_t = total municipal solid waste generated (Tg)
MSW_f = fraction MSW disposed in engineered landfill
MC_f = CH_4 correction factor (fraction MSW decomposing anaerobically); default = 0.4-1.0
DOC = fraction biodegradable organic carbon in MSW (defaults = 10-15% dry weight)
DOC_f = fraction DOC dissimilated to CH_4 or CO_2 (default = 0.77)
F = CH_4 fraction of landfill gas (default = 0.5)
R = recovered CH_4 via active extraction (Tg/yr)
OX = methanotrophic oxidation factor (fraction); default = 0

IPCC (1996) provides default values for variables if country-specific information is not available. Overall, emissions estimated with this methodology show a high bias due to high rates of waste generation, landfilling and anaerobic landfilling, and assuming that waste generated is collected and disposed of. For example, default landfilling rates were ~60% for Asian countries (IPCC, 1996). These values, combined with high estimates of the fraction of landfilled waste disposed of under anaerobic conditions (~40% for most countries), results in anaerobic landfilled waste equal to 24% for Asian developing countries. Table 3 (waste disposition) shows that assumptions of landfilling and anaerobic landfilling rates in the IPCC method are not consistent with field observations and produce a high bias in methane production and emission. The method also implicitly assumes that generated waste is collected and disposed of at landfills, further introducing a high bias in estimated emissions. Carrying out the full set of calculations, from waste generation through methane emission, using the IPCC method and defaults produces emissions (~33 Tg CH_4 /yr) very similar to those reported by others who rely on the method confirming quantitatively the high bias in the method and defaults.

The work of Bogner and Matthews (2003) relied on a modified version of this methodology as follows:

$$\text{Methane emitted (Tg)} = \{[MSW_t * MSW_f * MC_f * DOC * DOC_f * F * (16/12)] - R\} * (1- OX) \quad (2)$$

where:

MSW_t = total municipal solid waste generated

DOC_t = dissimilated fraction DOC in MSW reduced from 0.77 (default) to 0.5

OX = methanotrophic oxidation factor increased from 0 (default) to 0.1

The major difference in this approach relates to MSW generation; defaults for per capita waste-generation are replaced with the proxy of per capita energy consumption. This approach, together with reducing the fraction of dissimilated DOC from 0.77 to 0.5 and accounting for methane oxidation in the landfill cover, lowers the global estimate of methane emission by >50%. Matthews and Themelis (2007) employed this proxy approach to explore the impact of recycling and waste-to-energy efforts on reducing emission from solid waste for the period 2000-2030. The study incorporates estimates for MSW recycled (14% of total MSW generated) and MSW treated in WtE plants (4 Tg) for the start year of 2000); DOC content was set to 0.3 for all countries. Note that we now consider that this recycling rate is an overestimate but has modest influence on emission results. However, assumed DOC content is also considered an overestimate with a substantial impact on emission estimates. I.e., emissions are likely lower than reported by Matthews and Themelis (2007).

3.2 Projections of solid waste and methane emission

Figure 3 shows five global projections of methane emission from municipal solid waste (MSW) illustrating some of the range and uncertainty in global estimates of emissions for current and future periods. Emissions in 2000 vary by factor of four. The Environmental Protection Agency's estimates (EPA-REF06 and REF11) reflect primarily the IPCC Tier I methodology with high rates of waste generation, landfilling, and anaerobic landfilling resulting in high methane production and emission (EPA, 2006, 2011). Baseline (Current Legislation) emissions from the GAINS model (GAINS-CLE) developed at the International Institute for Applied Systems Analysis (IIASA) (Hoglund-Isaksson, 2012) start in 2005 and are similar to EPA. The highest (RCP-8.5) emission scenario from the IPCC's Representative Concentration Pathways (RCP) (Moss et al. 2010) totals ~40 Tg in 2000.

The GISS-REF result relies on most of the modifications discussed above, e.g., lower per capita MSW generation rates derived from a per capita energy consumption proxy, as well as lower landfilling and anaerobic landfilling rates based on regional data, and lower efficiencies for landfill gas capture.

Relevant populations (urban populations for developing countries and total populations for developed countries) rise ~35% between 2000 and 2030 suggesting that unabated emissions could rise a minimum of ~35% solely in response to population dynamics. However, CH_4 increases of >35% can be expected due to, e.g., faster growth of urban vs. total populations and rising landfilling rates whereas future emissions could be moderated by other management practices such as declining per capita waste generation and diversion of organic waste to composting.

The numerous variables influencing solid-waste methane emission, along with poor transparency for some projections, make comparing causes for different trends difficult. However, the flat EPA06- and EPA11-REF trajectories, rising 9% and 19%, respectively, in response to 25% larger population by 2020 and 35% larger by 2030, are difficult to explain without invoking mitigation measures that are not documented; legislative impacts are not included in this inventory approach and thus do not contribute to trends.
GAINS-CLE shows modest growth of 11% which amounts to 4 Tg CH_4 more annually by 2030. The GAINS-CLE trajectory is somewhat predictable because these CLE scenarios account for legislation that acts to reduce emissions, although is not designed to do so. GISS-REF rises by 120%. However the low initial 2000 value of ~10 Tg in GISS-REF means that this large relative increase only brings the global emission total to ~22 Tg CH_4 in 2030.

Current methane emissions from landfills are likely closer to 10 Tg CH_4/yr than to 35 Tg as reported in most studies relying on IPCC-based methodology. While developing countries will account for the majority of population growth in coming decades, including disproportionate growth of urban populations, methane emission from solid-waste management is not likely to grow at the high rates exhibited by projected trends in population and economic growth. There are reasons to support the hypothesis that developing countries are on a different trajectory than that historically followed by industrialized countries i.e., almost complete reliance on landfilling of waste, followed by conversion to incineration. Reasons include:

- Developing countries have well-established cultures (and increasing need) of recycling, reuse and recovery.
- Rapid growth of large cities is competing for peri-urban space where waste has historically been deposited and where new housing is needed.
- Chronic lack of funds for waste management and other services in poor countries, together with space limitations, suggests that constructing methane-producing sanitary landfills will not be the primary solution to managing municipal waste.
- High organic content (50-80%) of waste in developing countries, together with emerging plans for source separation and collection of waste, suggests that the role of aerobic composting will rise in coming decades if problems of marketability, product quality and source separation can be solved.
- Reduction of the amount of waste requiring disposal at dumps or landfills—particularly of organics that contribute most to methane production and emission—represents a decoupling of landfilling and methane emission from population and economic growth.
- Low current methane emissions from waste disposal, together with future modest trends outlined here, imply that mitigation of waste-related CH_4 emission, including Clean Development Mechanism (CDM) projects, is a weak candidate for limiting climate change.

The GISS-REF scenario reflects a plausible trajectory for solid waste generation and management and associated methane emission. The results rely largely on the modifications discussed above. However, DOC contents were lowered from

30% (Matthews and Themelis, 2007) to those used by Bogner and Matthews (2003) (15-20% of waste on a dry weight basis) after confirming these lower values from observations of waste composition and water content. Note that waste composition reported in Table 1 is on a wet weight basis; converting to dry weight reduces carbon contents by about 50%.) Additional assumptions include gradual increases in landfilling rates for developing countries.

Three projections investigating the potential for mitigating future emissions through more aggressive incineration and composting practices were developed in relation to the GISS REF estimate:

MIT1-I (incineration): REF + incineration prescribed at 1% of generated waste for all developing countries in 2015 and evolving at +1%/yr of waste generated afterward
MIT2-C (compost): REF + composting prescribed at 1% of DOC for all countries in 2010, evolving at +1.5% DOC/yr afterward
MIT3-I+C: REF + MIT1-I + MIT2-C

Global results are shown here although calculations were carried out for each country and year. For context, 2000 values are: MSW production, 887 Tg; DOC production, 133 Tg; CH_4 production, 16 Tg; CH_4 capture, 4 Tg; CH_4 oxidation in the landfill cover, 2 Tg; and CH_4 emitted, 10 Tg. MSW and DOC production are constant for all scenarios.

Figure 3 compares GISS 2030 REF and MIT results, relative to 2000, grouped by variable; Figure 4 shows 2030 results, relative to 2000, grouped by projection, to better illustrate the dynamics generated by projection assumptions; Table 7 summarizes these relative results; Table 8 summarizes 2030 results in Tg for all but MIT projections which are shown as percentage change relative to 2030 REF. While relative results highlight interrelationships among variables and scenarios, absolute values, especially of methane produced, emitted and mitigated, govern the impact of scenarios on climate-chemistry interactions and may guide policy decisions regarding the effectiveness of alternative mitigation options.

In the reference case, landfilled DOC (Fig. 3, Table 7) rises faster than landfilled MSW because landfilling is assumed to increase modestly over time for most developing countries. Incineration (MIT1-I) exerts a larger impact on MSW landfilled than does composting (MIT2-C) but this relationship is reversed for methane-relevant variables because composting preferentially diverts only organic waste from the waste stream. DOC landfilled (including anaerobically) and CH_4 produced and emitted in 2030 for MIT1-I are all ~14% below 2030 REF whereas MIT2-C lowers each of these values by ~34% compared to REF in 2030. Implementing both incineration and composting (MIT3-I+C) mitigation strategies reduces DOC landfilled and CH_4 produced and emitted by ~43%. While the mitigation projections show large relative impacts on methane capture (Fig. 3, Table 7), the absolute amounts are small (Table 8).

MSW production in 2030 is 110% above that in 2000 for all projections and DOC produced is ~92% higher. Incineration in the reference case almost triples between 2000 and 2030, rising from 40 to 119 Tg due gradual increases in countries already incinerating waste in 2000. By 2030, methane production in the reference case is 31.7 Tg, slightly more than twice that in 2000, but a slower increase in methane capture results in REF emission ~2.2 times that in 2000 (22 Tg vs. 10 Tg CH_4/yr).

In MIT1-I, incineration removes waste from the stream destined for landfilling, thereby reducing 2030 landfilled DOC by 14% compared to REF (Fig. 4, Tables 7 and 8). This diversion provides less substrate for methane production and thus less CH_4 for capture and emission. MIT-I methane capture rises 46% by 2030, slightly below the 61% rise in REF. MIT1-I emission rises 90% above the 10.1 Tg CH_4 emission in 2000, representing 14% mitigation of 2030 REF emission (19.2 vs. 22.3 Tg CH_4).

The introduction of composting (MIT2-C) exerts major impacts on all processes in the methane estimate by preferentially removing organic material from the waste stream. Although the reduction in landfilled waste is only 5% and smaller than the 15% decline in MIT1-I (Table 7), this plausible expansion of composting reduces methane emission by 34% compared to REF in 2030, primarily by lowering landfilled DOC through, diversion of organics (Fig. 4, Table 8).

Despite the large relative rise (120%) in REF emission over the 30 year period, this increase represents only ~12 Tg CH_4/yr and total baseline emission from this study in 2030 remains below emissions reported for 2000 by others, highlighting the importance of reliable initial-year emission values (Fig. 1). Similarly, the substantial mitigation of 43% in 2030 emissions, achieved through implementing both incineration and composting strategies, amounts to <20 Tg CH_4/yr.

The incineration and composting mitigation projections presented here (MIT1-Iand MIT2-C) are designed to reflect plausible strategies, i.e., assuming low initial, and gradually rising, rates of implementation, unlike most scenarios that assume near complete adoption of mitigation technologies in all countries (EPA, 2006b; UNEP, 2011a,b; Hoglund-Isaksson, 2012).

4. Comparison to existing methodologies and data, and implications for methane emissions

The results and data compilations from this study are compared to current methods and defaults used to estimate methane emissions from solid waste (IPCC and EPA) and to waste-related data relevant to estimating methane and other emissions (Hoornweg and Bhada-Tata, 2012). As discussed above, current global methane emissions, including those of IPCC, EPA and IIASA, are ~35 Tg CH_4/yr whereas our recent estimate is ~10 CH_4/yr; differences in future emissions are also substantial in trend and absolute amounts. Causes for these differences are attributable to differences in underlying data, default values and, to some extent, methodology among the studies.

Equations 1 and 2 assume oxidation of methane in landfill cover materials of 0% and 10%, respectively. The latter, from a single study of a New Hampshire landfill (Czepial et al., 1996), remains the IPCC standard. Subsequent laboratory and field measurements of oxidation rates in cover soils confirm the occurrence of higher oxidation rates that vary with cover type, season (temperature) and moisture (e.g., Boeckx and Van Cleemput, 1996; Chanton et al., 2009; Spokas et al., 2012). Chanton et al. (2009) reviewed oxidation rates in landfill cover soils from 72 studies. A subset of 15 extending over a full annual cycle displays a range of oxidation rates from 11 to 89%, with a mean of 35%; only 4 of 72 studies reported methane oxidation rates of 10% or less suggesting that the 10% IPCC default contributes to overestimates of emission. It is important to note that applying more realistic oxidation rates would lower estimated emissions only from managed landfills, which occur overwhelmingly in developed countries. However, IPCC (1996) landfilling defaults (and thus emissions) are likely overestimated for many developing countries and the 10% oxidation default further contributes to the high bias in emissions for these countries.

Table 1 lists waste-composition data for a wide variety of countries and cities compiled as part of this study; Table 9 lists regional IPCC default values for waste composition from IPCC's Good Practices (2000). (Note that Table 9 is missing many values requiring caution when applying the numbers. Percentages for half the 19 regions in the table sum to <90%, which may underestimate emission if the missing values are not filled in to total 100%.) Despite variability in the observations, differences between the data compilation and IPCC default values are evident. The most important difference with relevance for methane estimates is that IPCC default fractions for food waste (Table 9) are substantially lower than waste studies indicate (Table 1). For example, IPCC proposes default food fractions for Asia from 26% to 40% whereas observed fractions are higher (~45% to 82%), barely overlapping with the IPCC range. Similarly, except for South Africa, IPCC food defaults for African regions are 40-54% whereas most studies report values of 50-95%. For Europe and the US, IPCC values are similar to those in Table 1 whereas South and Central American IPCC values for food appear to be somewhat low. Paper and cardboard is the second most important waste component influencing methane emission. Differences between IPCC defaults and the new data compilation are less pronounced although these composition data are more variable than those for food, making comparisons difficult. However, IPCC defaults appear to be higher than the data for most of Asia while more closely resembling the field reports for developed Asian countries and cities. Taken alone, low IPCC defaults for food waste underestimate methane emissions from solid waste. This low bias may be modesty offset if default paper fractions are overestimated for some regions.

The low food/organic default fractions from IPCC (2000) are more than offset by high default rates for landfilling. These rates are major contributors to high current and future estimates of methane emissions from waste from studies following IPCC methods, including those by EPA and by UNFCCC when estimating emissions for countries that do not submit their own reports. As noted, IPCC methods do not explicitly account for collection rates, which are substantially <100% of generated waste according to field measurements and estimates (Table 2). However, IPCC (1996) includes implicit collection efficiency in the form of landfilling rates. The latest IPCC (2006) guidelines dispense with landfilling rates, and indirectly address collection rates via defaults for proportion of waste disposed of in SWDSs. As in the 1996 guidelines, uncollected waste then drops out of the calculation. More importantly, non-specific disposal information—i.e., SWDS—does not facilitate applying methane-correction factors in an informed way.

Hoglund-Isaksson (2012) reported methane emissions from the GAINS model for all anthropogenic methane sources for a baseline scenario - referred to as Current Legislation (CLE) - and a mitigation scenario (Maximum Feasible Reduction (MFR)). GAINS-CLE emissions for MSW are shown in Fig. 2. This CLE scenario is not strictly comparable to other inventory-based results such as those of GISS and EPA because legislation exerts a considerable influence to lower emissions although the purpose is not mitigation. For MSW, emissions with legislative effects are ~30% lower than the non-legislation case; technological mitigation further reduces 2030 CLE emissions by 85%.

Data are currently lacking to characterize the extent of anaerobicity in dump sites. Nevertheless, it is anticipated that further data analysis will confirm that defaults for DOC decomposing under anaerobic conditions in unmanaged dumpsites are overestimates in IPCC methods. IPCC's high anaerobic landfilling rates, in combination with high methane potential of the waste, are the dominant controllers of the high bias in methane emissions resulting from IPCC-based estimates.

Composting, open burning and waste-to-energy presumably account for the difference between generated and landfilled waste although these disposal mechanisms were not explicitly addressed in IPCC (1996). While waste diverted to WtE plants may be reasonably well quantified and is included in the 2006 methodology, the extent of informal composting and open burning is highly uncertain and poorly documented. Although IPCC landfilling rates indirectly 'subtract' some waste from that destined for landfills (landfilling rates <100%), the fate of this waste remains unaddressed despite the fact that some guidance is given for emissions if these data are available. The consequence of dropping this waste fraction from the calculation is to underestimate the waste disposed of via informal and/or spontaneous open burning, and perhaps via informal composting. Informal burning produces little methane but emits other air pollutants including black carbon that have known negative impacts on both climate and human health (UNEP, 2011a). It is critical to deal explicitly with this unaccounted-for waste disposal in order to reduce uncertainties associated with methane emissions and emissions of other pollutants generated from burning.

Hoornweg and Bhada-Tata (2012) recently published *What a Waste: Waste - A Global Review of Solid Waste Management* which may be used to estimate methane and other emissions from waste although the report's focus is on planning for integrated waste management. They compiled data from a several large data sets (PAHO, OECD, and UN). The authors applied information on per capita waste generation to population statistics to estimate total waste produced, collected and disposed of for the current period; projections of population and increases in per capita waste generation were used to estimate waste in 2025. Hoornweg and Bhada-Tata (2012) stratified the country/city data with World Bank's income classification to report typical values for variables by income and region. A preliminary comparison of Hoornweg and Bhada-Tata's country lists and underlying data sets against the data compiled for this report (Tables 1, 2, 3) reveals several patterns. Some of the same data sources were used in both reports but there was less source overlap than expected:

- Food-waste fractions from Hoornweg and Bhada-Tata (2012) are higher than the low defaults from IPCC (2000) (Table 9) and appear to be modestly lower than those in Table 1 which might introduce a low bias into methane-emission estimates if these data are used.
- Waste-collection rates from Hoornweg and Bhada-Tata (2012) are generally similar to those listed in Table 2; the impact of explicitly including waste-collection rates in methane estimates has not yet been investigated; while the fate of uncollected waste will determine whether emission is higher or lower by accounting for this waste amount, the most likely impact of integrating collection data would be to lower emission estimates.
- Disposal sites are classed into landfills and dumps by Hoornweg and Bhada-Tata (2012), which is of more practical use than IPCC's generic SWDS, as well as being relevant for waste planning. However, this distinction does not provide sufficient information about disposal to improve estimates methane emission from solid waste. Table 3 distinguishes among sanitary landfills, controlled landfills and dumps, and open dumps which is of direct relevance to methane studies. Identifying the prevalence of sanitary landfilling as a disposal strategy is important for estimating methane emissions, whereas characterizing depth and anaerobicity of controlled landfills/dumps and of open dumps is more difficult but also critical for emissions.

5. Missing Links and Reducing Uncertainties

5.1 Missing links between waste studies and modeling studies

The lack of connection between waste studies and 1) inventory methods, 2) integrated assessment modeling and 3) climate-chemistry modeling is remarkable and curious (IPCC, 1996, 2000, 2006; Nakicenovic et al., 2000; Monni et al., 2006; EPA, 2006a,b; Bahor et al., 2009; Lamarque et al., 2010; UNEP, 2010c, 2011a, b). This problem is particularly obvious in studies investigating future climate, health and other impacts of emissions and mitigation technologies (UNEP, 2011a) that rely on a list of mitigation technologies proposed more than a decade ago (EPA, 1999).

The reasons for this lack of connection are unclear. For example, UNEP's waste report (2010c) states that "reliable data is costly and time-consuming to obtain. For these reasons, the IPCC provides a set of default values, which can be used where data is unavailable to calculate national GHG emissions from landfill." However, the origin of the IPCC defaults is obscure, and UNEP offers no assessment of the IPCC defaults or of their impact on estimated methane emission. While acknowledging that the international literature linking waste and climate change focuses largely on developed countries, the report attributes this to a lack of data on waste streams and management for developing countries, a conclusion inconsistent with data reported here and elsewhere. The problem does not seem to be that data are unavailable but rather that the extensive array of waste publications is ignored. UNEP (2010c) also states that the assumed rate of landfill gas capture is a key parameter in estimating methane emissions whereas the present study identifies alternate assumptions and data, including waste composition, disposal, and landfilling rates, as most critical to global methane emission from solid waste; assumed capture rate is not a major determinant since most countries do not have landfills and even fewer have gas capture in place.

The massive literature on all aspects of waste is dominated by studies that assess current conditions in order to develop plans for integrated solid-waste management; they report on waste composition, collection, and disposal along with cultural, institutional, financial and regulatory influences on conditions and practices associated with solid waste, and propose practical solutions to recognized problems. In contrast, the majority of inventory methods and projections/scenarios of emissions (IPCC, 1996, 2000, 2006; Nakicenovic et al., 2000; EPA, 2006a; Moss et al., 2010; Hoglund-Isaksson, 2012) rarely refer to this literature. This historical pattern continues for the next IPCC assessment report (AR5), which relies on very aggregated emission scenarios (RCPs) (Moss et al., 2010; Lamarque et al., 2010) from updated versions of the integrated assessment models that provided emissions in 2000 (Nakicenovic et al., 2000). Further complicating matters is the lack of transparency typically surrounding emission estimates, making it difficult to determine specifics about assumptions and technologies that drive baseline and mitigation projections, and consequently to interpret results of the climate-chemistry studies based on these emissions. The RCP projections are almost completely lacking in transparency whereas the recent work of Hoglund-Isaksson (2012) offers comprehensive information on data sources, underlying data, assumptions, emission factors etc.

For reasons discussed above, estimates of methane emission from solid waste based on the commonly-used IPCC methodology, are high— perhaps 2-3 times actual values for the contemporary period (Figure 1). Mitigation projections reported in the literature also probably overestimate abatement potential by assuming almost universal adoption, and substantial reduction potential, of implemented technologies (EPA, 2006b; Hoglund-Isaksson, 2012). The present study, designed to represent plausible trajectories for baseline and mitigated emissions, reports much lower current emission and less dramatic abatement potential in 2030.

Development of policies aimed at mitigation of emissions from solid waste crucially depends on the reliability of both the magnitude of future methane emission (i.e., is the source large enough to warrant mitigation?) and plausible abatement of emission (i.e., is it possible to implement policies widely enough to plausibly reduce emission from the source?). While providing a wide range of possible emission futures for climate-chemistry studies is of scientific value, wide emission ranges do not provide the information necessary to make policy decisions. Similarly, the standard approach of assuming near-universal adoption of abatement technologies to define maximum mitigation potential has little relevance when policies must be considered for implementation in real circumstances. For example, exploring the impact of landfill-gas capture as a methane-mitigation strategy is largely irrelevant in light of the documented ubiquity of uncontrolled waste dumping together with the likelihood that landfills will not be a primary disposal strategy for solid waste in coming decades.

The consequence of the gulf between waste studies and modeling studies is that projections/scenarios, and the studies that rely on them, may fail to realistically reflect solid-waste conditions and processes thus failing to address plausible approaches to projecting future baseline and mitigation emissions of methane and other climate-relevant constituents. The problem is not lack of data *per se*; large amounts of data are available albeit much remains in dispersed form and data reliability remains a challenge in improving estimates of methane emission from solid waste. However, a willingness to cross disciplinary barriers will speed progress in improving the reliability, and reducing the uncertainties, inherent in quantifying the role of solid waste in biogeochemical and climate dynamics.

5.2 Reducing uncertainties

5.2.1 Fires

Fires in dumps and other uncontrolled environments occur for several reasons. Some accidentally ignite while others are purposely set in dumps and elsewhere. Once ignited, fires in dumps deep enough to produce methane are fueled not just by the waste but also by methane migrating from below. Methane is explosive in concentrations between 5 and 15% by volume of air so methane in decomposing waste is fuel awaiting a fire. Catastrophic collapses in large dumps, following destabilization by rain (e.g., Payatas and Smokey Mountain in the Philippines), bury homes and agricultural fields killing hundreds maybe thousands of people in and near the dumps. Spontaneous fires, fueled by methane migration in deep dumpsites, can erupt when landsides release pressure and thus cause further destruction following the collapses.

Many studies anecdotally note fire as a waste management tool (Table 3) although quantification is difficult because of their ubiquitous and small-scale occurrence, especially when informally carried out in communities. Set and spontaneous fires in landfills and dumpsites in developing countries are common, the former to reduce waste volume and retrieve valuable metals, the latter as a consequence of uncontrolled conditions. For example, Smokey Mountain in the Philippines was named for the continuous fires that pollute the environment surrounding the dump. In addition to causing explosions in dumps, fires contribute to the release of an array of other pollutants (i.e., black carbon, CO, mercury) that negatively influence human health and atmospheric chemistry and climate.

How common are fires as a strategy for waste management? What is the role of fires at landfills, dumpsites, and communities? How can we reduce the large uncertainties associated with estimates of amount of waste burned and gases and particles emitted from these fires?

Very briefly outlined here are several approaches that may reduce uncertainties related to waste fires.

1. If dump/landfill locations are established, it may be possible to use selected, high resolution satellite data such as MODIS or Terra to characterize the seasonality and extent of fires at large sites. It may be useful to explore combining these temporal and spatial fire patterns with information on waste composition to estimate emissions from large dumpsite fires surrounding large population centers. It may also be possible to evaluate these estimates through local or regional modeling efforts and additional satellite data on air quality.
2. Another possible approach to reduce the uncertainty in amounts of waste burned informally on small scales (backyards, within cities) is to integrate city data on waste generation and disposal with local waste-collection rates to deduce the uncollected fraction of waste whose fate is unaccounted for and unknown. This amount provides an upper estimate for waste that is informally burned or otherwise disposed of outside of collection systems. This uncollected portion is a nontrivial amount—about 50% in many cities of the developing world—and is not explicitly unaccounted for in inventories of methane and other constituents associated with waste (Table 2). The likely impact of the current methodological gap is an overestimate of landfilled waste, which translates into overestimated emission.

5.2.2 Anaerobicity in uncontrolled landfills and dumps

Dumping in low-lying areas including rivers, riverbanks and 'water bodies' is commonly mentioned in the waste literature. How much waste goes to open dumps that support anaerobic (methane-producing) conditions either because they are deep or they are located in wet areas? How deep are dumps and how prevalent are inundated conditions? How can we explicitly address the world's substantial use of uncontrolled sites for waste disposal and its role in emitting methane?

A large and representative data base on waste composition has been developed for this study but needs augmentation and quality control. Hoornweg and Bhada-Tata (2012) also report on a new data compilation, including waste composition. Although individual numbers may not all be reliable, robust patterns emerge from analysis of the data in Table 1, particularly for the organic (food) waste fraction that constitutes the dominant controller of methane production and emission in most of the world's disposal sites.

Reducing uncertainties may be accomplished via further data mining to better characterize uncontrolled waste-disposal sites to improve estimates of the fraction of waste deposited in anaerobic conditions; existing data sets (OECD, 2008; PAHO, 2005) are not equipped to address this issue. Similar to others, the GISS methodology employs landfilling and anaerobic landfilling rates to estimate the amount of waste in anaerobic conditions in uncontrolled landfills and dumps. Landfilling rates reported in this study (Table 3) are lower than the IPCC defaults (Table 9) but there is little to confirm or reject these lower values without more focused data collection and site characterization. Because the extensive study of Hoornweg and Bhada-Tata (2012) does not distinguish disposal at sanitary, partially controlled and uncontrolled landfills, their data cannot be used to characterize the extent of anaerobic waste disposal in poorly controlled sites.

6. Prospects for solid waste management and methane emissions

As of 1999, no new landfills can be built within the European Union. This legislation was preceded by years of consistent and strong government implementation and facilitation of recycling, composting and reuse programs. For example, he Netherlands landfills only 3% by weight of all waste produced in the country, consisting mostly of ash from incineration. Moreover, bulky products like wood, furniture, and construction and demolition waste, as well as clothing, paper and plastics, are recycled in an industrial ecology model that operates on a quasi-regional scale. Many countries in Eastern Europe, such as the Czech Republic, have a short history of landfills. It is therefore likely that methane emission will continue to decline in Europe

The US continues to landfill a high fraction of waste (~65%) due in part to high consumption of disposable items, excessive packaging, and low recycling rates for paper, plastic, and bulky items like furniture, and C&D waste. The environment for businesses producing and using recycled products is volatile in price and supply although public projects in cities sometimes incorporate recycled building materials. Paper recycling is relatively high but a small fraction of plastics is recycled because many cities recycle only a small faction of plastic materials and because compliance and education are generally poor. Rather than reducing waste, and boosting reuse including recycling and composting, the US has moved toward closing small landfills and establishing regional megafills (Staley and Barlaz, 2009). While many of the small landfills did not capture landfill gas, and therefore probably emitted more methane per unit waste than larger facilities, the regional model requires long-distance transport of waste via rail and truck, adding to greenhouse gas emissions associated with solid-waste management.

Developing countries have a long history of informal recycling and reuse, and few sanitary landfills. Informal sectors continue to play a large role in waste management but rapidly growing megacities, especially in Asia, are straining or overwhelming current systems, and unmanaged and unsorted waste is causing serious health hazards due to toxics, fires in dumps, and water pollution. Despite historical and current pressure from industrialized countries to build sanitary landfills and mechanized composting plants, integrated indigenous systems are emerging in developing countries.

The waste literature discussed here is almost universally focused on integrated waste management plans comprising collection, transport, sorting/separation, and disposal; the latter includes composting, recycling, reuse, materials recovery, landfilling, and leachate capture with treatment or recirculation. Space for controlled landfills is universally limited as is funding for waste management in developing countries.

Unlike the EU and North America, developing countries have many illegal and/or unregulated dumps while managed landfills, including sanitary landfills, are relatively scarce. In order to provide controlled locations for disposal of solid wastes, dumps require upgrading and addition of services such as recycling and composting areas, and leachate capture. For example, the Centro de Tratamento de Resíduos Sólidos (CTRS, Solid Waste Treatment Centre) in Belo Horizonte, Brazil, includes a sanitary landfill, a small materials recovery area and leachate capture and treatment.

Rehabilitation is costly for the large, deep sites that are likely producing methane. Because most dumps in developing countries receive waste from all sectors (residential, industrial, commercial, construction and demolition and hospitals), they represent large mixed reservoirs including toxic and other dangerous constituents such as heavy metals, pathogens, and medical waste. Leachate capture and treatment is essentially nonexistent in existing dumps even when waste disposal is controlled to some extent. Leachate is a long-term problem posing serious risks to soil, ground and surface water, and human health and treatment systems are expensive. An alternative is to capture leachate and re-circulate it into the site's waste, which reduces but does not eliminate pollution risks.

Composting the large fraction of organics in waste of developing countries (Table 1) is the most likely candidate to mitigate waste-related methane emission now and in the future. It would also divert the dominant source of leachate that contaminates soil, and ground and surface water at disposal sites. Composting could also reduce costs associated with waste collection and disposal but only <u>if</u> municipalities are providing these services. However, because illegal dumping is prevalent (Table 3) and inexpensive, implementation of composting programs would represent additional costs if these programs replace open dumping for the disposal of organic waste. For this reason, plans for initiating and/or broadening composting programs in developing countries typically address development of steady markets for the finished product which is not a trivial effort. For example, even in the U.S., where large-scale composting is carried out primarily by municipalities and yields a usable product, the finished compost is usually given away because markets have not materialized.

If composting is further implemented in developing countries, low-cost and low-technology manual composting is most likely to succeed given the historical failure of costly, mechanized plants. While composting is the disposal approach best suited to the waste composition and financial constraints of developing countries, crucial barriers to successful composting must be addressed to ensure success. These include, *inter alia*, the poor quality of input material due to lack of source separation and lack of expertise in the biological and environmental requirements of the composting process.

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8. Appendix

What conditions favor growth of incineration (with or without energy recovery)?

- Large cities:
  - large population requiring housing space (competing for landfill/dump space)
  - sufficient supply of high CV waste to support efficient operation of large plants
- Wealthy cities: can afford high expense of plants
- Countries undergoing rapid economic growth
- China (>100 waste-to-energy plants), some large cities in India; Japan; US

What conditions favor growth of composting?

- High organic waste fraction
- Limited funds for waste management and expensive, high technology solutions
- Land constraints
- Need for soil supplements for agriculture, gardens, etc.
- Abundant labor
- May take form of decentralized plants or larger plants co-located with recycling, materials recovery, and/or landfill
- Most areas in developing countries

What conditions favor growth of landfilling?

- Sufficient land to accommodate limited lifespan (20-30 years) of landfills.
- Disposal of some inerts (e.g., post incineration ash) will always require landfills
- Environmental and health problems associated with uncontrolled dumping
- Landfilling is becoming a last-choice option for waste disposal in integrated waste-management plans

Which management techniques are complementary?

Some components of waste will always require landfilling. These comprise materials such as ash from incineration, and inert, nonreusable/ nonrecyclable materials separated from the waste stream and street sweepings. However, these materials typically constitute small fractions of waste streams.

Waste-to-energy plants require feedstocks with low moisture content and high calorific value, i.e., low organics, high plastic and paper content. Source separation of organics is essential to produce appropriate feedstock for waste-to-energy plants unless they are capable of mass incineration which then requires auxiliary fuel and/or preprocessing such as drying or pressing to remove moisture. Consequently, waste-to-energy and composting could, in principal, be complementary because of their mutually exclusive feedstocks. However, plastics have among the highest calorific values of any potential fuel making them excellent feedstock for waste-to-energy plants at the same time that they are the primary recyclable, by volume, in developing countries. Consequently, expensive waste-to-energy facilities are not likely to be paired (put in competition) with plastics recycling due to prevailing economic conditions. Moreover, large centralized composting plants have proven unsuccessful in most cases outside of Europe. Thus, while feedstock and processing (source separation) also make WtE and composting complementary in principal, the different scales and costs of these waste-management strategies strongly suggest that they will not be widely practiced in concert.

Figure 1. Tanner Triangle for rapid assessment of combustibility. Perimeter of shaded area indicates maximum values for main variables supporting combustion without auxiliary fuel.

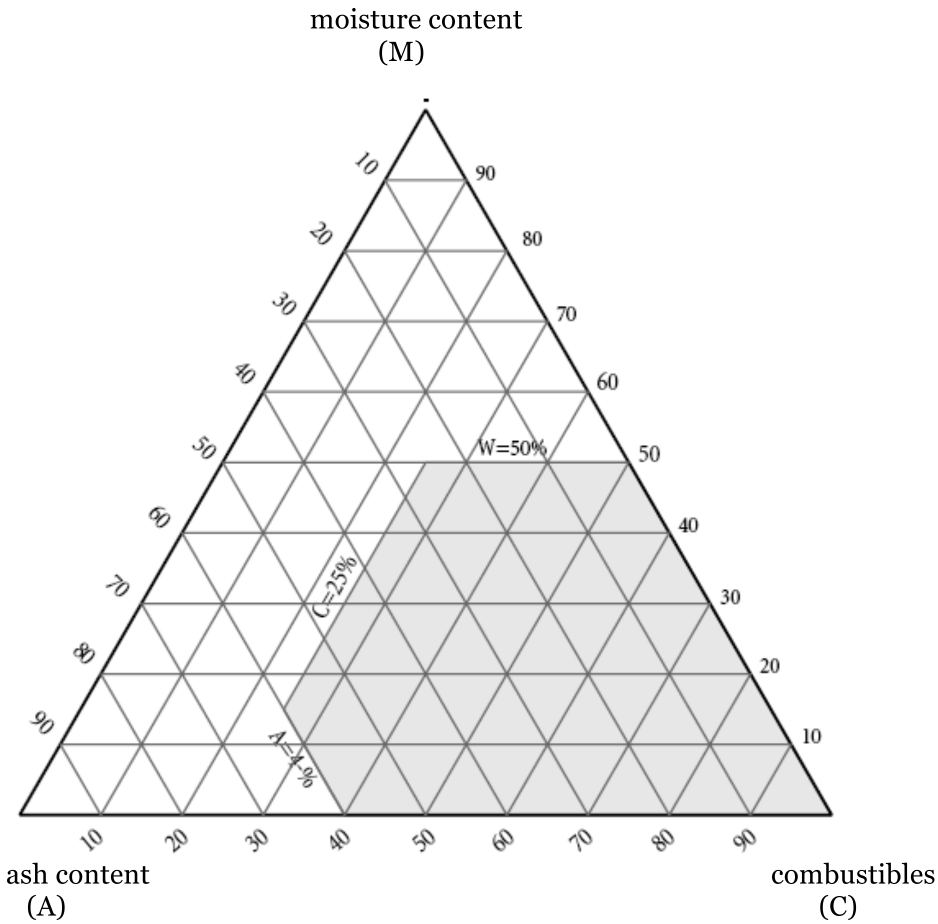
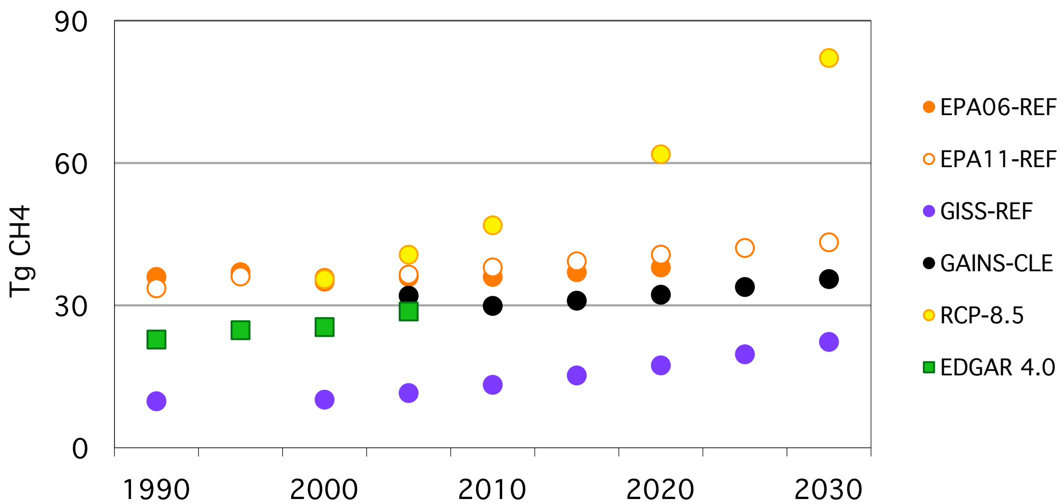


Figure 2. Comparison of reference estimates of methane emission from municipal solid waste, 1990-2030.



References:
EPA06-REF: EPA, 2006
EPA11-REF: EPA, 2011
GISS-REF: this study
GAINS-CLE (current legislation): Hoglund-Isaksson, 2012
RCP-8.5: Riahi et al., 2007
EDGAR: Edgar version 4.0

Figure 3. GISS 2030 results relative to 2000, grouped by variable (2000 = 1). MSW and DOC produced are constant in all cases.

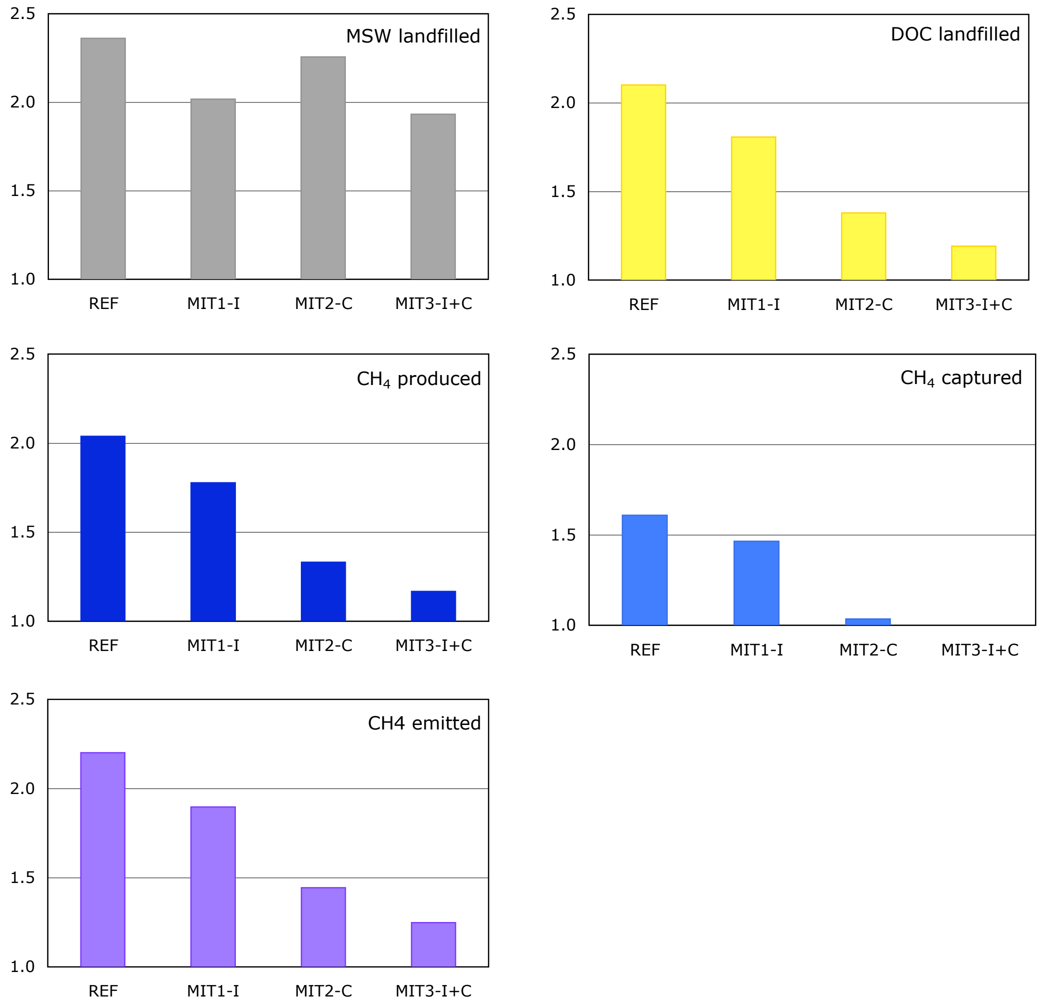


Figure 4. GISS 2030 results relative to 2000, grouped by projection (2000 = 1).
Growth in MSW Incineration is 9.16 for MIT1 and 8.74 in MIT3.

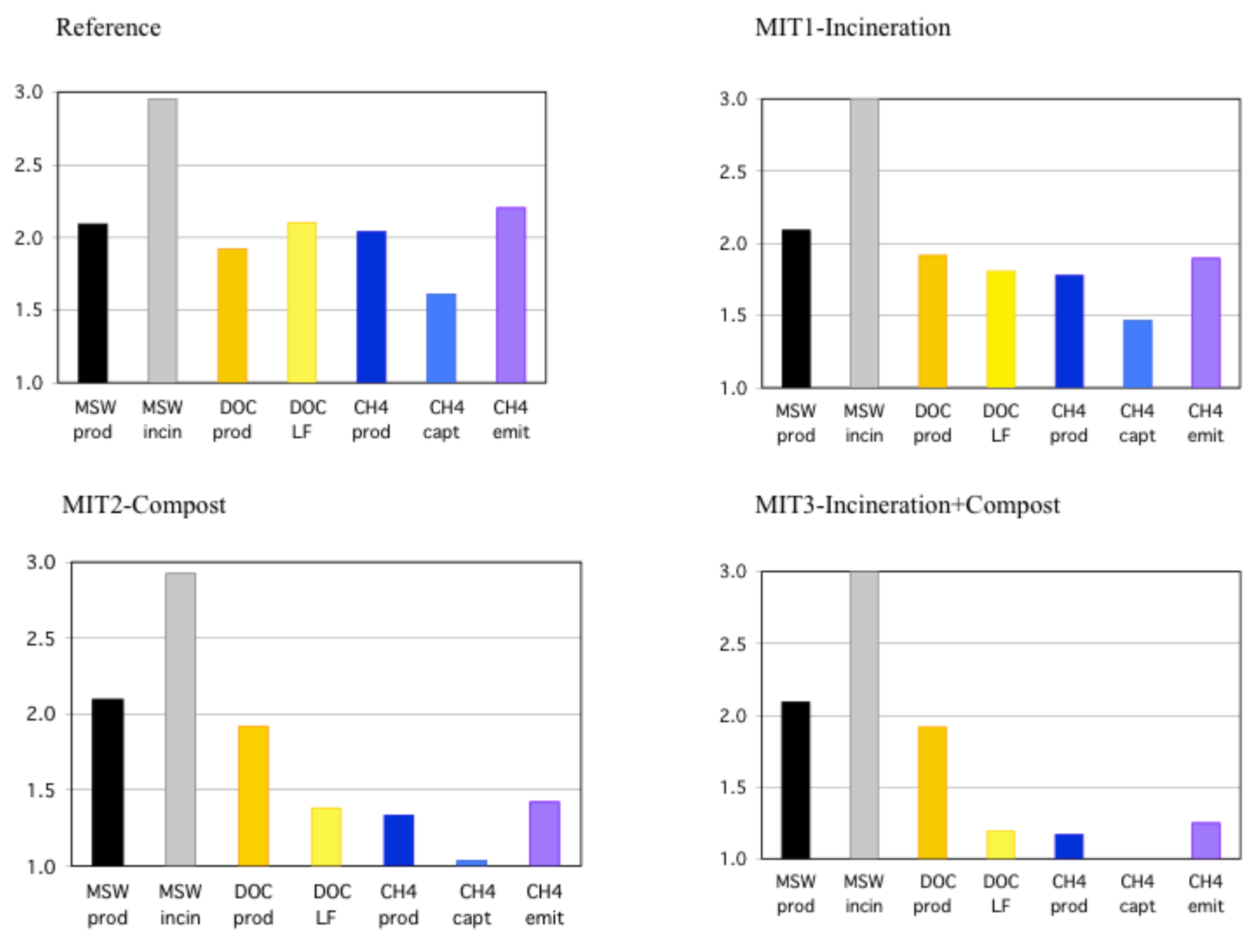


Table 1. Waste composition as percent of total waste.

Southeast Asia	food	paper	wood/ grass	rub/ leath	textile	plastic	glass	metal	inert	other	reference
Brunei Darussalam, Brunei-Muara	36	18				16	3	4		23	AIT/UNEP, 2010
Cambodia, Phnom Penh	63.3	6.4				15.5	1.2	0.6		13	AIT/UNEP, 2010
China	35.8	3.7				3.8	2	0.3		47.5	World Bank, 1999b
China	31	2.5	2.5			1.5	1	1	60.5		Fricke et al., 2007
China	49	16				16	1	2		16	AIT/UNEP, 2010
China, Pudong New Area	55	4.0	2.0		3.0	33.0	3.0				Minghua et al., 2009
Indonesia	63	11				10	1.5	1		13.5	AIT/UNEP, 2010
Indonesia	74	10		2		10	2	2	2		Zurbrügg et al., 2002
Indonesia, Taiping: mid-income	48	21				12	4	2		8	Fricke et al, 2007
Indonesia, Bogor	82.8	5.15	0.5	0.75	1.3	7	1	1.3		0.4	Parmadi & Wangsaatmodja, 2007
Indonesia, Bandung,	65	11			1.8	13.8	1.6	2		6.7	Sundana, 2007
Indonesia (Bandung)											
Kota Bandung	63.6	10.4			1.7	9.8a	1.5	0.95		12.2	Sundana, 2007
Kabupaten Bandung	65	11			2	13a	2	1		6	Sundana, 2007
Kota Cimahi	67.4	7.35			1.7	18.2a	1	1.2		1.1	Sundana, 2007
Kabupaten Sumedang	52.2	13.2				14.2a	2.1	3.1		7.4	Sundana, 2007
Laos	54.3	3.3			0.8	7.8	8.5	3.8		22.5	Visvanathan & Glawe, 2006
Laos, Vientienne	30					recyclables = 22 paper, metal plastic					Sundana, 2007

Table 1. Waste composition as percent of total waste (continued).

Southeast Asia	food	paper	wood/ grass	rub/ leath	textile	plastic	glass	metal	inert	other	reference
Malaysia	40	15			3	15	4	3		20	World Bank, 1999b
Malaysia	47	15	4		3	14	3	4		10	AIT/UNEP, 2010
Malaysia, Penang	45	21	4		4	17	6	3			Zhang et al., 2010
Malaysia, Kuala Lumpur: high income	45.7	29.9				9	3.9	5.1		4.3	Fricke et al., 2007
Myanmar	73.3	2.2				17.8	0.5	0.2		6.1	AIT/UNEP, 2010
Philippines	41.6	19.5				13.8	2.5	4.8		17.9	Zhang et al., 2010
Philippines	32.7	12.5				24.7	3.1	5		22	AIT/UNEP, 2010
Philippines, Manila	46	14.5				8.6a	2.7		1.3		Diaz et al., 2007b
Philippines, Manila	45	12	8	1.4	3.5	23.1	1.3	4.1	0.8	0.7	World Bank, 1999b
Philippines, Manila	49	19				17		6	9		World Bank 2001, in Zurbrügg et al., 2002
Sri Lanka	76.4	10.6				5.7	2	1.3		4.7	Zhang et al., 2010
Sri Lanka, Colombo	83	7				6	1	2		1	Zhang et al., 2010
Sri Lanka, Matale: low income	82	6.3			0.9	4	0.3	1.3		3.9	UNEP, 2008a
Sri Lanka, Matale: mid-income	79	6.7			5.1	5.6	0.5	0.3		3.1	UNEP, 2008a
Sri Lanka, Matale: high income	59	5.7			3.7	3.5	0.4	0.3		0.1	UNEP, 2008a
Thailand	48.6	14.6				13.9	5.1	3.6		14.2	Shapkota et al., 2007
Thailand	43	12.1				10.9	6.6	3.5		23.9	AIT/UNEP, 2010

Table 1. Waste composition as percent of total waste (continued).

Southeast Asia	food	paper	wood/ grass	rub/ leath	textile	plastic	glass	metal	inert	other	reference
Thailand, Bangkok	53	9		7		19	3	1			UNEP, 2001 in Zurbrügg et al., 2002
Thailand, Phitsanulok	61	5				26	2	1		5	Huttner & Kebekus, 2005
Thailand, Hua Hin	48.4	31.8				17.1	0	0.35		2.5	Shapkota et al., 2007
Thailand, Nan Dong	62	7.7				12	2	0.5		15.8	Fricke et al., 2007
Thailand, Udonthani	67.2	11.4		0.8	1.6	10.5	6.1	0.8		1.6	AIT, 2004
Thailand, Nakhon Ratchasima	44.6	17.2	1.3	1.6	1.3	10.7	1.1	1.1		21.3	AIT, 2004
Thailand, Chang Mai	59.3	10.9	2.5	4.4	1.4	11.6	3.6c	5.6		0.8	AIT, 2004
Thailand, Hat Yai	56.5	5.25	11.2	2.8	0.7	14.2	3c	3.5		3.1	AIT, 2004
Thailand, Rayong	38.6	9.7	6.5		3.4	13.4	6.3c	5.5		1.4	AIT, 2004
Thailand, Pattaya	64.3	3	1.1	2.8	1.1	21	2.3c	1.5		3.3	AIT, 2004
Thailand, Pathumthani	49.6	4.5	6.5	3.9	5.5	24	2.7c	2.9		0.4	AIT, 2004
Vietnam	58	4			1.8	5.6	8.5	1.5		27.5	World Bank, 1999b
Vietnam, Hanoi	41.9	1.9				15.6	7.2	6		27.4	AIT/UNEP, 2010
Vietnam, Hanoi	57-89				0-9	3-14		0-10	0-18	0.6	Gheewala et al., 2007
Vietnam, Hanoi	50.1	4.2				5.5		2.5	37.7		UNEP, 2001, in Zurbrügg et al., 2002
Vietnam, Haiphong	50.6	7.5				4.5		0.2	0.6	36.5	Gheewala et al., 2007
Vietnam, Habong	40-45	6				3-5		0-1	4-9	36-48	Gheewala et al., 2007
Vietnam, Danang	32	6.8				22.5		1	2	36	Gheewala et al., 2007
Vietnam, Ho Chi Minh	41.3	24.8				8.8		1.6	5.6	18	Hazra & Goel, 2009

Table 1. Waste composition as percent of total waste (continued).

Developed Asia/Pacific	food	paper	wood/ grass	rub/ leath	textile	plastic	glass	metal	inert	other	reference
Australia	47	23			13	4	7	5			OECD, 2008
Hong Kong	38	26			3	19	3	2		9	World Bank, 1999b
Japan	26	46				9	7	8		12	World Bank, 1999b
Japan	15	50				20	1	2		4	AIT/UNEP, 2010
Singapore	44.4	28.3				11.8	4.1	4.8		6.6	AIT, 2004
Singapore	19.8	22.8				22.8	2.3	3.4		28.9	AIT/UNEP, 2010
Taiwan	31	26			9	22	7	4			World Bank, 1999b
South Korea	26.3	21.4				8.9	4.7	8		30.7	AIT/UNEP, 2010
South Korea	28	24			28	8	5	7			OECD, 2008
South Korea, Seoul	22.3	16.2			27.5	9.6a	10.3	4.1			Diaz et al. 2007b

Table 1. Waste composition as percent of total waste (continued).

South & West Asia, Middle East	food	paper	wood/ grass	rub/ leath	textile	plastic	glass	metal	inert	other	reference
Bhutan, Phuntsholing City	31	20		9		11	11	5	8	5	Norbu & Dilokwanich, 2010
Bhutan, Thimphu City	49	25			3	14	4	1		5	Royal Gov't of Bhutan, 2009
Bangladesh, Dhaka	65	12	12			1			5	7	Yousef & Rahman, 2007
Bangladesh, Dhaka	70	4.3		4.6		4.7	0.3	0.1	16		Kasi 1999, in Zurbrügg et al., 2002
India, cities	42	6			4	4	2	2		40	Sharholy et al., 2008
India, cities	40-60					<1	<1	<1	30-40		Kumar et al., 2006
India, Tier I cities	32-55					16			43		Kumar et al., 2006
India, Tier II cities	32-73					17			34		Kumar et al., 2006
India, Bangalore	75.2	1.5			3.1	0.9	0.2	0.1	19		Fricke et al., 2007
India, New Delhi	38	6				6	1	0.2	35	14	Agarwal et al., 2005
India, Allahabad	45.3	3.6			2.22	2.9	0.7	2.5	41.7	1.1	Sharholy et al., 2007
India, Pune	65	8				7a	4	6	10		UNEP, 2007
India, Kolkata	45	9									Hazra & Goel, 2009
Iraq	46-71	~4			~4	5-8	~4	~4	10		Glawe et al., 2007
Iran	62.3	10.9	5.5		4.1	10.3	4.2	3.2			Visvanathan & Glawe, 2006
Kuwait	37.5	35				5	3.5	5.5			Abu Qdais et al., 1997
Mongolia	16.8	25.2				12.1	4.4	2.5		39	AIT/UNEP, 2010
Nepal	65	9		1	2	8	3	1	10	2	Zhang et al., 2010
Nepal, Kathmandu	68	10			4	12	1	1		6	Visvanathan & Glawe, 2006
Pakistan, Karachi	40	10			9	7	2	1		32	Visvanathan & Glawe, 2006
Qatar	53.3	17.7				15	15	4.3			Abu Qdais et al., 1997
Saudi Arabia	35	34				1	1	5			Abu Qdais et al., 1997
Turkey	40-65	7-18				5-14	2-6	1-6		7-24	Turan et al., 2009
United Arab Emirates, Abu Dhabi	49	6				12	9	8		16	Abu Qdais et al., 1997

Table 1. Waste composition as percent of total waste (continued).

Africa	food	paper	wood/ grass	rub/ leath	textile	plastic	glass	metal	inert	other	reference
Africa	35-80	10-15				<10	<10	<10			Yousef & Rahman, 2007
Ethiopia, Bahir Dar (city average)	43.5	9.4	13.6	0.9	1.3	3.3	1.1	1.3	27.4e	2.6g	UNEP, 2010b
Ghana, Kumasi	84	4.9									Mwesigye et al., 2009
Ghana, Accra	85.1	12.9				3.4	1.9				Mwesigye et al., 2009
Kenya, Nairobi: high income	52	17.3	6.7	2.4	2.7	11.8	2.3	2.6		2.7	UNEP, 2010a
Kenya, Nairobi: mid-income	50	17	8	2	3	14	2	3		7	UNEP, 2010a
Kenya, Nairobi: low income	57	16	2	3	2	12	2	1		4	UNEP, 2010a
Kenya, Nairobi: at source	51	17.5				16.1	2	2		11.4	UNEP, 2010a
Kenya, Nairobi: at collection sites	43	12.1				15.1	5.6	2.7		21.7	UNEP, 2010a
Lesotho, Masera	23.9	22.5	3.4			14.5	9.1	3.6		25.1	UNEP, 2008b
Morocco	73	~25									El Edghiri, 2002
Nigeria, Ibadan	55.8					6.3	1.8	2.6			Mwesigye et al., 2009
Nigeria, Ogbomosa											Abel et al., 2007
city core	21.6	15.7	24.3	3.7	2.5	10.4	1.5		9.8	10.5b	Abel et al., 2007
transition	15.3	17	25.6	6.1	2.5	11.9	5.6		8.2	7.8b	Abel et al., 2007
suburb	10.7	17.3	13.5	5.5	3.4	12.4	6.4		6.3	24.5b	Abel et al., 2007
Senegal	69.6	7.4			4.1	6.7	1.8	3.2	7.2		Seck et al., 2006
Rwanda, Kigali	94										Mwesigye et al., 2009
Uganda, Kampala	75										Mwesigye et al., 2009

Table 1. Waste composition as percent of total waste (continued).

Americas/Caribbean	food	paper	wood/ grass	rub/ leath	textile	plastic	glass	metal	inert	other	reference
Argentina, Asuncion	61	12.2			13.2	4.4a	4.6	2.3			Diaz et al., 2007b
Brazil, Indaiatuba	40	9.2	13.5			10.7	3.2	2.7	0.9	16.4	Mancini et al., 2007
Brazil, Rio de Janeiro	50.9	19.8	0.4			17.6	2	3.2			Fricke et al., 2007
Brazil, Alto Paranaiba	67.1	10.2				8.7	3	3.7		8.8	Fricke et al., 2007
Brazil, Ilhabela	49	19.9				17				14.4	Fricke et al., 2007
Brazil, Novo Hamburgo, commercial downtown	18.6	20.2				29.8	5.9	4		21.5d	UNEP, 2009
Brazil, Novo Hamburgo, high income	40.5	12.6				18.8	3.8	4.9		19.3	UNEP, 2009
Brazil, Novo Hamburgo, middle income	38.2	10.3				11.2	1.2	1.4		37.7	UNEP, 2009
Brazil, Novo Hamburgo, low income	39.3	11.8				23.6	1	<1		24.1	UNEP, 2009
Canada	24	47			8	3	6	13			OECD, 2008
Cuba, Havana	60	9.0	9.0	1.2	3.1	8.0	3	0.6	14.8	14.0	Korner et al., 2008
Mexico, Mexico City	59.8	11.9				3.5					Fricke et al., 2007
Mexico	51	15			18	6	6	3			OECD, 2008
U.S.	17.9	23.8	14.4	1.5	4.2	15.8	4.9	1.4		16.2	Staley & Barlaz, 2009
U.S.	25	34			16	12	5	8			OECD, 2008

Table 1. Waste composition as percent of total waste (continued).

Europe	food	paper	wood/ grass	rub/ leath	textile	plastic	glass	metal	inert	other	reference
Austria	35	22			19j	11	8	5			OECD, 2008
Belgium	39	17			29j	5	7	3			OECD, 2008
Denmark	29	27			32j	1	5	6			OECD, 2008
France	32	20			26j	9	10	3			OECD, 2008
Germany	14	34			12j	22	12	5			OECD, 2008
Hungary	29	15			35j	17	2	2			OECD, 2008
Iceland	26	26			24j	17	4	3			OECD, 2008
Ireland	25	31			23j	11	5	4			OECD, 2008
Italy	29	28			22j	5	13	2			OECD, 2008
Luxembourg	45	22			16j	1	12	4			OECD, 2008
Netherlands	35	26			12j	19	4	4			OECD, 2008
Norway	30	33			20j	9	4	4			OECD, 2008
Portugal	34	21			23j	11	7	4			OECD, 2008
Slovakia	38	13			31j	7	8	3			OECD, 2008
Spain	49	21			7j	12	8	4			OECD, 2008
Sweden	i	68i			17j	2	11	2			OECD, 2008
Switzerland	29	20			29j	15	4	3			OECD, 2008
small province	29.8	9.8	7.8		1.4		3.3	1.6	25.7g	20.6	Nas & Bayram, 2008
3 medium cities h	50.3	7.7			0.9	5.2	2.6	1.8	4.9g	28.4	Nas & Bayram, 2008
5 large cities h	53.9	31.2				10.1	4	2.9		15.1	Nas & Bayram, 2008

Notes to Table 1.

rub/ leath is rubber and leather
a rubber, leather and plastic
b animal dung
c glass and stone
d mixed
e ash, soil and stone
f animal remains, hazardous, e-waste and other
g ash and scoria
h multi-city means do not add to 100%
i presumably 68% paper includes organic
j textiles and other

Table 2. Waste-collection rates as percent of population or of generated waste.

location	%	reference
Afghanistan	0-22	Visnathathan & Glawe 2006
Argentina	100	Espinoza et al., 2010
Bangladesh	40-90	Visnathathan & Glawe 2006
Bangladesh, Dhaka	50	Yousef & Rahman, 2007
Belize	85	Espinoza et al., 2010
Bolivia	68	Gamarra & Salhofer, 2007
Bolivia	83	Espinoza et al., 2010
Brazil	71	Gamarra & Salhofer, 2007
Brazil	96	Espinoza et al., 2010
Cameroon, Yaoundé	43	Parrot et al, 2009
Chad, Ndjamena	15-20	Parrot et al, 2009
Chile	98	Espinoza et al., 2010
Côte d'Ivoire, Abidjan	30–40	Parrot et al, 2009
Costa Rica	66	Gamarra & Salhofer, 2007
Costa Rica	90	Espinoza et al., 2010
Ecuador	81	Hazra & Goel, 2009
Ecuador	84	Espinoza et al., 2010
El Salvador	79	Espinoza et al., 2010
Guatemala	78	Espinoza et al., 2010
Haiti	30	Gamarra & Salhofer, 2007
Honduras	20	Gamarra & Salhofer, 2007
Honduras	65	Espinoza et al., 2010
Hungary	90	OECD, 2008
India	50-90	Visnathathan & Glawe 2006
India, 59 cities	50-70	Kumar et al., 2009
India, New Delhi	62	Visnathathan & Glawe 2006
India, Calcutta	61	Hazra & Goel, 2009
standard housing	57	Hazra & Goel, 2009
registered slums	67	Hazra & Goel, 2009
unregistered slums	13	Hazra & Goel, 2009
India (mean)	72	Hazra & Goel, 2009

Table 2. Waste-collection rates as percent of population or of generated waste (continued).

location	%	reference
India		
Andra Pradesh	74	Sharholy et al., 2008
Bihar	59	Sharholy et al., 2008
Gujarat	61	Sharholy et al., 2008
Haryana	82	Sharholy et al., 2008
Karnataka	80	Sharholy et al., 2008
Kerala	82	Sharholy et al., 2008
Madhya Pradesh	73	Sharholy et al., 2008
Maharashtra	72	Sharholy et al., 2008
Orissa	61	Sharholy et al., 2008
Punjab	71	Sharholy et al., 2008
Rajasthan	62	Sharholy et al., 2008
Tamil Nadu	73	Sharholy et al., 2008
Uttar Pradesh	78	Sharholy et al., 2008
West Bengal	74	Sharholy et al., 2008
Iraq, Kabul	23	Glawe et al., 2007
Ireland	76	OECD, 2008
Jamaica	74	Espinoza et al., 2010
Kenya, Nairobi	30-45	Parrot et al, 2009
Mauritania, Nouakchott	20-30	Parrot et al, 2009
Mexico	93	Espinoza et al., 2010
Mexico	70	Gamarra & Salhofer, 2007
Nicaragua	92	Espinoza et al., 2010
Pakistan	81	Visnathathan & Glawe 2006
Pakistan, Karachi	24	Visnathathan & Glawe 2006
Panama	85	Espinoza et al., 2010
Paraguay	48	Gamarra & Salhofer, 2007
Peru	84	Espinoza et al., 2010
Peru	74	Gamarra & Salhofer, 2007
Sri Lanka	10-40	Visnathathan & Glawe 2006
Senegal, Dakar	30–40	Parrot et al, 2009
South Africa, Eastern Cape	19	Blight & Mussane, 2007
Tanzania, Dar es salaam	48	Parrot et al, 2009
Togo, Lomé	42	Parrot et al, 2009

Table 2. Waste-collection rates as percent of population or of generated waste (continued).

location	%	reference
Turkey	73	OECD, 2008
Uruguay	98	Espinoza et al., 2010
Venezuela	100	Espinoza et al., 2010
Vietnam, cities (mean)	71	Nguyen, 2005
Vietnam	72	Zhang et al., 2010
Vietnam		Nguyen, 2005
cities >500K	76	Nguyen, 2005
cities 100-250K	70	Nguyen, 2005
rural, high income	20	Nguyen, 2005
rural, low income	~0	Nguyen, 2005
Vietnam, Lon An	45	Nguyen, 2005
Vietnam, Hue	75	Nguyen, 2005
Vietnam, Hanoi	80	Zhang et al., 2010
Vietnam, Hai Phong	79	Zhang et al., 2010
Vietnam, Hai Duong	51	Zhang et al., 2010
Vietnam, Quang Ninh	40	Zhang et al., 2010

Table 3. Waste-disposal methods as percent of generated waste.

Southeast Asia	sanitary LF	control LF/dump	open dump	inciner-ation	compost	recycle	other	reference
Cambodia, Phnom Penh			74	5a		15		UNESCAP, 2005
China	57		29	13	1			EEC, Coumbia Univ.
China						9		UNEP, 2010c
China, Pudong New Area		22			40	38		Minghua et al., 2009
Indonesia						5		UNEP, 2010c
Indonesia								
Jakarta	78						22	UNESCAP, 2005
Bandung	79			16a			5	UNESCAP, 2005
Semarang	74						26	UNESCAP, 2005
Surabaya	70					30		UNESCAP, 2005
Cebu	100							UNESCAP, 2005
Malaysia, Penang			80	10		10		UNESCAP, 2005
Malaysia, Kuala Lumpur						4		UNEP, 2010c
Myanmar, Yangon			86			14		UNESCAP, 2005
Myanmar, Mandalay						10		UNEP, 2010c
Philippines						54		UNEP, 2010c
Sri Lanka, Matale		49	20		6	5	20	UNEP, 2008a
Vietnam, Hanoi						20		Nguyen, 2005
Vietnam, Hanoi	65					15	20	UNESCAP, 2005
Thailand, Bangkok	99						1	UNESCAP, 2005
Thailand, Chiang Mai	98			2				UNESCAP, 2005
Vietnam						18-22		UNEP 2010c

Table 3. Waste-disposal methods as percent of generated waste (continued).

Developed Asia	sanitary LF	control LF/dump	open dump	inciner-ation	compost	recycle	other	reference
Australia	1			14	0	30	0	OECD, 2008
Hong Kong	57					43		Singh et al., 2011
Japan						20		UNEP, 2010c
Japan	0.0			14	0.0	17	<1	OECD, 2008
New Zealand	1			0	0	15	0	OECD, 2008
Singapore	34			66				UNESCAP, 2005
South Korea	<1			74	0	49	0	OECD, 2008
Taiwan	21			79				Kumar et al., 2009
South & West Asia, Middle East								
Bhutan, Phuntsholing City		80e		e				Norbu & Dilokwanich, 2010
Bangladesh			95				5	Visvanathan & Glawe, 2006
Bangladesh, Dhaka City		51	37			11		Yousef & Rahman, 2007
India	10		60	5	10		10	Visvanathan & Glawe, 2006
India, New Delhi						17		Agarwal et al., 2005
Iran		60	24	15a			2	Zhang et al., 2010
Nepal			70					Visvanathan & Glawe, 2006
Pakistan		5	80		5		10	Visvanathan & Glawe, 2006
Africa								
Namibia			'most'					Nehrenheim et al., 2011

Table 3. Waste-disposal methods as percent of generated waste (continued).

Americas/Caribbean	sanitary LF	control LF/dump	open dump	inciner-ation	compost	recycle	other	reference
Argentina	65	10	25	1a				Espinoza et al., 2010
Argentina, cities								
small	10							Gamarra & Salhofer, 2007
medium	40							Gamarra & Salhofer, 2007
large	75							Gamarra & Salhofer, 2007
largest	100							Gamarra & Salhofer, 2007
Belize	0	0	85	15a				Espinoza et al., 2010
Bolivia	45	16	11	2a			26c	Espinoza et al., 2010
Bolivia	50							Gamarra & Salhofer, 2007
Brazil	28							Gamarra & Salhofer, 2007
Brazil	55	20	25				<1c	Espinoza et al., 2010
Brazil, Minas Gerais	14	18	64		4			Azevedo et al., 2011
Brazil, Indaiatuba, Sao Paulo	3	21	67		7			Azevedo et al., 2011
Canada					12	27		OECD, 2008
Chile	82	14	4	0			1	Espinoza et al., 2010
Colombia	82	4	13	1a			<1c	Espinoza et al., 2010
Colombia	32							Gamarra & Salhofer, 2007
Costa Rica	68	24	9	0			0	Espinoza et al., 2010
Cuba	90							Gamarra & Salhofer, 2007
Dominican Republic	34	25	32	10a			<1c	Espinoza et al., 2010
Ecuador	66	19	14					Gamarra & Salhofer, 2007
Ecuador	30	46	21	1			2c	Espinoza et al., 2010
El Salvador	78	0	14	7a			1c	Espinoza et al., 2010
Guatemala	15	10	70	0			5c	Espinoza et al., 2010
Honduras	11	60	15	14a			0	Espinoza et al., 2010
Honduras	0							Gamarra & Salhofer, 2007
Jamaica	0	100	0	0				Espinoza et al., 2010

Table 3. Waste-disposal methods as percent of generated waste (continued).

Europe	sanitary LF	control LF/dump	open dump	inciner-ation	compost	recycle	other	reference
Austria	7			21	45	27	1	OECD, 2008
Belgium	12			34	23	31	0	OECD, 2008
Czech Republic	80			14	3	1	0	OECD, 2008
Denmark	5			54	15	26	0	OECD, 2008
Finland	60			10	0	30	0	OECD, 2008
France	36			34	14	16	0	OECD, 2008
Germany	18			25	17	33	7	OECD, 2008
Greece	92			0	0	8	0	OECD, 2008
Hungary	90			6	1	3	0	OECD, 2008
Iceland	72			9	9	16	0	OECD, 2008
Ireland	66			0	0	34	0	OECD, 2008
Italy	54			12	33	0	0	OECD, 2008
Luxembourg	19			39	19	23	0	OECD, 2008
Netherlands f	2			32	23	25	0	OECD, 2008
Norway	26			25	15	34	0	OECD, 2008
Poland	92			0	3	4	0	OECD, 2008
Portugal	64			21	6	9	0	OECD, 2008
Slovakia	78			12	1	1	7	OECD, 2008
Spain	52			7	33	9	0	OECD, 2008
Sweden	5			50	10	34	1	OECD, 2008
Switzerland	1			50	16	34	0	OECD, 2008
Turkey	98			0	1	0	1	OECD, 2008
UK	64			8	9	17	1	OECD, 2008

Notes to Table 3.

a open burn
b Latin America and Caribbean
c water bodies, animal feed
d landfilling and 'other'
e dry waste deposited at landfill is burned in open
f components sum to 83%

Table 4. Calorific values (CV) of waste materials.

Material	CV (kcal/kg waste)
Food	1310
Poultry litter	2103
MSW - before recycling	1673-3823
MSW - after recycling	2389-3345
Paper	3226
Dry wood	3441
Straw	3585
Cardboard	4157
Refuse-derived waste	4422
Meat/bone	4445
PET plastic	5164
Tires	7648
HDPE plastic	9573

Table 5. Environmental ranges and optima for composting.

	Optimum	Impacts above/below range
Moisture	40-60%	<40%: microorganisms may go dormant >60%: anaerobic
C:N ratio	25-30:1	>30: heat production declines, decomposition slows <25: ammonia is released, pH increases, may be toxic to microorganisms
Temperature	psychrophilic, 10-21˚C mesophilic, 21-38˚C therrmophilic, 38-71˚C	<10˚C: microorganisms go dormant >71˚C: microorganisms die off
pH		~7 >7: may be toxic to microorganisms

Table 6. Typical carbon-to-nitrogen (C:N) ratios of compostable materials.

Material	C:N ratio
Wood ashes	25:1
Cardboard, shredded	350:1
Corn stalks	50-100:1
Fruit waste	35:1
Leaves	30-80:1
Newspaper, shredded	175:1
Paper	170-200:1
Peanut shells	35:1
Pine needles	80:1
Sawdust	200-500:1
Straw	75:1
Woodchips	500-700:1
Alfalfa	12:1
Clover	23:1
Coffee grounds	20:1
Food waste	20:1
Garden waste	30:1
Grass clippings	12-25:1
Hay	25:1
Manures	20-25:1
Vegetable scraps	25:1
Seaweed	19:1

Source: http://web.extension.illinois.edu/homecompost/science.html

Table 7. GISS 2030 results for all projections, relative to 2000 (2000 = 1).

	MSW incin.	MSW LF	DOC LF	CH_4 prod.	CH_4 capt.	CH_4 emit.
REF	2.95	2.36	2.10	2.04	1.61	2.20
MIT1-I	9.16	2.02	1.81	1.78	1.46	1.90
MIT2-C	2.93	2.26	1.38	1.33	1.03	1.44
MIT3-I+C	8.74	1.93	1.19	1.17	0.96	1.25

LF, landfilled
prod, produced
capt, captured
emit, emitted

High values for MSW incinerated in MIT1-I and MIT3-I+C reflect the low level of incineration in 2000.

Table 8. GISS 2030 results for all projections, in Tg except CH_4 mitigation in percent difference from REF.

	DOC prod.	DOC compost	DOC LF	DOC LFan	CH_4 prod.	CH_4 capt.	CH_4 emit.	CH_4 mit.
All	256							
REF		0	172	95	31.7	6.9	22.3	
Mit1-I		0	148	83	27.6	6.3	19.2	-13%
Mit2-C		11.8	113	62	20.7	4.5	14.6	-35%
Mit3-I+C		11.8	98	55	18.2	4.1	12.7	-43%

Table 9. Regional waste-composition defaults as percent of generated waste (IPCC, 2000).

	food	paper	wood	plastic	tex-tile	rub/ leath	metal	glass	other	*total*
Asia										
E Asia	26	19	4	14	4	1	2.7	3.1	7	*81*
S-C Asia	40	11	8	6	3	1	4	4	22	*98*
S-E Asia	44	13	10	7	3	1	3	4	16	*101*
W Asia/ME	41	18	10	6	3	1	1	2	5	*88*
Africa										
East	54	8	7	6	2	1	2	2	12	*92*
Middle	43	17	7	5	3		4	2	2	*81*
North	51	17	2	5	3		4	2	2	*84*
South	23	25	15							*63*
West	40	10	4	3	1		1			59
Europe										
East	30	22	8	6	5	1		10	15	*96*
North	24	31	10	13	2		4	8		*91*
South	37	17	11				7			*72*
West	24	28	11							*64*
Oceania										
Aus/NZ	36	30	24							*90*
other	68	6	3							*77*
Americas										
North	34	23	6	9	4	1	5	7	10	98
Central	44	14	14	7	3	2	1	4	12	99
South	45	17	5	11	3	1	3	3	13	100
Caribbean	47	18	2	10	5	2	5	6	4	99

ME, Middle East

Totals summed from regional values are included to show that percentages do not consistently add to 100%.