LETTERS
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# Estimates of solid waste disposal rates and reduction targets for landfill gas emissions

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**Landfill disposal of municipal solid waste represents one of the largest anthropogenic global methane emission sources[1], and recent policy approaches have targeted significant reductions of these emissions to combat climate change in the US (ref. 2). The efficacy of active gas collection systems in the US was examined by analysing performance data, including fire occurrence, from more than 850 landfills. A generalized linear model showed that the operating status of a landfill—open and actively receiving waste or closed—was the most significant predictor of collection system performance. Gas collection systems at closed landfills were statistically significantly more efficient ($p < 0.001$) and on average 17 percentage points more efficient than those at open landfills, but open landfills were found to represent 91% of all landfill methane emissions. These results demonstrate the clear need to target open landfills to achieve significant near-term methane emission reductions. This observation is underscored by landfill disposal rates in the US significantly exceeding previously reported national estimates, with this study reporting 262 million tonnes in the year 2012 compared with 122 million tonnes in 2012 as estimated by the US Environmental Protection Agency[3].**

The decomposition of municipal waste in landfills is recognized as one of the largest sources of global anthropogenic methane emissions[1]. Landfills represent the third-largest anthropogenic source of methane in the US, comprising approximately 18% of domestic emissions[4]. As such, the capture and combustion of landfill methane has been identified as a critical and viable near-term strategy for greenhouse gas (GHG) reductions associated with the waste sector[5] in light of the cost and complexity of implementing wide-scale recycling and waste reduction efforts[5]. This is a particularly relevant strategy in lower- and lower–middle-income developing nations where waste generation is expected to increase 185% and 158%, respectively, over current rates by 2025 (ref. 6).

Although the US and many EU nations have required active landfill gas (LFG) capture for more than a decade[7,8], extensive data demonstrating the efficacy of these systems are limited. To fill this important gap, a new data set with more than 1,200 municipal solid waste landfills, both open and closed, resulting from the recently promulgated US GHG Reporting Rule[9,10] was analysed. The GHG reporting program requires municipal landfills that emit more than 25,000 tonnes of carbon dioxide equivalents to electronically report a substantial amount of operating data to the US Environmental Protection Agency (US EPA) annually, including: measured waste acceptance rates, locational data, projected disposal lifetime, and operational data for active gas collection systems (for example, total operational hours, collected methane content)[11], if present. In addition, the GHG reporting rule sets out uniform procedures stipulating how sites must collect, validate and report these data.

Our analysis of this data set revealed that the total amount of municipal waste disposed of in the US was 262 million tonnes in 2012, 115% greater than the US EPA disposal estimate for the year 2012 (122 million tonnes) that used a materials flow analysis (top-down) approach[3] and exceeds the World Bank's projected municipal waste generation rate for the US in 2025 (ref. 6) of 256 million tonnes by about 4% (Fig. 1). Previously published survey estimates suggested that the US EPA disposal estimate was low[12], but the facility-level nature of our estimate combined with the embedded quality assurance checks makes our estimate the most accurate for the US so far. As our estimate captures disposal at facilities subject to the GHG Reporting Rule, the quantities in Fig. 1 are likely to be underestimates because smaller landfills are not required to report. We estimated that an additional 10 million to 36 million tonnes of waste were disposed of in 2011 (see Supplementary Information). The differences in our estimate from the published top-down estimates are likely to stem from errors introduced in top-down methods associated with assumptions regarding waste generation factors for different economic indicators.

In the near term, landfilling is expected to be the dominant method to manage municipal waste in the US. We found that the average disposal rate increased 0.3% per annum, approximately 2.7 years of disposal capacity was added annually from 2010–2013, and landfills in the US have a median of 34 years of available capacity remaining ($n = 413$ sites). Thus, on the basis of the growth in disposal rates and indications of continued reliance on landfilling as a waste management method, capturing LFG generated and reducing these emissions must be a target to meet stated reduction goals in the waste sector.

LFG collection system efficiency, which generally reflects the amount of LFG collected relative to the amount generated, was computed within the US EPA GHG reporting program data set using facility-provided information on the areal coverage of LFG collection infrastructure and the type of cover material (for example, thin soil layer, thicker clay layer, or synthetic membrane). This methodology was adopted by the US EPA during the development of the GHG Reporting Rule to reflect best available data on efficiency of LFG collection systems measured at several operating landfills[13,14]. Although this approach may not provide the accuracy of direct site measurements[15], it is useful for understanding the degree of LFG collection system infrastructure deployment at a large population of sites spanning multiple site sizes and climates.

A generalized linear model was developed to examine the factors contributing to differences between LFG collection efficiency at

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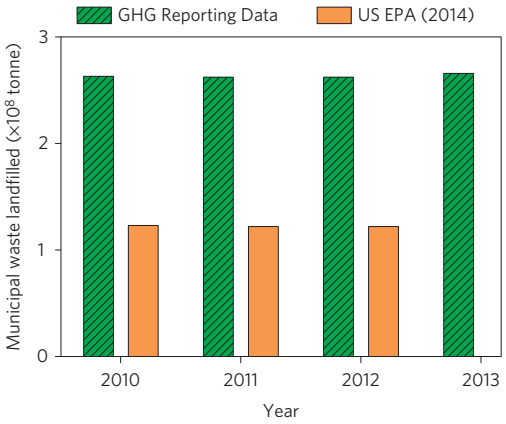


**Figure 1 | Quantity of municipal solid waste disposed of in US landfills.** This study calculated the 'GHG Reporting Data' columns. Reported US EPA (2014) data[3] were calculated using a materials flow analysis approach that calculates the disposal quantity on the basis of US census data and waste factors for industrial activity. US EPA data for the year 2013 were not available.

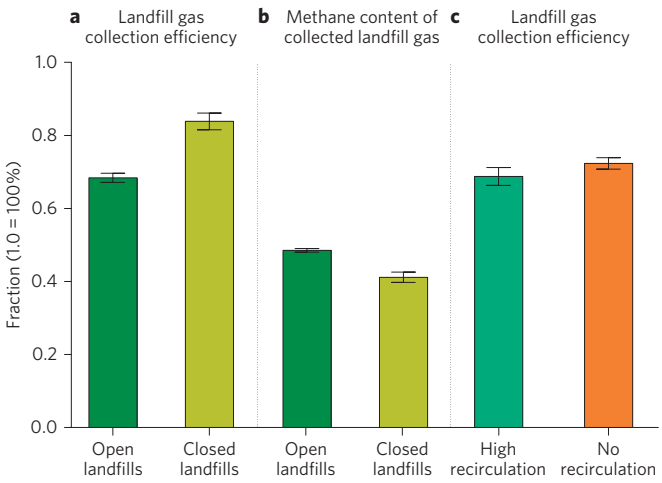


**Figure 2 | Gas collection efficiency and methane content of collected LFG calculated using year 2013 GHG reporting data from US EPA.** Top of the bar represents the mean and the whiskers represent the 95% confidence interval. **a**, Efficiency comparison of open landfills ($n=699$) compared with closed landfills ($n=217$) in 2013. **b**, Collected methane content of LFG at open landfills ($n=699$) compared with closed landfills ($n=217$) in 2013. **c**, LFG collection efficiency at landfills that have frequently recirculated leachate in the past 10 years ($n=172$) and landfills that have not recirculated leachate in the past 10 years ($n=525$).

each site (see Supplementary Information for more discussion of the model) and the most critical differentiating factor was whether the landfill was open or closed. A comparison of the gas collection efficiency for open and closed landfills shows that the efficiency at closed landfills is 17 percentage points greater than open landfills (Fig. 2). Year-by-year comparisons revealed statistically significantly greater LFG collection efficiency at closed landfills for all four reporting years analysed ($p < 0.001$). The LFG collection efficiencies at open sites were found to be independent of waste acceptance rate (see Supplementary Fig. 7), suggesting that challenges to collecting LFG exist at all open landfills, not just larger (or smaller) ones. The disparity in efficiencies between open and closed sites reflects the fact that open landfills have areas that lack a low-permeability barrier layer, which is often installed when the landfill reaches its capacity and is reflected in efficiency parameters selected by each site when reporting data to the US EPA.

The gas collection efficiency at landfills that recirculate leachate, which is the practice of deliberately adding liquids to the waste to accelerate waste decomposition as a potentially more sustainable method of landfilling[16], indicates that landfills that do not recirculate leachate have a statistically significantly greater ($p < 0.05$) LFG collection efficiency of 4%. This suggests that the deployment of LFG collection infrastructure at sites recirculating liquid is limited relative to those sites not recirculating liquids.

In light of the disparity in LFG collection efficiency observed between open and closed landfills, the methane emissions from open and closed sites were analysed to identify whether similar trends existed. Methane emissions are computed using measured data and modelled data at each site. This analysis showed that $91.0 \pm 0.5\%$ of all methane emissions by mass are from open landfills according to data from 2010 to 2013. The measured methane content of collected gas at closed and open landfills was also compared. The results showed that the methane content collected at open landfills was richer (48.5%) compared with that collected at closed landfills (41.1%), with an average difference of $6.2 \pm 1.1\%$, and year-by-year comparisons showed statistically significantly greater methane content at open landfills in each of the four years analysed ($p < 0.001$).

This comparison shows that the collected methane content is greater at open landfills but the efficiency of gas collection systems is substantially less at open landfills. These results, coupled with the disposal amounts and growth trends, further demonstrate that near-term efforts to reduce methane emissions must focus on implementing improved technologies and collection approaches at open landfills.

A challenge to improving gas collection at landfills is the potential for aggressive gas collection practices to contribute to the formation or sustenance of fires or pyrolysis-like reactions limiting the effectiveness of gas collection and potentially releasing other harmful compounds into the atmosphere[17–19]. This is of particular concern at open landfills because final capping systems, which are normally installed when a landfill closes, are typically not present[18,20–23]. Fires and heat-generating reactions are often initiated or exacerbated through the introduction of air into the waste mass, creating exothermic decomposition reactions and potentially explosive conditions[21].

Recently, large-scale, multi-year subsurface exothermic events have occurred at landfills in the US, and the introduction of air from gas collection systems has been identified as a contributor[24], which has also been observed in the literature as a contributing factor[21–23]. Although mechanisms of landfill exothermic events or fires have been explored in the literature, an accounting of the frequency of fires in the US along with their presence at sites with gas collection has not been explored. According to fire incident reporting data for municipal landfills in the US from the Federal Emergency Management Agency[9], approximately 839 unique landfill fire incidents were estimated to have occurred in the US annually from 2004–2010, and more than 25% of these incidents were repeated incidents at the same site (Fig. 3). Details regarding the precise cause and magnitude of each fire were not available, but the number of fires occurring annually and the frequency of occurrence at a given site support observations that landfill fires are difficult to fully extinguish[21].

To examine the occurrence of fires at landfill sites with gas collection systems, locational information from each site in the fire incident data set was matched to landfills that are subject to the GHG Reporting Rule. Out of 869 landfills with an active gas collection system in 2010, 402 or 46% had at least one fire incident between 2004 and 2010 (Fig. 4). Of those sites, 151 had more than one reported fire incident during this 7-year span. These results suggest that fires are about as likely to occur at

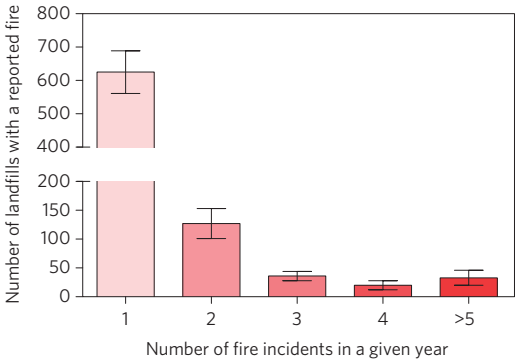


**Figure 3 | Average annual frequency of fire incidents at municipal landfills in the US, years 2004–2010.** Data from ref. 9. The top of each bar represents the mean and the error bar reflects the standard deviation for each bin. The mean and standard deviation values were calculated according to municipal landfill fire incident data from 2004–2010.

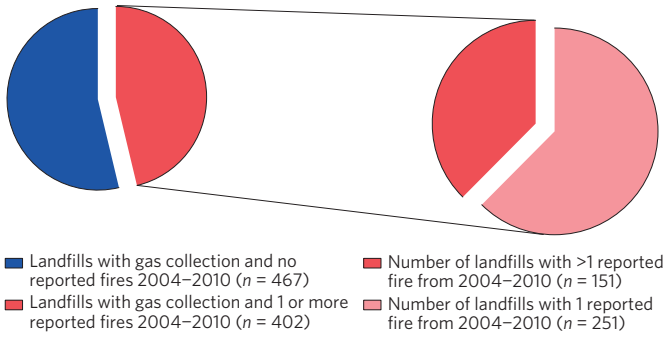


**Figure 4 | The number of landfills with active gas collection that have had one or more reported fire incidents between 2004 and 2010 according to NFIRS data and the inventory of landfills with active gas collection in the year 2010 from the US EPA GHG Reporting Rule data.** Approximately 42% of landfills that had active gas collection systems in 2010 had at least one reported fire between 2004 and 2010, and approximately 38% of those landfills had more than one reported fire during that period.

sites with gas collection as those without, and about 17% of the sites with gas collection experienced multiple incidents. Although a causal relationship from these data cannot be inferred, the data show that the common occurrence of fires at landfills necessitates planning for these conditions when contemplating new approaches to enhance LFG collection, regardless of whether a site is initiating LFG collection or already has an established LFG collection system.

The significant under-prediction of waste disposal quantities when comparing the new US disposal figure with the US EPA's previous figure and the World Bank estimate underscores the limitations of top-down waste generation estimates and could suggest that similar estimates in other developed and developing nations are low[25]. A high reliance on landfilling has been observed in the EU and in developing nations, similar to the US. In 2010, most EU countries landfilled more than 50% of the generated municipal waste, despite long-standing policies to divert waste from landfills such as the 1999 Landfill Directive and the 2008 Waste Framework Directive[26]. The World Bank projects that the generation rate of municipal waste will increase in nearly all parts of the world, with the largest increases occurring in low-income countries, which are expected to double waste generation rates over 2010 levels by the year 2025 (ref. 6). The collective, consistent global trend towards steady or perhaps increasing rates of landfilling clearly demonstrates that the waste sector warrants additional scrutiny to identify GHG emission reduction opportunities at landfills.

Improving the collection of LFG at open landfills must be a target for policymakers, researchers and practitioners to achieve near-term GHG emission reductions in the waste sector. New approaches to enhance LFG collection must acknowledge the common occurrence of landfill fires, which were found to occur about as equally likely at landfills with gas collection as those without according to seven years of fire incident data in the US. Given that US landfills have required access control for many years[27], the issue of fires could be of greater concern in nations that may lack such rules, because illicit dumping of burning or smouldering materials is also a common cause of landfill fires[21].

Collecting LFG earlier in a landfill's life and more quickly after waste placement should help to reduce emissions, but such measures must not promote conditions that can lead to or contribute to fires. Bottom-up design of integrated gas collection systems with traditional liquid collection systems at landfills and the use of temporary, low-permeability covers show promise as technological approaches to mitigate methane emissions from open landfills[28]. Although efforts to promote sustainable waste and materials management approaches such as waste reduction, composting and recycling in developed and developing nations must be bolstered, the trends clearly show landfilling as a major component of waste management for the coming decades. Thus, as the municipal waste generation rates continues to grow, policy approaches in developed and developing nations must provide flexibility to allow for innovative implementation of new technologies to enable the greatest level of methane reductions from landfills.

## Methods

Methods and any associated references are available in the online version of the paper.

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## Author contributions

J.T.P. conceived the paper, analysed the data, and wrote the manuscript; T.G.T. and J.B.Z. provided analytical guidance and writing contributions to the manuscript.

## Additional information

Supplementary information is available in the online version of the paper. Reprints and permissions information is available online at www.nature.com/reprints. Correspondence and requests for materials should be addressed to J.T.P.

## Competing financial interests

The authors declare no competing financial interests.

## Methods

**US EPA GHG Reporting Data.** Multiple queries were made through the US EPA's GHG Reporting Tool website (http://www.epa.gov/enviro/facts/ghg/customized.html) to source the municipal waste disposal quantity, LFG emissions, and LFG collection system performance data and metadata for reporting years 2010, 2011, 2012 and 2013. Every reporting landfill has a unique identification number, so data from the multiple queries were concatenated to develop a complete disposal and emissions profile for every open and closed landfill subject to the reporting rule. The total annual disposal quantity was calculated by summing the individually reported disposal quantities for every site in each reporting year. A generalized linear model was developed to identify significant predictors of LFG collection efficiency, including site operating status (open and actively receiving waste or closed), total methane generation, surface area containing waste, total landfill disposal capacity, number of gas collection wells installed, and measured methane concentration. Landfill operating status (open or closed) was found to be a significant ($p < 0.05$) predictor with limited residuals and no interaction with the variables that comprise the calculation of LFG collection efficiency. LFG collection efficiencies were analysed by first grouping open and closed landfills separately. The mean and 95% confidence interval of the mean collection efficiency were calculated in GraphPad Prism 6 (La Jolla). Statistical significance of LFG collection efficiency differences comparing open and closed landfills was calculated using two-sample *t*-tests in Minitab statistical software (State College). In a similar fashion, the significance of recirculating leachate at landfills on LFG collection efficiency was examined by conducting two-sample *t*-tests comparing sites that do and do not recirculate leachate frequently.

Methane emissions were calculated using a combination of data measured at each facility and modelled data—details of the equations used to determine methane emissions are presented in the Supplementary Information. Briefly, the emissions are computed using the amount of methane generated (modelled), the quantity of LFG collected (measured), the methane content of collected gas (measured), and the LFG collection efficiency (described previously). Although some uncertainty can be introduced when modelling LFG generation, the GHG Reporting Rule permits each facility to tailor LFG generation estimates according to the specific nature of the waste materials disposed of, if known, which results in greater model accuracy[29].

**Reported fire incidents at US municipal landfills.** US fire incident data were extracted from electronic databases provided by the National Fire Incident Reporting System (NFIRS), which reflects approximately 75% of all fire incidents in the US and represents fires electronically reported by fire departments across the US. Separate databases were provided to us by NFIRS for each year from 2004 to 2010. These data were compared with data from the US EPA's GHG Reporting data for the year 2010. Incidents specific to landfill fires were extracted from each year of the NFIRS data by isolating by incident type for 'sanitary landfills' (Code 152 in the database). Duplicate entries reflecting cases where more than one fire department responded to the same fire incident (corresponding to a 'help code' of 3 or 4 in the database) were removed. Annual fire frequency analysis was conducted in Microsoft Excel by creating a counting function for all fire incidents occurring in the same city. Identified repeat fire incidents at a single site were further analysed and incidents within the same city that occurred at a different address and at a location greater than 5 miles apart (as analysed using Google Maps Engine) were treated as separate fire incidents. Landfills with reported fire incidents were matched with landfills in the US EPA GHG Reporting database by matching the name and city (where available) of the site in each respective database. In limited cases, sites of the same name had mismatching cities, in which case the reported cities were mapped and those located within 5 miles of one another were considered to be the same site.

Additional analyses and corresponding methods related to the GHG Reporting data set and the NFIRS database are provided in the Supplementary Information.

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