ENVIRONMENTAL STUDIES

CH$_4$ mitigation potentials from China landfills and related environmental co-benefits

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China's CH$_4$ emissions from 1955 existing (old) and 495 planned (new) landfills are estimated and projected by adopting a bottom-up method, targeting a 2012 baseline year and a 2030 projected target year. Nine key CH$_4$ mitigation measures are proposed for the CH$_4$ mitigation assessment from landfills. Approximately 0.66 million metric tons (Mt) of CH$_4$ and 1.14 Mt of CH$_4$ will be released, respectively, from new and existing landfills under a 2030 business-as-usual (BAU) scenario, which is 23.5% lower than a U.S. Environmental Protection Agency estimation. It is estimated that 0.60 and 0.97 Mt of CH$_4$ can be reduced under new policies (NP) and low-carbon (LC) policy scenarios, respectively. The combined biocover and landfill gas collection and flaring system is the most promising mitigation measure, while mechanical biological treatment and mineral landfill also contribute substantially to CH$_4$ reduction. The odor-affected population under NP and LC scenarios will decrease by 39.5 and 64.2%, respectively, when compared to the 2030 BAU scenario. The LC scenario is a recommended policy for meeting China's nationally determined contribution targets and reducing the not-in-my-backyard impact due to this policy's significant reduction of CH$_4$ emissions.

INTRODUCTION

The waste sector is the third largest contributor to global non-CO$_2$ greenhouse gas (GHG) emissions, accounting for 13% of total non-CO$_2$ emissions in 2005 (1). In the United States alone, CH$_4$ from landfills reached 138 million metric tons (Mt) of CO$_2$-e (CO$_2$-equivalent) in 2015, accounting for 17.7% of all the national CH$_4$ emissions (2). CH$_4$ mitigation potential from developing countries' waste sectors is three times higher than that from developed countries (3). China, the largest developing country in the world, has agreed to peak CO$_2$ emissions by 2030. China's rapid economic development will cause total CH$_4$ emissions to continue to increase, representing a major challenge for China's climate change response.

Despite efforts to reduce municipal solid wastes (MSWs), landfilling is still the predominant disposal method. Landfilling in China has experienced substantial growth from 64.04 Mt of waste in 2003 to 107.28 Mt in 2014 (4). Much of this increase can be attributed to China's rapid economic growth and urbanization process. Landfilling predominance occurs because it has been typically the first choice for most cities in the past 30 years. This trend is expected to continue for the near future (5), especially for the medium and small cities in the middle and western Chinese regions.

China's mixed MSW landfilling has been characterized with high moisture content (40 to 60%) and perishable organic waste (50 to 70%) (6). This mixture has resulted in significant CH$_4$ and malodorous emissions (7–10). Moreover, typical short-lived GHGs such as CH$_4$ contribute to sea-level rise through thermal expansion, even after their atmospheric lifetimes have expired (11). Locally, landfill gas (LFG) and malodorous fugitive emissions have negative impacts on neighboring residents, resulting in commensurate localized policy concerns, particularly public complaints and concerns about landfilling (6, 8, 9). In addition, unaesthetic landscapes along with the fetid smells are triggers for the "not-in-my-backyard" (NIMBY) syndrome when trying to locate these facilities.

Accurate CH$_4$ emissions estimations are necessary for effective policy setting. CH$_4$ emissions are deemed to be 21 to 28 times more detrimental than CO$_2$ as a GHG (2, 3, 12). CH$_4$ emissions quantities typically depend on five key characteristics in landfills: (i) waste composition, (ii) degradable organic carbon ratio, (iii) CH$_4$ correction factor, (iv) oxidation factor, and (v) recovery rate. These major factors make estimation of CH$_4$ emissions from landfills a complex task and individual site/location-specific. Given the uncertainties in CH$_4$ estimation (13), especially in the LFG collection rate and the MSW landfilled amounts, more accurate estimates may be obtained by aggregating CH$_4$ emissions from each landfill. This aggregative approach has been defined as a bottom-up method (7, 14–16). The bottom-up estimation method is in contrast to averaged estimations at national and regional levels. Broad-based averaged estimations do not effectively consider idiosyncratic landfill-specific data, resulting in potentially erroneous estimations.

By adopting a bottom-up estimation approach, this comprehensive CH$_4$ emissions mitigation and spatial pattern analysis within China investigates three scenarios ending in 2030 and based on China's Intended Nationally Determined Contributions. The three proposed scenarios include business-as-usual (BAU), new policies (NP), and low-carbon (LC) scenarios. Detailed information on these policies is listed in table S1. The co-reduction of CH$_4$ and malodorous emissions can occur through the adoption of various CH$_4$ mitigation measures such as a landfill soil cover (10). Consequently, the reduction of odor and CH$_4$ emissions from landfill operations can achieve a win-win situation. Odor is a local concern, while CH$_4$ emission, a major GHG, is a global concern. Policy decision-makers at multiple levels will be more accepting of these mitigation policies due to environmental co-benefits not only to localized populations but also to the global community. These corresponding environmental malodorous co-benefits (technical

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details in section S2.1) can be evaluated using hydrogen sulfide (H_2S) emissions and the affected populations.

Here, on the basis of our previous work on CH_4 emissions from landfills in 2012 (*17*), CH_4 emissions patterns within China from 1955 existing (old) and 495 new landfills are estimated for the year 2030, when China agreed to reach a peak in CO_2 emissions. There are a number of major contributions from this study. The CH_4 emissions estimations and projections adopt a bottom-up method for the three scenarios. Bottom-up calculation techniques can provide more accurate and thoughtful directions for CH_4 emissions mitigation within China. Regional discrepancies in CH_4 emissions and the contribution of each mitigation option under the three scenarios are also determined. The spatial distributions of these sites are illustrated so that governmental agencies, at multiple jurisdictional levels including local, provincial, and national levels, can identify key hotspots and prepare for more effective regional CH_4 emission mitigation policies. In addition, human health and quality-of-life co-benefits are evaluated by computing malodorous emissions reductions.

METHODS
Emissions calculation process and mitigation scenario descriptions
CH_4 emissions reduction potential calculations consider both CH_4 mitigation options and specific conditions for each landfill. We compiled the CH_4 emissions reduction measures and analyzed the feasibility of these measures for each landfill. Figure 1 is a schematic diagram of the calculation and analysis process.

To identify different CH_4 emissions patterns, we designed three scenarios for the year 2030 for CH_4 emissions estimation based on the tendency of China's urbanization and industrialization processes. These scenarios include BAU, NP, and LC scenarios. These three scenarios are detailed and shown in section S1.

CH_4 calculation process
The FOD model (see Eq. 1) was used for CH_4 calculations using the three-dimensional emission factors from the matrix and point sources database (*7, 18, 19*)

$$E_{CH_4} = M \cdot \sum_{i=1}^{4} C \cdot f_i \cdot D_i \cdot D_F \left(e^{-(T-1) \cdot k_i} - e^{-T \cdot k_i} \right) \cdot F \cdot 16/12 \cdot (1 - R) \times$$
$$(1 - O) \qquad (1)$$

where E_{CH_4} is the CH_4 emitted for a period of T years of operation; M is the mass of MSW landfilled at time 0, when the reaction starts (that is, when the landfill began operation); C is the correction factor; f_i is the fraction of waste type i; i is the waste type (kitchen waste, paper, textile, wood, etc); D_i is the fraction of degradable organic carbon in the waste type i; D_F is the fraction of degradable organic carbon that decomposes; T is the length of time this landfill has been in operation at the time of this study; k_i is the reaction constant; F is the fraction of CH_4 by volume units in generated LFG; R is the methane recovery rate; and O is the oxidation factor.

FOD emission factors were obtained from field surveys and laboratory analyses completed at the Chinese Academy for Environmental Planning, Tsinghua University, Tongji University, and Shanghai Jiao Tong University. Detailed data are summarized in tables S2 to S4 (*6, 7, 20, 21*).

The landfills were categorized into three levels based on their sizes. Level I landfills have capacity volumes of more than 5 million m^3, level II landfills have capacity volumes between 2 million and 5 million m^3, and level III landfills have capacity volumes of less than 2 million m^3. The larger landfills have better operating status, with higher LFG collection rates (*14*).

A Gaussian dispersion model was used for landfill malodorous emissions diffusion (see Eq. 2)

$$C(x, y, z, 0) = \frac{q}{\pi u \sigma_y \sigma_z} \exp\left[-\frac{1}{2} \left(\frac{y^2}{\sigma_y^2} + \frac{z^2}{\sigma_z^2} \right) \right] \qquad (2)$$

This model considers malodorous emission sources from landfills as ground-level point sources. H_2S was selected as the representative odor from landfills, and the corresponding concentrations were calculated according to CH_4 concentrations (*9, 10, 22*).

Data sources
The year 2012 was set up as the baseline year for all the existing landfills. Data on these existing landfills, covering 1955 landfills, were investigated by the Chinese Ministry of Environmental Protection and collected from provincial environmental protection bureaus and field investigations (*8*). The site-specific data include geographic coordinates (latitudes and longitudes), administrative properties, detailed addresses, annual and total amounts of landfill wastes, and management levels.

The landfills planned to be constructed between 2012 and 2030 were regarded as the planned (new) landfills. The planned landfill capacities were estimated using local populations and per-capita MSW generation. During the period 2012–2030, 495 additional landfills are expected to be in operation. This number includes 13 level I landfills, 160 level II landfills, and 322 level III landfills (for detailed information, see section S3).

Nine CH_4 emissions mitigation measures have been identified for the three scenarios. These technologies and options may be categorized into direct CH_4 mitigation technologies and waste diversion measures. The collection and flaring of LFG are the most common abatement measures and could be divided into LFG collection and flaring (LCF), collection and power generation (LCP), and collection and purification for further utilization (LCPU), depending on the final utilization of LFG. Landfill operation area reduction and leachate enclosure operation can help reduce fugitive CH_4 and odors. These two alternatives were defined as refinement process for MSW landfilling (RPL) and leachate treatment with biogas collection, respectively. Source reduction of organic matter content in landfills can also reduce CH_4 emissions. These approaches/technologies include mechanical biological treatment (MBT), renewable landfill (RL), and mineral landfill (ML) (the details of the nine CH_4 mitigation measures are presented in section S2.2.1). The application potentials of these measures were obtained through expert judgments and are summarized in tables S5 and S6.

RESULTS
The trend and projected CH_4 emissions in 2030
CH_4 emissions from all the landfills for the year 2012 (baseline year) and projected for the three future scenarios in 2030 are summarized in Fig. 2. The baseline CH_4 emission in 2012 was 1.48 Mt from the 1955 existing landfills. The 2030 BAU scenario shows that total CH_4 emissions will increase to 1.80 Mt, including 1.14 Mt of CH_4 emissions from existing
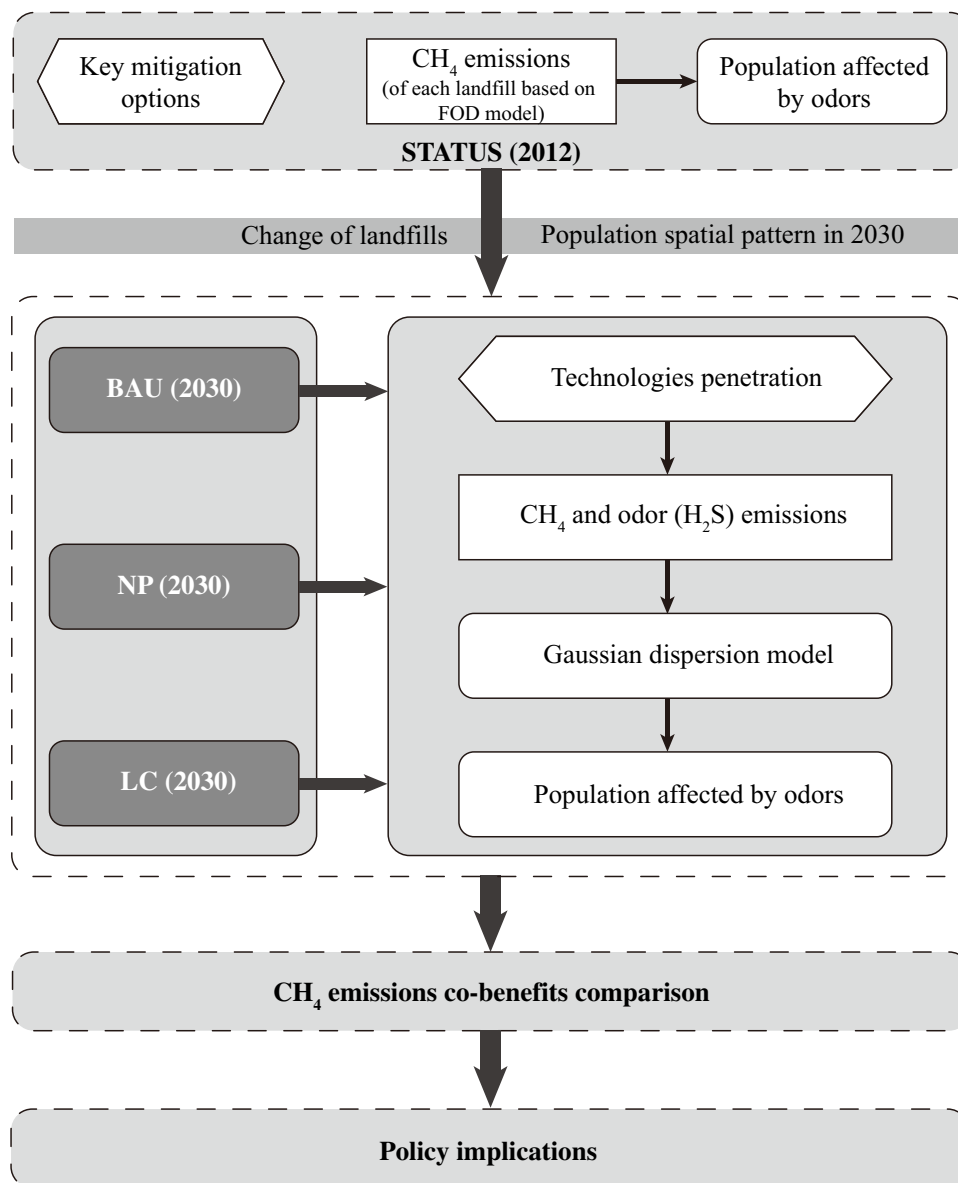
Fig. 1. A schematic diagram of the analysis process. The BAU, NP, and LC represent three scenarios in 2030. FOD, first-order decay.

(old) landfills and 0.66 Mt from the newly planned landfills. It is estimated that a total of 0.44 and 0.76 Mt of CH4 will be released from new and old landfills under the NP scenario, leading to a mitigation of 0.60 Mt of CH4. The LC scenario assumes that stricter CH4 emission mitigation policies are implemented with increasing CO2 emissions prices in a carbon trade market. In this scenario, the CH4 emissions are expected to be approximately 0.83 Mt, including 0.33 and 0.50 Mt from new and old landfills, respectively. The estimated emissions from the LC scenario represents a 53.89% decrease compared to the BAU scenario, with a reduction of 0.97 Mt of CH4. Estimations and projections also show significant affected population decreases due to malodorous emissions under the NP and LC scenarios, with 39.5 and 64.2% lower emissions than the 2030 BAU scenario, respectively. The affected populations under the BAU scenario are higher than the baseline year.

From a geographic perspective, China is separated into seven regions, namely, East China (EC), North China (NC), South China

(SC), Northeast China (NE), Northwest China (NW), Southwest China (SW), and Middle China (MC) (see fig. S2). Under the NP scenario, the LFG collection and burning efficiencies are set according to each landfill's local conditions. Old landfill mitigation processes contribute to 62.8% of the 2030 total CH4 emissions reduction, while 37.2% of total CH4 emissions reduction is from waste diversion measures. For existing landfills, feasible measures include minimizing the disposal areas and introducing gas extraction and flaring measures. These measures include LCF, LCP, and functional soil cover (FSC), which are more convenient for landfill managers to apply. ML and RL are the other two measures for CH4 reduction, especially in more developed EC and NC regions. In addition, ML in EC and LCF in NE are the most preferred options from a total CH4 mitigation potential perspective. The LCF, FSC, and LCP options are the most prominent CH4 mitigation measures for all the landfills. With regard to geographical distribution, the EC and NE regions have more CH4 mitigation potentials, with 33.4 and 21.1% of

total CH_4 reduction, followed by the SC and NC regions of 14.6 and 11.6%, respectively. The NW region has relatively less projected CH_4 reductions, with only 5.4% of CH_4 mitigation potential. Under the LC scenario, the introduction of flaring technologies (including the LCF and LCP) at the existing landfills and new landfills can greatly reduce the total CH_4 emissions with a cumulative value of 0.37 Mt, followed by the application of ML, which may further reduce CH_4 emissions by 0.29 Mt. In general, EC and NE regions have the greatest potentials for CH_4 reduction, with approximately 31.4 and 18.1% of total CH_4 emissions reductions, respectively. SC and NC regions follow with respective

total CH_4 emissions reductions of 13.7 and 13.6%. Geographically, economic and operating conditions are the main reasons for this regional discrepancy. High average temperatures in SC and EC regions result in more concentrated CH_4 emissions. These concentrated emissions favor the use of LFG collection and utilization and thus contribute significantly to CH_4 reduction.

The current and projected CH_4 emissions of each landfill for the year 2012 and the three future scenarios for the year 2030 are spatially summarized in Fig. 3. CH_4 emissions show a spatially clustered pattern, with intensive concentrations in the Beijing-Tianjing, Shanghai-Shaoxing-Ningbo, and Guangzhou-Dongguan-Qingyuan corridors. These regions are well-developed Chinese regions with mature urbanization settlements.

EC, SC, and NC were the top three regional contributors of CH_4 emissions in 2012. These three regions had annual CH_4 emissions of 0.49 Mt (33%), 0.22 Mt (15%), and 0.18 Mt (12%) in 2012, respectively. Level I landfills contributed the most CH_4 emissions, with figures of 53.5, 66.4, and 44.0% in the EC, SC, and NC regions, respectively. CH_4 emissions in the SW, MC, and NW regions were mostly from level II and level III landfills. The NW region has the least CH_4 emissions due to its lower population density and less developed economic situations.

Statistical analysis of CH_4 emissions from Chinese landfills
Distributions of individual landfill CH_4 emissions in different regions are shown in Fig. 4. CH_4 emissions from Chinese landfills vary from less than 10 metric tons of CH_4 emissions per annum in small landfills (level III) to more than 10,000 metric tons of CH_4 emissions per annum in large (level I) landfills.
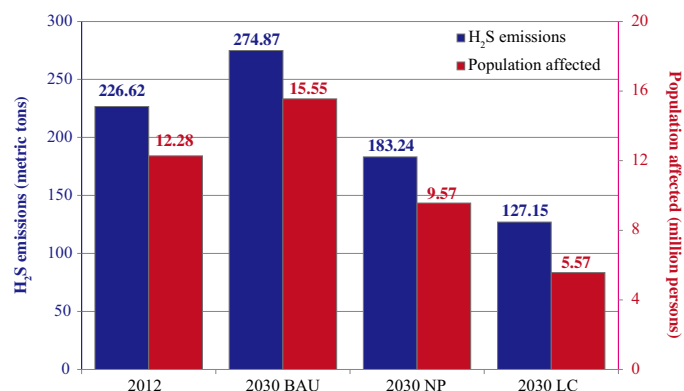

Fig. 2. Landfill CH_4 emissions (Mt) and populations (million persons) affected by malodorous emissions in 2012 and under three 2030 scenarios. The BAU, NP, and LC represent three scenarios in 2030.
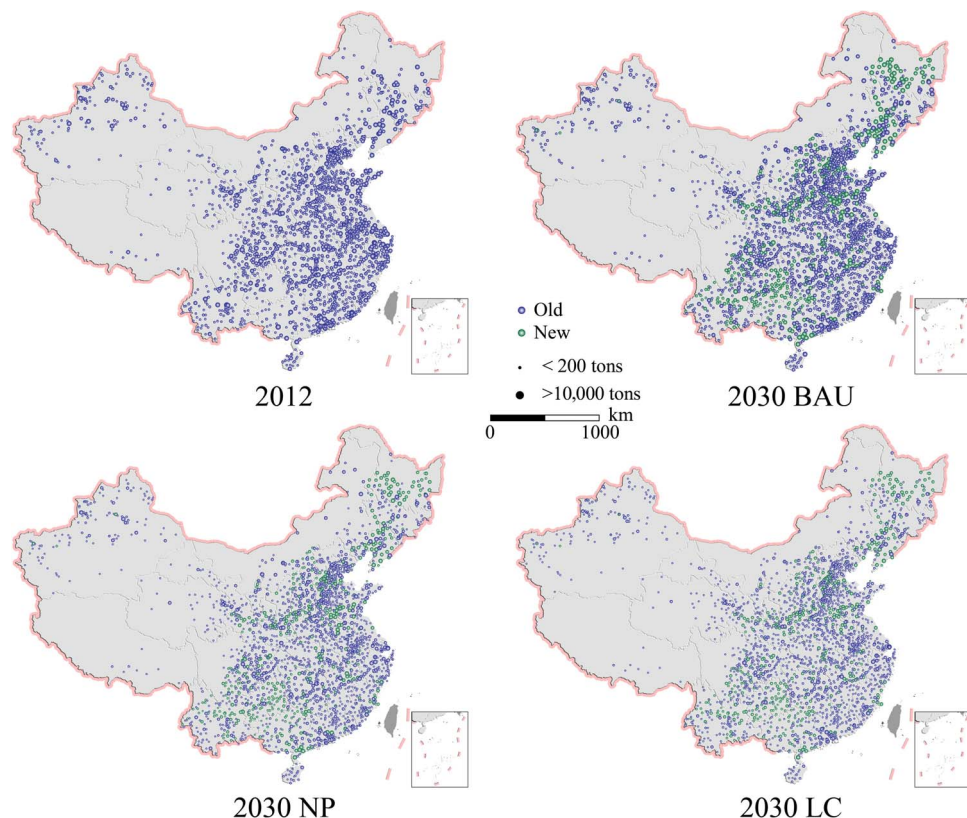

Fig. 3. Geographic spatial patterns for landfill CH_4 emissions in 2012 and three 2030 scenarios. The BAU, NP, and LC represent three scenarios in 2030.

The median CH_4 emissions values from landfills located in the NE, NW, and SC regions are higher under the 2030 BAU scenario when compared to the 2012 baseline year. It is expected that more MSW landfills will be operated in these regions. Median and maximum values of landfill CH_4 emissions for the 2030 LC scenario are lower than those under the 2030 BAU scenario. Emissions in the NE, EC, and NW regions are expected to be an order of magnitude lower over these time periods. For example, annual CH_4 emissions of the distribution of landfills shift from a range of 1000 to 10,000 metric tons in the NE under the 2030 BAU scenario to a range of 100 to 1000 metric tons under the 2030 LC scenario.

The EC and NE regions have the greatest potentials for CH_4 reduction under the 2030 LC scenario when benchmarked against the 2030 BAU scenario. These locations account for 31.4 and 18.1% of total CH_4 emissions reductions, respectively. The SC and NC regions follow in terms of reductions and respectively account for 13.7 and 13.6% of total CH_4 emissions reductions.

For the 2030 NP scenario, direct landfill CH_4 mitigation measures are estimated to contribute to 63% of total CH_4 emissions reductions, leaving an estimated 37% of total CH_4 emissions reductions attributable to the application of waste diversion options. For the old landfills, major CH_4 emissions reduction measures are LCF, LFG, LCP, and FSC. ML and RL are two additional mitigation measures for CH_4 emissions in the EC and NC regions. ML is used in the EC region, and LCF is used in the NE region as their respective leading CH_4 mitigation measures. LCF, FSC, and LCP are the expected most prominent CH_4 mitigation measures for all the landfills.

The 2030 LC scenario requires the implementation of a number of economically and technologically feasible mitigation measures. Direct CH_4 mitigation measures contribute to approximately 0.56 Mt of CH_4 emissions reductions. Waste diversion measures can contribute to approximately 0.42 Mt of CH_4 emissions reductions. Flaring technologies, including the LCF and LCP, have the greatest contributions to CH_4 emissions reduction, with a figure of 0.37 Mt. ML can also contribute 0.29 Mt to CH_4 emissions reductions.

An environmental co-benefit of CH_4 mitigation

Landfill malodorous emissions are key pollutants and are a source of significant local residential complaints. The reduction of malodorous emissions that arise from CH_4 mitigation is substantial. The 2030 BAU scenario shows that H_2S emissions, one typical malodorous gas, will be approximately 274.87 metric tons, about 48.25 metric tons more than in 2012. These emissions will reduce to 183.24 and 127.15 metric tons under the 2030 NP and 2030 LC scenarios, respectively. Among the nine landfill emissions mitigation measures, RPL can lead to most malodorous emissions reductions with around 30% reduction of total H_2S emissions from MSWs during the time frame (6). Other measures, such as LCF, LCP, and LCPU, could also decrease H_2S generation significantly because most of these gases could be separated and adsorbed before the flaring. The removal efficiency of H_2S could reach 90 to 95% with the implementation of these measures. The removal efficiency from the source reduction process of MBT, ML, and RL depends on the separation rates of organic matter within the source stations at the MSW sites.

Using geographic information systems, it is predicted that approximately 15.6 million people will be affected by landfill malodorous emissions under the 2030 BAU scenario, higher than the baseline 2012 situation (12.3 million people affected). The affected population will decrease to about 9.6 million and 5.6 million persons under the 2030 NP and 2030 LC scenarios, respectively. These results indicate
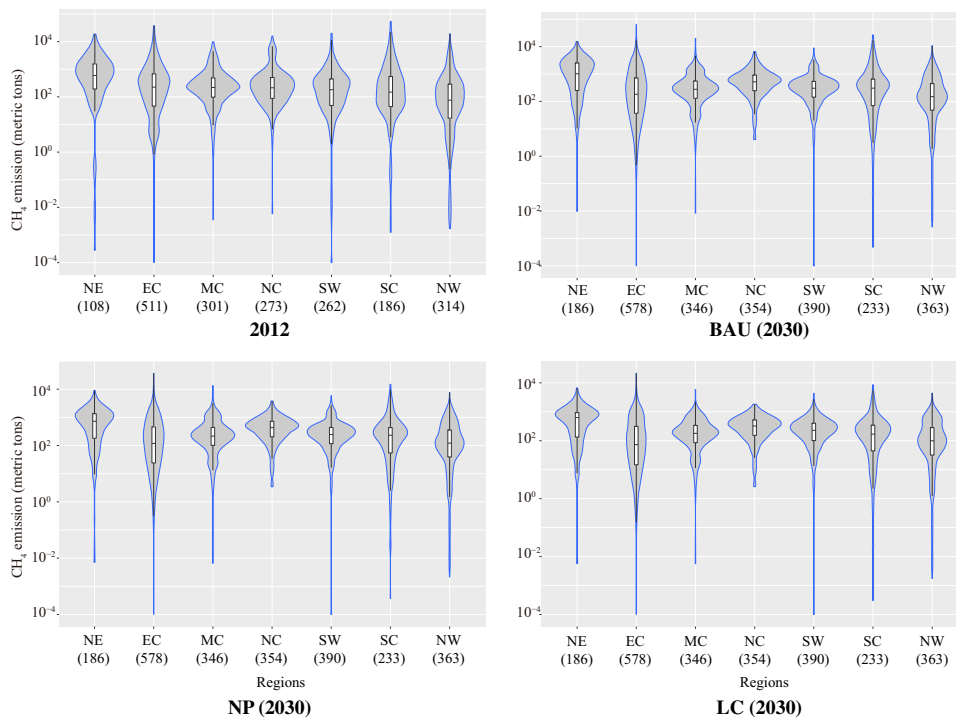

Fig. 4. Frequency distributions of individual landfill CH_4 emissions for different geographic regions for the year 2012 and three 2030 scenarios. The BAU, NP, and LC represent three scenarios in 2030. The violin plots show the distributions of landfill emissions, with each side representing the same value. The box plot inside the distribution indicates the first, second (the median), and third quartiles of the distribution. The number of landfills in each region for each time period are parenthetically represented.

that approximately 6 million and 10 million persons can avoid the landfill odor problems as a co-benefit from CH_4 mitigation measures.

DISCUSSION
CH_4 emissions estimation gaps
The projected landfill CH_4 emission under the 2030 BAU scenario is approximately 1.80 Mt, or about 37.73 Mt of CO_2-e, when CH_4 is measured as 21 times CO_2-e, which was ratified by the United Nations Framework Convention on Climate Change. Our result is 23.5% lower than the U.S. Environmental Protection Agency's (EPA) estimation of 49.3 Mt of CO_2-e emissions from all Chinese landfills in 2030 (3). This gap in CH_4 emissions projections can be mainly attributed to methods and data discrepancies. Here, activity data and local conditions from all the landfills were explicitly considered, while the EPA estimation provided an averaged estimate at the country level by using the Intergovernmental Panel on Climate Change data, given that Chinese data were not publicly available.

Other CH_4 emissions estimation results have also been reported based on different baseline years. Significant differences, even in order of magnitude, were found due to limited data for different emissions types and conditions. The total CH_4 emissions were estimated to be around 2.204 Mt (22), 2.1885 Mt (3), and 3.2032 Mt in the 2005 baseline year (23), and 3.789 Mt (23) and 4.7372 Mt in 2008 (24). Geographically, eastern, central, and western areas were responsible for 27.0, 44.7, and 28.3% of the national anthropogenic CH_4 emissions, respectively (25).

However, our results are much lower than those estimated in the above studies. The discrepancies include the total emission amounts and emissions from various geographic distributions. To have more accurate results, it is necessary to use available and reliable landfill-specific data so that emissions factors for CH_4 emissions from different landfills can be region-specific and more accurate (13, 18, 19, 26). For example, the LFG collection rate has proven to be one of the critical uncertainty factors for the CH_4 model estimation from landfills (13).

The data in this study are mainly from long-term on-site investigations. The results from such a bottom-up approach are more indicative and reliable. For example, only 580 landfills were recorded in the official Chinese statistical yearbook (4), but this study collected detailed data from 1955 existing landfills. In addition, waste composition data from 56 cities in the seven regions were compiled. These data can fairly represent the overall CH_4 emissions from all the landfills in China (the detailed waste compositions are listed in tables S2 to S4). This bottom-up approach can reduce uncertainties from variability across space and time for point-source estimates (3). These discrepancies require careful rethinking for a more accurate audit of current baseline emissions and projections of future emissions. More accurate information is necessary to effectively address current landfill challenges that include NIMBY barriers. Also, accurate emissions baselines and projections are necessary for planning and supporting various carbon emissions mitigation and future landfill management policies.

CH_4 mitigation potential and policy implications
The study results indicate significant potential CH_4 emissions reduction disparities across the seven Chinese regions. Accordingly, to support landfill emissions mitigation programs, CH_4 mitigation goals should be included in local officials' appraisal systems, particularly in regional CH_4 emissions hotspot areas. For example, the National and Local Development and Reform Commission and EPA are responsible for the management of CH_4 reductions. These agencies have the authority to assign mitigation policies and actions to various functional departments and managers such as a local department of sanitation. With targeted appraisal systems such as co-reduction goals, key decision-makers and managers in these agencies will likely pay greater attention to these various technologies. Incentive systems need to be tied to these appraisal systems. Providing a bonus structure for achieving various levels of goals, with some flexibility on selection of technology, may allow for localized innovative management practices to achieve these mitigation goals. Given that some of these solutions may occur over years, implementing long-term appraisal and reward systems may be prudent. For example, meeting project goals for implementation and not just outcomes of emissions reduction is one such longer-term tactic. Another potential policy management direction is to consider incremental emissions achievements and goals over multiple years with a focus on continuous improvement.

A major contrast in emission magnitude and intensity for CH_4 emissions from landfills exists between the eastern coastal regions and the western inland regions. Mitigation of regional CH_4 emissions from landfills should first be initiated in the EC, NE, and SC regions because these regions have the largest landfill CH_4 emissions. This requires the implementation of various mitigation measures by considering the local realities.

The CH_4 estimation results show reductions of approximately 0.599 Mt of CH_4 emissions in the NP scenario and 0.966 Mt of CH_4 emissions in the LC scenario, with 33.4 and 53.7% reductions, respectively, in total landfill CH_4 emissions. The CH_4 emissions reductions mainly rely on the application of CH_4 mitigation measures, such as collection and flaring. In addition, a useful CH_4 emissions reduction measure is to limit the amount of organic matter at sources through the introduction of RL and MBT. CH_4 mitigation measures, such as LCF (12), FSC (10, 27), and LCP, are preferable choices for western inland regions due to the lack of efficient LFG collection and utilization systems (3).

LFG collection at existing landfills requires cooperation between numerous stakeholders (14). Policy-makers should assign and manage reasonable mitigation targets to different landfills, preparing appropriate policies to reduce the overall generation of MSWs. These policies should be science-driven. Science-driven policies require that researchers identify, investigate, and share more efficient collection and reduction methods and technologies, such as those evaluated in this study. Landfill managers should actively engage and apply these mitigation actions. These managers should use the scientific knowledge and share practical findings with feedback. This feedback should be additional information for both researchers and policy-makers in furthering development and implementation directions.

With the application of FSC, a cover material with a high H_2S adsorption coefficient as landfill cover soil would result in the smallest volume of material required and could be the most cost-effective material to adsorb H_2S emissions, such as fine concrete (10). Waste diversion options are the most promising measures in eastern coastal regions, because it has been proven that the global warming impact was estimated to be −260 to 260 kg of CO_2-e metric ton^{-1} emissions for food waste landfilling (28).

According to EPA estimates (1), nearly a quarter of global CH_4 emissions can be mitigated at a marginal abatement cost of 15 U.S. dollars (USD) per ton of CO_2-e in 2020. The mitigation potential would likely increase as CO_2 trading prices increase. For example, after the implementation of the Paris Agreement, CO_2 prices are expected to increase to more than 60 USD per ton (12). Applying CH_4 abatement in landfills seems like a feasible and suitable solution especially using MSW source

separation and reduction of MBT and RL. In this regard, it has been reported that the cumulative reduction from the landfills can reach nearly 23.77 Mt of CO_2-e, if the carbon trading price is 89 USD_{2010} per ton of CO_2 (*3*). It could increase to around 37.03 Mt if the carbon trading price is above 250 USD per ton of CO_2-e (*3*). Consequently, the carbon trade market will play a vital role on further mitigating the overall CH_4 emissions.

Adopting the LC scenario for CH_4 mitigation is recommended because more landfills will be established and operated over the period 2012–2030 due to a rapid urbanization process and improved living standards (*29*). The prohibition of organic matter into landfills will be one important approach to reduce CH_4 emissions, such as the European Union Landfill Directive of 1999. A priority project called "zero landfilling of degradable wastes" was identified in 2011 by the Global Methane Initiative, which might accelerate such a process.

Moreover, market-driven mitigation options will be more efficient and effective for applying all CH_4 mitigation measures. An important policy mechanism that can result in almost immediate actions while generating necessary resources to support new technology mitigation strategies is to potentially use taxation approaches for landfill management, such as landfill taxes. This economic instrument can aid in waste source reductions, although careful implementation of the policy is required with expected barriers and pushback from communities. One of the difficult aspects of this policy mechanism is a determination of a fair and equitable tax rate.

Other financial and economic incentive mechanisms may also prove useful. Governmental subsidies that encourage new practices and technology implementations can be used; joint taxation and subsidy programs can prove to be effective complementary mechanisms. Properly monitored, educated, and supported local landfill managers can use subsidies to adopt more efficient methods for landfill recovery approaches. Higher landfilling fees, such as a usage tax, may also be a policy measure that can be applied to change both landfill management and local resident behavior to reduce overall organic matter landfill depositions. Given that this study found co-benefits associated with mitigation of GHG emissions, utilization of regional GHG emissions trading schemes may be an innovative policy mechanism. Using the principles of cap and trade (*30*), landfills may be assigned permitted levels and flexibility in technology adoption or trading for permits for emissions. There is ample room for creative policy instruments in this area.

Source reduction policies, as alluded to in the previous paragraph, are useful for overall MSW generation and future landfill emissions. This policy requires cooperation and significant effort from all waste producers, including individual households, consumers, and public and private organizations. Given that the Chinese public, in general, has relatively lower environmental awareness (*31*), there is a need to initiate various knowledge-building activities. Workshops, television and radio promotions, social media, and school textbooks and courses can help to change lifestyles and behaviors toward green and LC consumption. In addition, international collaboration is also necessary so that advanced MSW management experiences from other countries can be shared with the Chinese communities (*32*).

CONCLUSIONS

CH_4 emissions have increased as China has gone through rapid economic development. Around 1.48 Mt of CH_4 was released from the existing 1955 landfills in 2012, and 1.79 Mt may be released from the projected 2450 landfills in 2030. Using a bottom-up estimation method,

more accurate CH_4 estimation results were obtained in this study. It was found that the total CH_4 emissions in this study were 23.5% lower than EPA estimates. It is expected that CH_4 emissions in China will geographically shift from the EC, SC, and NC regions in 2012 to the EC and NE region in 2030 under a BAU scenario. Simultaneous reduction of malodorous emissions could be obtained as a co-benefit from CH_4 emissions mitigation in landfills, thus reducing the environmental impact from the landfills to local residents. The affected populations will decrease by about 64.7% from 15.55 million people under the 2030 BAU scenario to 5.57 million people under an LC scenario.

An important finding is that additional efforts should be made on implementing an LC scenario. This scenario could reduce CH_4 emissions by over 50% when compared to the 2030 BAU scenario. In addition, with co-reduced odor emissions, over 10 million residents can benefit in health and quality of life. These results will be helpful to understand the importance of China's CH_4 emissions and to support policy-making for the comprehensive control of CH_4 emissions.

Some limitations remain and deserve further study. The first limitation is the lack of a complete data set available for current and future estimations, as well as unclear policy targets. For example, the waste compositions are mainly from the regional level, instead of from each landfill directly, although in reality, it is extremely difficult to collect the detailed data on waste compositions for every single landfill. We did complete some landfill field investigations to supplement the data acquired through other means. Another limitation is some simplified assumptions we have made, such as just using H_2S as the target odor for environmental impact assessment and neglecting other malodorous gases that may emanate from landfills. Lastly, we relied on expert opinions was another major limitation, although we cannot find a better solution.

SUPPLEMENTARY MATERIALS

Supplementary material for this article is available at http://advances.sciencemag.org/cgi/content/full/4/7/eaar8400/DC1

Section S1. Scenario descriptions
Section S2. Calculation methods
Section S3. Data sources
Fig. S1. The total abatement cost curve of different GHG mitigation processes for landfills.
Fig. S2. The seven regions of China.
Fig. S3. The graphic list of the typical landfills in 30 provinces.
Table S1. The summary of the policy, mitigation, and market prices in three scenarios.
Table S2. Waste compositions in seven regions of China.
Table S3. The wet-based ratios of degradable organic carbon in different components of MSWs.
Table S4. Key parameters in the FOD model.
Table S5. The mitigation costs, potentials, and efficiency for the different treatment processes.
Table S6. The application potentials of different mitigation processes.
References (*33–38*)

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