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Global Methane Emissions from Pit Latrines

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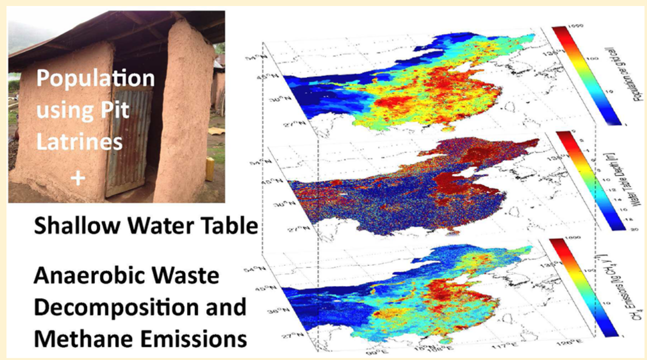
Supporting Information

ABSTRACT: Pit latrines are an important form of decentralized wastewater management, providing hygienic and low-cost sanitation for approximately one-quarter of the global population. Latrines are also major sources of the greenhouse gas methane (CH_4) from the anaerobic decomposition of organic matter in pits. In this study, we develop a spatially explicit approach to account for local hydrological control over the anaerobic condition of latrines and use this analysis to derive a set of country-specific emissions factors and to estimate global pit latrine CH_4 emissions. Between 2000 and 2015 we project global emissions to fall from 5.2 to 3.8 Tg y^{-1}, or from ~2% to ~1% of global anthropogenic CH_4 emissions, due largely to urbanization in China. Two and a half billion people still lack improved sanitation services, however, and progress toward universal access to improved sanitation will likely drive future growth in pit latrine emissions. We discuss modeling results in the context of sustainable water, sanitation, and hygiene development and consider appropriate technologies to ensure hygienic sanitation while limiting CH_4 emissions. We show that low-CH_4 on-site alternatives like composting toilets may be price competitive with other CH_4 mitigation measures in organic waste sectors, with marginal abatement costs ranging from 57 to 944 \$/ton carbon dioxide equivalents (CO_2e) in Africa and 46 to 97 \$/ton CO_2e in Asia.



INTRODUCTION

Methane (CH_4) is produced in wastewater streams by the anaerobic decomposition of organic matter. There is active interest in reducing anthropogenic CH_4 emissions because of its role as a greenhouse gas (GHG) and precursor to tropospheric ozone,[1] and identifying low-cost mitigation strategies is an international priority.[2,3] While most analyses of CH_4 emissions and mitigation opportunities from wastewater have focused on centralized treatment plants,[4,5] it has become increasingly clear that on-site wastewater treatment technologies like septic systems and pit latrines are also important, though poorly quantified, sources of CH_4.[6−8] Pit latrines alone, which are concentrated in rural areas of developing and middle income countries, have been estimated to emit ~14 Tg CH_4 y^{-1},[6] or >4% of global anthropogenic emissions.[7] The mitigation measures for wastewater CH_4 that are discussed in the literature, like upgrading from primary to secondary/tertiary treatment,[9] are not applicable to on-site systems, so there is a need to revisit CH_4 emissions from decentralized wastewater sources and reassess the appropriate actions for emissions reductions.

Pit latrines are utilized by 1.77 billion people[10] and are low cost, require little maintenance, and use little to no water. They are an essential component of public health campaigns to provide adequate sanitation for the 2.5 billion people who currently lack improved sanitation services,[11] which contributes to the more than 800000 deaths annually from poor water, sanitation, and hygiene.[12] As the United Nations (UN) sustainable development goals near finalization with a proposed target of universal access to adequate sanitation by 2030,[13] the international development community is poised to make decisions that will significantly impact global wastewater management, and concomitant CH_4 emissions, for a generation. Given the cross-cutting importance of environmental sustainability to the post-2015 development agenda, it is vital for policymakers to have a comprehensive understanding of GHG emissions from on-site sanitation systems and to be aware of appropriate mitigation technologies and their costs.

The implications of sanitation development on global CH_4 emissions, and how impacts will vary geographically, have not been discussed in detail in previous research. Pit latrine CH_4 emissions are controlled in part by local hydrology, since methanogenesis is contingent on anaerobic conditions that

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occur when organic waste in pits is submerged beneath the water table.[14] Spatial variation in groundwater level and its effect on biogeochemical decomposition pathways in pit latrines are not captured by the coarse calculations underlying pit latrine emissions in the current generation of GHG inventories. In order to characterize geographic variations in hydrological control over pit latrine emissions, we develop the first spatially explicit approach to estimating pit latrine CH_4 emissions and use the analysis to create a discussion of the linkages between pit latrines, sanitation development, and global CH_4 emissions.

Our approach uses spatial analyses of population, urbanization,[15] and groundwater level[16] in 21 developing and middle income nations to develop a set of emissions factors (EFs)[14] that reflect local hydrology. These spatial data sets are combined with country-level health and sanitation surveys to determine rural and urban populations using pit latrines and to quantify the resulting CH_4 emissions. We use this analytical framework to characterize variations in latrine CH_4 emissions within and between countries, to predict changes in global emissions between 2000 and 2015, and to evaluate the costs of mitigation measures like composting toilets that can provide low-CH_4 on-site alternatives to pit latrines.

METHODS

Spatial CH_4 Emissions Model. Pit latrine CH_4 emissions were estimated by integrating EFs from the 2006 IPCC Guidelines for National Greenhouse Gas Inventories[14] with country-level latrine utilization data and a high-resolution geospatial analysis of population, urbanization, and water table depth in 21 countries in Asia, Africa, and Latin America. Countries were selected to represent a range of geophysical settings as well as to capture most global pit latrine users. Emissions were calculated for grid cells at 30 arc-s (~1 km at the equator) grid spacing and summed for each country:

$$CH_4 \text{ emissions} = \sum_i P_i \cdot T_i \cdot EF_i \cdot BOD_i \quad (1)$$

P and T are the total population and the fraction of the population using pit latrines, respectively, in grid cell i. T was a function of the urban or rural classification of the cell. BOD is the country- or region-specific per capita production of biochemical oxygen demand (BOD) [kg BOD person^{-1} y^{-1}], taken from the IPCC guidelines (Table 1). EF is the CH_4 emissions factor [kg CH_4 kg^{-1} BOD].

Table 1. Emissions Model Parameters[14]

methane correction factors (MCF) for decentralized treatment systems			
disposal pathway	description	MCF	range
pit latrine	water table below latrine, 3−5 people	0.1	0.05−0.15
pit latrine	water table higher than latrine	0.7	0.7−1.0
septic system	half of BOD settles in anaerobic tank	0.5	0.5

biochemical oxygen demand (BOD)		
region/country	BOD [kg person^{-1} y^{-1}]	range
Africa	13.51	12.78−16.43
Asia, Latin America	14.60	12.78−16.43
Turkey	13.87	9.86−18.25
India	12.41	9.86−14.97
Brazil	18.25	16.43−20.08

Pit Latrine Prevalence. Latrine utilization ratios (T) in urban and rural areas were determined from country-level health and sanitation surveys compiled by the WHO/UNICEF Joint Monitoring Program (JMP) for Water Supply and Sanitation.[17] We aggregated data from 1998−2003 to determine a mean and standard error of latrine prevalence ca. 2000 (Table S1, Supporting Information). We followed the classification scheme from Graham and Polizzotto[10] and considered the following categories to be pit latrines: toilets that flush to pits, ventilated improved pit (VIP) latrines, pit latrines with concrete slabs, traditional latrines, and pit latrines without slab/open pit. Hanging latrines and bucket latrines were not included, since the ultimate disposal location may not be a pit. We do not separate urban populations into "urban high income" and "urban low income" groups, as is done in the IPCC guidelines, because JMP surveys only include data on an urban/rural basis.

Selection of Emissions Factors. EFs were determined from

$$EF = B_o \cdot MCF \quad (2)$$

B_o is the maximum CH_4 producing capacity for domestic wastewater, and the default value of 0.6 kg CH_4 kg^{-1} BOD was used due to the lack of country-specific values.[14] MCF is the methane correction factor and depends on the type of treatment and/or discharge method, ranging from 0 for a fully aerobic process to 1 for a fully anaerobic process. MCFs were taken from the IPCC methodology and are listed in Table 1. The MCF selected for each grid cell depended on the latrine depth relative to the groundwater level, since organic matter submerged beneath the water table will decompose anaerobically while dry decomposition will be largely aerobic. These MCFs will yield conservative emissions estimates that may underestimate the true CH_4 emissions, since they assume that decomposition in pits in dry climates will be mostly aerobic. In reality, pits with many users, those with flush water use, or those in impermeable soils will retain water and remain at least partially anaerobic, even in dry climates. The simplified grouping of pit latrines into "wet/below the water table" and "dry/above the water table" was necessary because detailed data on latrine water use, number of users, and water retention was not available from JMP country files or other data sources.

A global groundwater level model[16] was used to determine pit depths relative to the groundwater level. The model represents a mean annual water table depth and does not account for seasonal fluctuations or long-term variations in groundwater level. We assume a globally uniform pit latrine depth of 2.5 ± 0.5 m, which spans the 2−3 m depth range typical of pit latrines.[18,19] It is good practice for the bottom of latrines to be above the water table to avoid groundwater contamination, though this recommendation is often disregarded in practice.[10,20,21] P and EF in rural grid cells were used to determine population-weighted average rural EFs for each country:

$$\overline{EF} = \frac{\sum_{i=1}^{n} P_i \cdot EF_i}{\sum_{i=1}^{n} P_i} \quad (3)$$

Population and Urbanization. The model calculation in 2000 used a global gridded population data set for the year 2000 and an urban extents mask ca. 1995 in 30 arc-s resolution.[15] 2015 population projections were only available in a coarser 2.5 arc-min resolution,[22] so a linear interpolation was used to generate a 30 arc-s mesh for the 2015 population figures, which were then adjusted to match 2015 UN population figures[23] by multiplying each grid cell by a country-specific scaling factor. An urban extents mask for 2015 was not available, so the urban/rural classification was performed by manually tuning the population threshold for urban areas so that the urban/rural population ratio matched UN figures. Using the water table and urban/rural determination, grid cells were grouped into one of four types: (1) urban-shallow water table, (2) urban-deep water table, (3) rural-shallow water table, or (4) rural-deep water table. Each grouping yielded a unique combination of EF and T for each grid cell, which were used along with P and country-specific BOD to calculate the pit latrine emissions for each cell following eq 1.

2015 Projection. A linear regression analysis of country-level survey data from 1998 through the latest available data, typically 2010 or 2011, was used to predict latrine usage in 2015 (see Figure S1 for representative data). Unambiguous positive or negative trends were sometimes not clear. In order to filter the data for statistically significant changes in latrine utilization, the projection was only used if the slope of the regression was significantly different than 0 at a 90% confidence level. That is, the projections were only used when there was 90% confidence that a trend existed in latrine utilization, and when a positive or negative trend could not be extracted from the noise the 2015 latrine utilization was assumed to be the mean of the two most recent utilization ratios. The standard error determined for latrine usage ratios in 2000 was applied to the 2015 projections to account for potential deviations from the linear trend which may occur as rural areas approach latrine saturation. Table S1 (Supporting Information) compares the latrine utilization ratios determined here to estimates in other recent studies.[10,24] The same groundwater level model was used for 2000 and 2015.

Model Uncertainties. Uncertainty intervals of CH_4 emissions were determined by propagating uncertainties in the model parameters T, MCF, BOD, and latrine depth through the emissions model. Uncertainties in MCF and BOD (Table 1) are based on expert judgment and represent the range of values for domestic wastewater. Uncertainties in T represent ±2 s.e. of latrine usage estimates from JMP country reports, and uncertainties in latrine depth represent a depth range of 2−3 m. No specific confidence levels for the uncertainty ranges are reported since our input data uncertainties are partially based on expert judgment. An additional sensitivity analysis into the influence of pit depth on CH_4 emissions (Figure S2, Supporting Information) showed that broadening the range of latrine depth from 1 to 5 m contributed an additional 10−20% uncertainty beyond that described by the uncertainty range of 2−3 m.

Marginal Abatement Costs. Marginal abatement costs (MACs) were calculated as the additional cost of a CH_4 mitigation technology beyond the cost of a simple pit latrine per ton of carbon dioxide equivalents (CO_2e) averted:

$$\mathrm{MAC} = \frac{\mathrm{TACH}_{\mathrm{abate}} - \mathrm{TACH}_{\mathrm{pit\,latrine}}}{\mathrm{BOD}\cdot S\cdot \overline{\mathrm{EF}}\cdot \mathrm{GWP}} \quad (4)$$

TACH is the total annual cost per household. The subscript abate refers to the abatement technology and pit latrine to a simple pit latrine. Regional BOD values are included in Table 1, and Table 2 lists the mean regional household size (S) and representative regional $\overline{\mathrm{EF}}$. We use the global warming potential for CH_4 of 21 from the IPCC Second Assessment Report.[25] Composting toilets[26] and household biogas digesters[27] were considered as abatement technologies, and this approach assumes zero CH_4 emissions from either treatment system. TACH was computed using

Table 2. Costs of Traditional and Low CH_4 on-Site Sanitation Systems

	Africa	Asia
capital costs per capita (US$)		
simple pit latrine[a]	39	26
ventilated improved pit (VIP) latrine[a]	57	50
septic system[a]	115	104
composting toilet[b]	39−213	37−58
household biogas[c]	94−330	70
regional parameters		
mean household size (S)[d]	4.5	4.3
$\overline{\mathrm{EF}}$[e]	0.12	0.23
marginal abatement cost (MAC)[f] (US$/ton CO_2e)		
composting toilet	57−944	46−97
household biogas	338−1541	127

[a]Reference 19. [b]References 29−31 [c]References 28 and 32. [d]Reference 42. [e]Representative regional $\overline{\mathrm{EF}}$ (Figure 3). [f]Calculated from eq 4.

$$\mathrm{TACH} = \left[\frac{r(1+r)^L}{(1+r)^L - 1}\right]\cdot C_{\mathrm{CAP}} + C_{\mathrm{O\&M}} \quad (5)$$

The capital recovery factor[18] is in brackets, C_{CAP} is the initial capital cost of the investment, and $C_{O\&M}$ is the annual operating and maintenance (O&M) cost per household. The interest rate (r) was 4%, the investment lifetime (L) was 20 years, and S was used to scale from per capita to household costs. Capital cost estimates were collected from technical documents and case studies of on-site sanitation development in Africa and Asia,[19,28−32] and annual O&M costs were assumed to be 5% of capital costs for simple pit latrines and 10% of capital costs for more maintenance-intensive composting toilets and biogas.[33]

RESULTS AND DISCUSSION

Determinants of Pit Latrine CH_4 Emissions. A schematic illustrating the inputs to the geospatial model and the estimated CH_4 emissions for the case of China is shown in Figure 1. Spatial distributions of population, urbanization, and water table depth are combined with pit latrine utilization ratios to evaluate the population using either "wet" or "dry" pit latrines. These values are then used with parameters for per-capita BOD production and "wet" and "dry" pit latrine emissions factors to create spatial emissions maps (also see Figure 2 for maps of East Africa and Vietnam).

Population-weighted average rural emissions factors ($\overline{\mathrm{EF}}$) were developed for each country to evaluate regional variations in pit latrine CH_4 emissions (Figure 3). We focus on rural grid cells because those areas are most likely to be served by pit latrines. Countries with greater population density in areas with shallow water tables have higher $\overline{\mathrm{EF}}$, since a greater share of human excreta is disposed of in wet, anaerobic latrines. This analysis revealed geographic trends in the colocation of population and shallow water tables, with countries in East, Southeast, and South Asia characterized by high $\overline{\mathrm{EF}}$ because populated areas largely overlap with shallow water tables (e.g., China in Figure 1 and Vietnam in Figure 2; also see maps of

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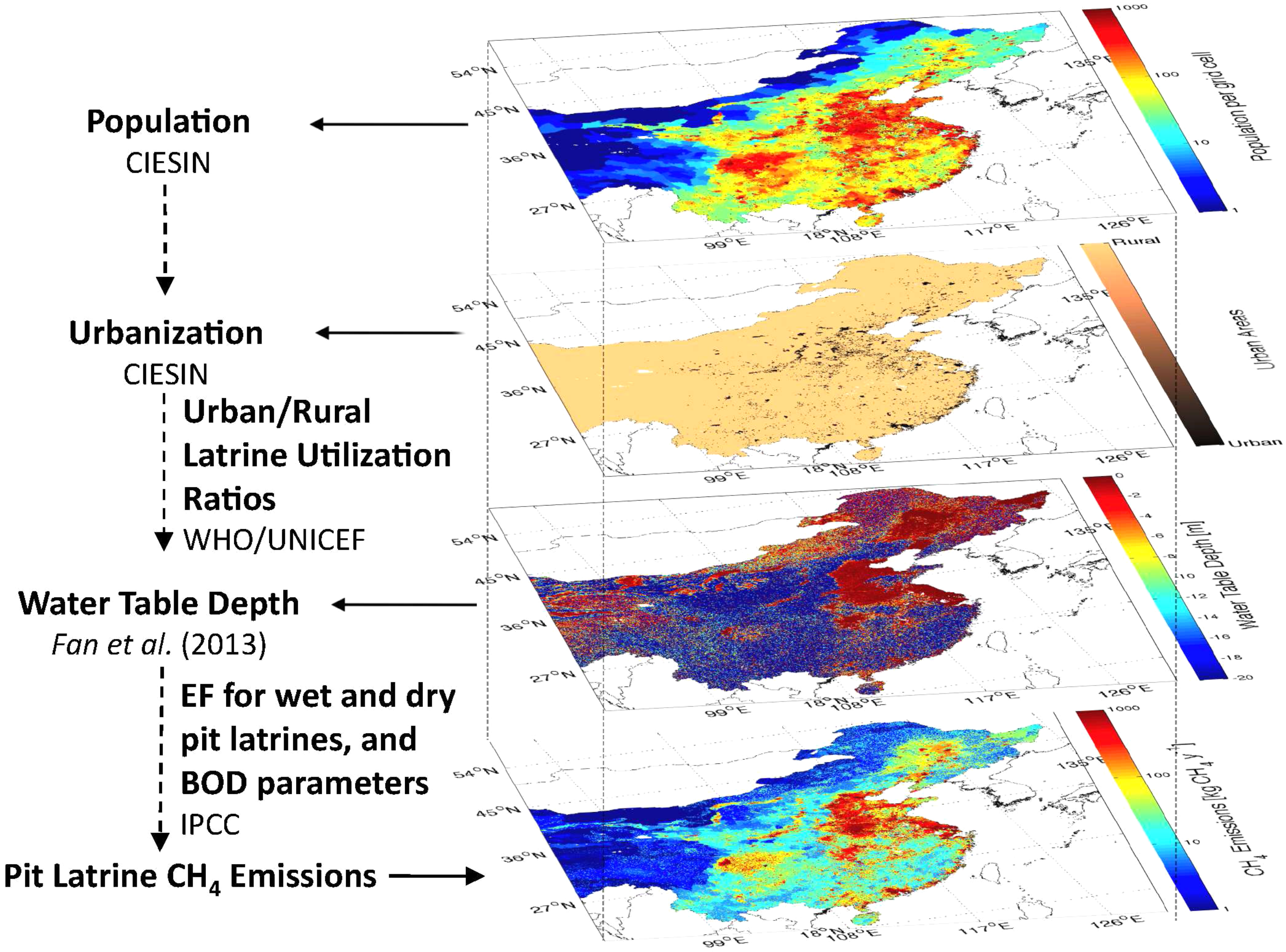

Figure 1. Schematic of geospatial emissions model for China in 2000. Population, urbanization, and water table are gridded at 30 arc-s resolution, latrine utilization ratios are on an urban/rural basis at the country level, and BOD and EF parameters are at country or regional levels. In the water table map, red indicates shallow water tables and blue represents deep water tables.

Bangladesh and India in the Supporting Information). The percentage of the rural population living in areas with water tables shallower than 2.5 m, a standard pit latrine depth, in China, India, and Bangladesh is 41%, 48%, and 88%, respectively. In contrast, many Latin American and African countries have lower $\overline{EF}$ because populated areas are more arid (see maps of East Africa in Figure 2, as well as maps of Brazil, Ethiopia, and South Africa in the Supporting Information). Just 18% of Kenya's rural population lives in areas with water tables shallower than 2.5 m, and in South Africa the ratio is only 4%. Variability within regions is also significant, with Nigeria and Cameroon characterized by greater $\overline{EF}$s than those in East and Southern Africa.

Trends in Emissions from 2000 to 2015. Pit latrines are a globally significant CH_4 source, with aggregate emissions in 2000 of 4.8 Tg y^{-1} (3.3−9.4) from the 21 country sample. Emissions are projected to fall to 3.4 Tg y^{-1} (2.3−6.6) for 2015, however, as a net result of different regional trends. In China, for example, the decrease from 2.5 to 1.1 Tg y^{-1} (Figure 4) is the result of sharply declining latrine utilization ratios (Table S1, Supporting Information). This trend is driven by rapid urbanization and is reinforced by the modernization of China's urban wastewater infrastructure. Modest emissions decreases of 10−30% are projected elsewhere in Asia as a result of similar social and infrastructure changes. In contrast, the large relative increases from African countries are caused by robust population growth and a sustained, and in some cases growing, reliance on pit latrines in both rural and urban areas. Strong growth in emissions in Ethiopia, for example, is due to major sanitation improvements in rural areas, leading to a projected 3-fold increase in the fraction of the rural population utilizing pit latrines between 2000 and 2015 (Table S1, Supporting Information). The magnitude of increases in Africa and Latin America is small relative to the scale of declines in China, however, so overall global emissions are expected to fall despite growth in some regions. China is expected to remain the largest emitter of pit latrine CH_4 in 2015 (1.1 Tg y^{-1}), followed by Bangladesh (0.61 Tg y^{-1}) and India (0.32 Tg y^{-1}) (Figure 4).

Wastewater CH_4 in Emissions Inventories. Table S2 (Supporting Information) lists CH_4 emissions estimated by the present study alongside previous estimates of emissions from pit latrines,[6] decentralized wastewater treatment,[24] and all wastewater sources.[7,34] The total wastewater sector emissions are included for reference only, while the studies of pit latrine or decentralized wastewater sources provide a suitable comparison to the results of the present study. Discrepancies between inventories are due to uncertainties in either the pit latrine utilization ratios or the appropriate EF. The large

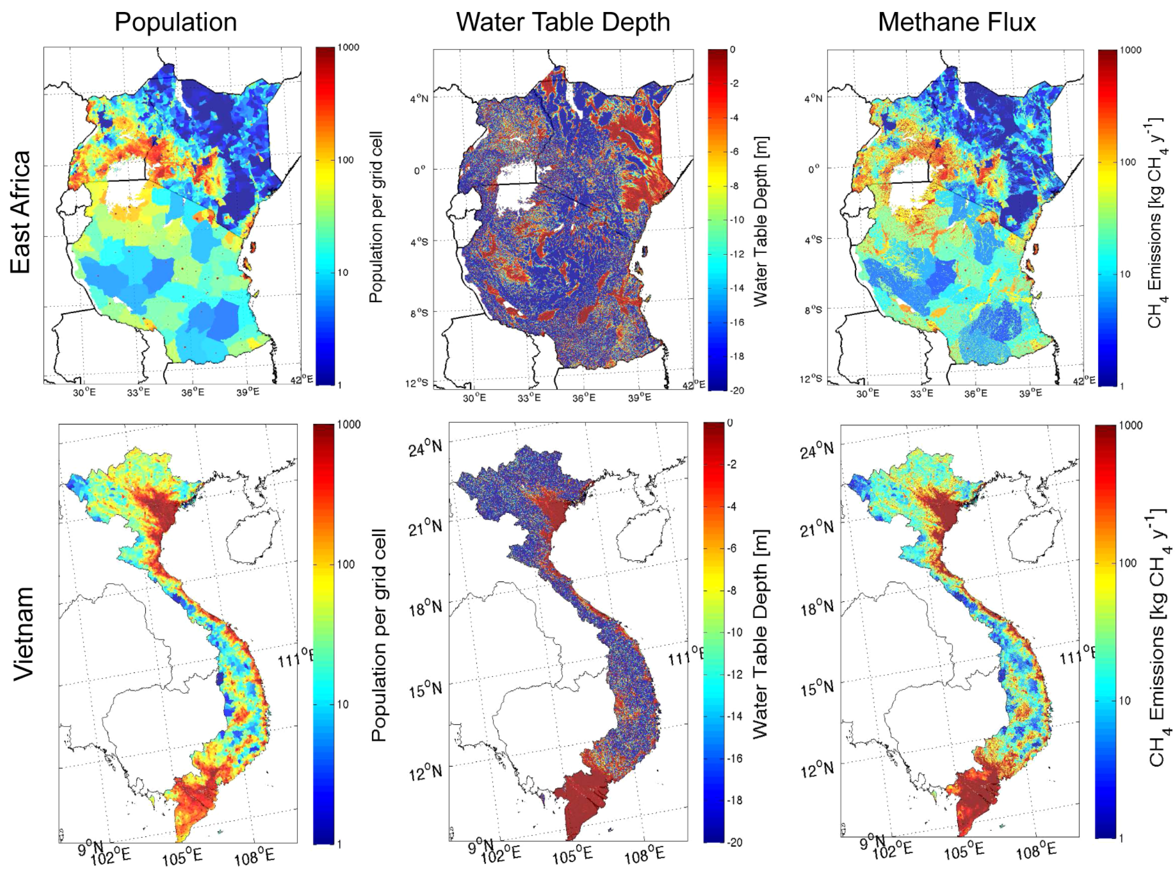

Figure 2. Regional variation in the colocation of population and shallow water tables, with impacts on pit latrine emissions, in East Africa (Kenya, Tanzania, and Uganda) and Vietnam.

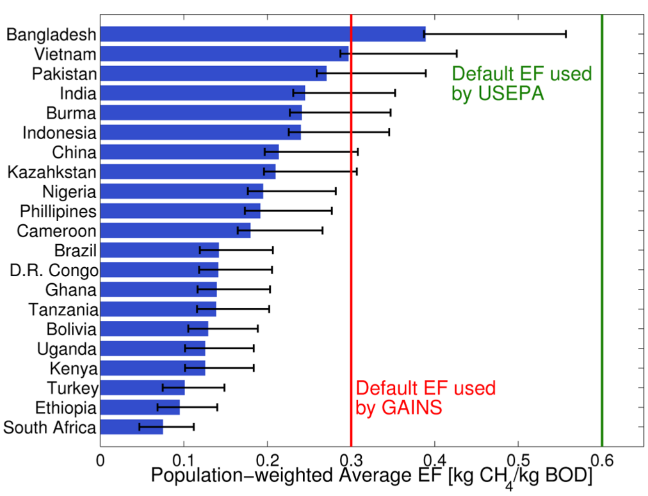

Figure 3. Population-weighted average emissions factors ($\overline{EF}$) in rural areas. Error bars were determined using uncertainties in pit latrine depth and in MCF for wet and dry pit latrines. The default EF used by ref 6 of 0.72 is outside the scale of this figure.

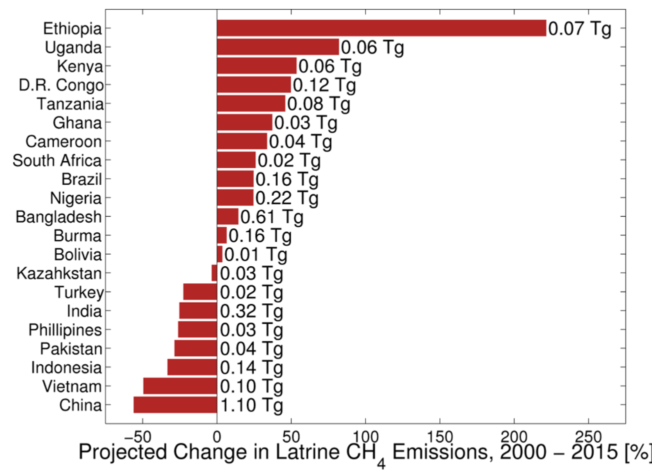

Figure 4. Projected percentage change in latrine CH_4 emissions from 2000–2015, with estimated 2015 emissions (in Tg y^{-1}) next to each bar.

difference in estimated emissions from India, for example (3.3 Tg y^{-1} by USEPA[6] vs 0.44 Tg y^{-1} by the present study in 2000), is due to an assumption of latrine utilization ratios in rural India of 47% by the earlier study, while recent surveys have shown the actual number is closer to 10%.[10,17] This discrepancy has led to a sharp downward revision of emissions estimates for India. There is better agreement between the present study and the GAINS integrated assessment model[3,24] for China and India, though GAINS uses lower latrine utilization ratios in southeast Asia relative to figures developed in the present study and those reported by Graham and Polizzotto[10] (Table S1, Supporting Information). This discrepancy leads to emissions estimates for Bangladesh, Vietnam, and other southeast Asian nations that are significantly lower than the estimates reported here.

The default EF employed by GAINS agrees relatively well with the $\overline{EF}$s derived here for Asian countries, though it is greater than our $\overline{EF}$ estimates for Brazil, Bolivia, and the African nations (Figure 3). The default EF of 0.72 used by ref 6 is significantly greater than our $\overline{EF}$ estimates for all countries, which explains why their emissions estimates are generally greater than the emissions reported in the present study.

The 21 countries in our sample include 1.51 of the estimated 1.77 billion global pit latrine users and thus contribute a major fraction of global pit latrine emissions. Many of the 260 million remaining latrine users are in sub-Saharan Africa, so using the regional BOD (Table 1) and representative regional $\overline{EF}$ of 0.12 kg CH_4 kg^{-1} BOD we conservatively estimate an additional 0.4 Tg CH_4 y^{-1} from populations not included in our 21 country sample. Total global pit latrine emissions are thus estimated to be 5.2 Tg y^{-1} (3.7−9.8) for 2000 and 3.8 Tg y^{-1} (2.7−7.0) for 2015. The 2000 estimate is intermediate between the 14 Tg CH_4 y^{-1} estimated by USEPA[6] and the 3.3 Tg CH_4 y^{-1} estimated by GAINS. For 2015 there is improved agreement between this study and GAINS, with estimates of 3.8 and 3.6 Tg y^{-1}, respectively.

Our global emissions estimate represents ∼2% of global anthropogenic CH_4 emissions in 2000 and ∼8% of CH_4 emissions from waste management.[7] These fractions decrease to ∼1% of total emissions and ∼5% of emissions from waste in 2015, as pit latrine emissions are projected to fall while total anthropogenic and waste-related emissions are expected to increase. Pit latrines contribute 25% of anthropogenic CH_4 emissions from Bangladesh and 5−10% from many African nations, though the fraction falls to ≤1% in countries with large agricultural sectors like Brazil or energy sectors like Bolivia or Kazahkstan (Figure S3, Supporting Information).[7]

Empirical Pit Latrine Emissions Estimates. Pit latrine CH_4 emissions measurements are not available in the literature, but gas production from a South African pit latrine sludge has been measured with laboratory incubations.[35] Surficial sludge produced gas at a higher rate (0.059 ± 0.013 mL gas g^{-1} sludge d^{-1} at standard temperature and pressure) than samples from the bottom of the pit (0.0025 ± 0.002 mL gas g^{-1} sludge d^{-1}). The fraction of CH_4, CO_2, and other trace constituents was not determined, but biogas is typically ∼50% CH_4.[27] Based on a representative fecal production of 400 g $person^{-1}$ d^{-1} for a largely vegetarian diet,[18] the biogas production from the fresh surficial sludge corresponds to 1.10 ± 0.25 kg CH_4 $person^{-1}$ y^{-1}. Using South Africa's $\overline{EF}$ of 0.075 (range: 0.047−0.112) kg CH_4 kg^{-1} BOD and the per capita BOD production for Africa, the model developed in the present study predicts a range of emissions from 0.64−1.51 kg CH_4 $person^{-1}$ y^{-1}, with a best estimate of 1.01 kg CH_4 $person^{-1}$ y^{-1}. The model prediction thus agrees well with the incubation measurement.

Post-2015 Outlook. Future changes in CH_4 emissions from pit latrines will depend on the balance between urbanization, which decreases reliance on latrines and thus reduces emissions, and expanded latrine coverage in rural areas that have been historically underserved by improved sanitation. High rates of open defecation (Figure S4, Supporting Information) indicate countries likely to be the foci of future sanitation interventions, and pit latrines are expected to remain the dominant form of rural sanitation due to cost and growing water scarcity in developing regions.[36,37] While the expansion of pit latrine use in these regions is difficult to predict, countries with growing rural populations (Figure S5, Supporting Information) along with high rates of open defecation are most likely to experience growth in pit latrine utilization. India, Pakistan, and Nigeria each combine limited sanitation coverage, rural population growth, and high $\overline{EF}$s and thus may experience strong growth in pit latrine CH_4 emissions. In contrast, urbanization in East and Southeast Asia will drive declines in rural population that may decrease latrine emissions, depending on the sanitation services available in cities.

Uncertainty Analysis. The uncertainty intervals reported in this study reflect uncertainties in pit latrine depth and the model parameters BOD, MCF, and T. Other sources of error may influence pit latrine CH_4 emissions in some settings but were difficult to quantify within the model framework. Raised pit latrines are sometimes built in locations with shallow water tables (e.g., Bangladesh) or where rocky soils prevent the excavation of deep pits.[18] Elevated latrines store excreta above ground level or in shallow pits, leading to a smaller fraction of pits below the water table, and consequently lower emissions, relative to estimates generated with our approach. The static groundwater level[16] used in our analysis is another potential error source, particularly in monsoon climates where water tables fluctuate seasonally by several meters. The net effect on CH_4 dynamics is unclear, since more aerobic conditions in premonsoon periods could be partially or fully balanced by flooded, anaerobic conditions during the monsoon. A third important uncertainty is the distribution of household and public pit latrines, as latrines with many users are associated with more anaerobic conditions and a higher EF.[14]

Mitigation Opportunities and Costs. CH_4 emissions from on-site sanitation can be reduced by using aerobic treatment or by capturing anaerobically produced CH_4 before it is released to the atmosphere. Aerobic decomposition can be most simply achieved by digging shallow pits that remain above the water table, which is also preferable for limiting groundwater pollution.[10] This approach will only reduce rather than eliminate CH_4 emissions since even "dry" latrines are partially anaerobic due to the commingling of liquid and solid waste. More fully aerobic disposal can be achieved through the use of well-maintained composting toilets, also known as ecological sanitation ("ecosan") methods. Composting toilets separate liquid and solid waste, and with proper maintenance the solids decompose aerobically to a nutrient-rich compost within a few months.[18] Composting toilets have traditionally been promoted for their low water use, avoided groundwater contamination relative to pit latrines, and the opportunity for nutrient recycling.[26]

Small-scale biogas digesters, in which human excreta are combined with manure and the generated CH_4 burned as an energy source, are another potential mitigation option.[27] While their advantages as renewable and clean-burning energy sources are well-recognized,[38] their climate benefits are equivocal due to the potential for significant leakage from poorly maintained systems which may negate emissions reductions due to fuel substitution or reduced latrine emissions.[39] Adoption of biogas may also be limited by the need for a reliable supply of manure as feedstock[27] and possible failure in cold climates.[40]

We estimate MACs for reducing emissions with these alternative on-site technologies in Africa and Asia (Table 2 and eq 4-5), since these are the regions likely to see the greatest growth in latrine emissions. MACs for composting toilets range from 46 to 97 \$/ton CO_2e in Asia and 47 to 944 \$/ton CO_2e in Africa. The upper limit of MACs is lower in Asia due to the combination of lower sanitation costs and higher emissions per latrine. These costs lie above the 80th percentile on the global curve of potential CH_4 mitigation costs, though they are

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competitive with some other measures in the waste management sector like source separation of municipal food waste (weighted average of 134 \$/ton CO_2e) or upgrading wastewater treatment plants to anaerobic treatment with biogas recovery (average 193 \$/ton CO_2e).[3] Benefits of CH_4 emissions reductions are estimated to range from 33 to 238 \$/ton CO_2e,[2] so in some settings composting toilets may be effective from a cost-benefit perspective without including the ancillary benefits of fertilizer and avoided groundwater contamination. The high MACs associated with household biogas digesters are a further drawback to their utility as mitigation measures.

Composting toilets have traditionally been promoted for reasons unrelated to CH_4 mitigation, so the recognition of a new benefit in CH_4 emissions reductions will only add to their existing advantages and may attract financing based on GHG mitigation opportunities. Before recommending specific mitigation actions, however, it is critical that both CH_4 and nitrous oxide (N_2O) emissions from on-site sanitation systems be characterized with greater certainty. N_2O is another potent GHG and is emitted from aerobic processes in municipal treatment plants,[41] though emissions from on-site systems are not known. Direct measurements of CH_4 and N_2O from pit latrines and composting toilets are not present in the literature but are needed to validate and improve emissions factors and inventories. We additionally caution that the adoption of composting toilets may be limited in some areas due to cultural sensitivities to the handling of human excreta.[18]

The future path of pit latrine CH_4 emissions depends on the spread of latrines into previously underserved areas in South Asia and sub-Saharan Africa and on the policies promoting specific sanitation technologies. Recognizing both the global importance of pit latrine emissions and the availability of appropriate on-site mitigation measures highlights potential synergies between water and sanitation development and GHG mitigation efforts. Opportunities for abating CH_4 emissions could mobilize financial resources to promote composting toilets, which are broadly preferable from water quality and sustainable development perspectives as well due to avoided groundwater contamination[10] and the opportunity for nutrient recycling.[26] This analysis demonstrates that the problem of pit latrine CH_4 emissions can be reframed as an opportunity to incentivize progress up the sanitation ladder to composting toilets or more advanced systems, yielding cobenefits for both GHG mitigation and water and sanitation development.

■ ASSOCIATED CONTENT

Supporting Information

Tables with complete sociodemographic data and emissions modeling results, additional figures, and population, water table, and CH_4 emissions maps for selected countries. This material is available free of charge via the Internet at http://pubs.acs.org.

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