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Authors

McNicol, Gavin
Jeliazovski, Julie
François, Junior Jules
et al.

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Climate change mitigation potential in sanitation via off-site composting of human waste

Gavin McNicol^{1,5}✉, Julie Jeliázovski², Junior Jules François^{2,3}, Sasha Kramer² and Rebecca Ryals^{1,4}

Approximately 4.5 billion people lack access to safely managed sanitation globally, and 1 billion live in slums, often relying on anaerobic waste containment in pit latrines. Providing access to safely managed sanitation may lead to reduced GHG emissions and thus simultaneously address both Sustainable Development Goals. Here we measure cumulative GHG emissions of carbon dioxide (CO₂), methane (CH₄) and nitrous oxide (N₂O) during the off-site composting of human waste to estimate scalable emission factors. We find that CH₄ emission factors are one to two orders of magnitude smaller than IPCC values for other excreta collection, treatment and disposal processes. After accounting for GHG emissions throughout the sanitation cycle, including transport, urine and compost end-use, the climate change mitigation potential is 126 kg of CO₂-equivalent per capita per year for slum inhabitants. If scaled to global slum populations, composting could mitigate 3.97 Tg CH₄ yr⁻¹, representing 13–44% of sanitation sector CH₄ emissions.

The global annual production of human faeces is likely to surpass 1 Pg of wet matter per year by 2030 (refs. ^{1,2}), driven primarily by population growth in slums, where faecal sludge is often contained anaerobically in pit latrines³. Tackling the public health impact of these untreated faecal matter fluxes is a sustainable development priority⁴ as they contributed to more than 870,000 sanitation-related deaths in 2016 (ref. ⁵). The provision of safely managed sanitation may offer a vital sustainable development synergy⁶ via the mitigation of GHG emissions. However, very few studies have quantified the potential reductions in GHG emissions when waste is diverted away from anaerobic containment systems^{7–9}.

Methane and N₂O are the most important GHGs directly produced from excreta in sanitation systems, as CO₂ emitted from human faeces is considered climate neutral¹⁰. Sanitation (encompassing all waste collection, treatment and disposal processes, including none) is estimated to account for 2–6% (9–30 Tg CH₄ yr⁻¹) of global CH₄ emissions¹¹, with 1–2% from pit latrines alone^{8,12}, and 1–3% of global N₂O emissions^{13,14}. By 2030, CH₄ emissions from the sanitation sector could be reduced by 30% using existing waste containment and treatment technologies¹⁵. However, quantifying GHG inventories and mitigation opportunities in sanitation is difficult due to the scarcity of data across different sanitation systems¹⁶, which can vary greatly in their propensity for anaerobic conditions and associated CH₄ and N₂O emissions^{11,17}.

Thermophilic composting (hereafter, composting) is a waste treatment technology used in circular sanitation designs (Fig. 1) that may mitigate GHG emissions relative to other waste fates, such as anaerobic pit latrines^{3,11}, stabilization ponds and open sewers⁹. Composting treatment approaches are increasingly being used in container-based sanitation (CBS) systems serving slum-dwelling populations who are otherwise reliant on pit latrines or open defecation^{3,16,18,19}. Composting sanitizes faecal matter after a prolonged initial thermophilic phase (>55 °C for about ten weeks)²⁰ via the transformation of the microbial community²¹, and produced

compost can be sold as an agricultural organic amendment that enhances crop growth and soil fertility^{18,22}. In addition, because effective composting requires aerobic conditions, well-managed composting favours climate-neutral CO₂ emissions over CH₄ (ref. ¹⁰), though emissions swapping from CH₄ to N₂O has been observed during the composting of agricultural solid wastes²³.

GHG emissions during off-site composting

We quantified cumulative CO₂, CH₄ and N₂O emissions over the composting treatment stages of a CBS service in Haiti to estimate scalable emission factors (EFs). We found that the dynamics of CO₂, CH₄ and N₂O emissions varied during the three management stages typical for the composting of human waste: Stage 1, static thermophilic; Stage 2, turned; and Stage 3, static curing¹⁸ (Fig. 2). Stage 1 exhibits an early thermophilic peak in respiration of >200 g of carbon from CO₂ (CO₂-C) per square metre per day, followed by a two-step exponential decline to ~50 gCO₂-C m⁻² d⁻¹. Methane emissions also peak in the first stage (~5 gCH₄-C m⁻² d⁻¹), following the peak in pile respiration. Turning in Stage 2 strongly aerates the material and causes a rapid reduction in pile volume¹⁸. We observed reinvigorated pile respiration in Stage 2, a peak in N₂O emissions and a complete loss of CH₄ emissions. All GHG emissions declined to close to zero in the static curing stage, as the pile material dried out and matured.

Off-site composting presents a range of operational decisions that can further impact GHG emissions, while human pathogen hazards can constrain management options in low-resource settings¹⁸. Pile management options that alter drainage, aeration or the use of bulking materials may further reduce CH₄ emissions, or may increase N₂O emissions (that is, emissions swapping), as observed in the composting of animal manure²³. Past work has found lower per-unit-area GHG emissions in composting treatment systems than in anaerobic containment systems⁹. However, robust and scalable EFs (that is, reported on per-unit-mass of waste) have not yet

¹Department of Natural Resources and Environmental Management, University of Hawai'i at Mānoa, Honolulu, HI, USA. ²Sustainable Organic Integrated Livelihoods, Cap-Haïtien, Haiti. ³L'Université Anténor Firmin, Cap-Haïtien, Haiti. ⁴Department of Life and Environmental Sciences, School of Natural Sciences, University of California, Merced, Merced, CA, USA. ⁵Department of Earth System Science, Stanford University, Stanford, CA, USA.

✉e-mail: gmcnicol@stanford.edu

Fig. 1 | Competing linear and circular models for sanitation and the associated environmental interactions from local to global scales. Linear sanitation (left) prevails globally and treats human excreta as waste, causing unsustainable environmental degradation that is mitigated at the cost of additional resources. Circular sanitation (right) treats human excreta as a resource, enabling sustainable environmental improvements that help recover costs. Non-profit research and development organizations are emerging internationally (for example, SOIL in Haiti, X-Runner in Peru, Sanivation and Sanergy in Kenya, and Safisana in Ghana) that use circular design to leverage the value of environmental improvements to make sanitation more affordable in low-resource settings.

been quantified for the composting of human waste under documented management conditions.

We tested the effects of two pile management options on GHG emission rates: a thicker cover material layer and the pile lining permeability of soil versus cement (Fig. 3). We expected that

these management options would impact GHG emissions via alterations to the biogeochemical conditions of compost piles^{10,23}. Fine-textured and aerated media have previously been found to support CH_4 -oxidizing microbial communities and to function as CH_4 biofilters²⁴. In our experiment, doubling the pile cover material depth from 10 cm to 20 cm increased the average pile temperatures by 2.5–3.1 °C (Supplementary Fig. 2), but it did not affect the overall respiration or CH_4 emissions (Fig. 3c). Methane reductions may require the engineered management of moisture and porosity, which was beyond the scope of this study. Greater cover material did, however, increase the mean nitrogen from N_2O ($\text{N}_2\text{O-N}$) emissions from 0.62% to 1.7% of initial waste N during Stage 2 (Fig. 3e), perhaps due to greater aeration as the cover material was mixed (via turning) into the pile. The pile lining experiment more closely followed our expectations. A permeable soil-lined pile led to drier base pile conditions ($74 \pm 2\%$ moisture by mass) than in the cement-lined pile ($90 \pm 1\%$) and threefold lower CH_4 emissions (Fig. 3d), though the lower oxygen concentrations observed in the top half of the soil-lined pile did not corroborate a mechanism of enhanced oxygenation (Supplementary Fig. 3). One important consideration for the implementation of permeable soil-lined piles is the risk of groundwater contamination via pathogen leaching early in the pile's lifespan, which should be addressed with further research.

Composting emissions compared with other waste fates

We report smaller CH_4 and larger N_2O emissions as a percentage of initial waste C and N ($\sim 0.5\%$ $\text{CH}_4\text{-C}$ and $\sim 1.5\%$ $\text{N}_2\text{O-N}$) for off-site composting than for containment or disposal systems typically found in the Global South (such as pit latrines; Table 1), reflecting predominantly aerobic compost pile conditions and confirming the findings of preliminary GHG surveys⁹. Source-separated faeces (from urine-diversion toilets) as a feedstock also seems to exhibit a more aerobic EF balance (lower CH_4 for similar or higher N_2O) than

Fig. 2 | GHG emission rate dynamics during three stages of thermophilic composting. a–i, Each Stage 1 (a,d,g) black circle is the mean (± 1 s.e.m.) CO_2 (a–c), CH_4 (d–f) and N_2O (g–i) emission rate ($n=12$) of a pile, and each Stage 2 (b,e,h) and 3 (c,f,i) black circle is an individual chamber flux measurement. The solid blue lines are smoothed spline fits to all mean or individual observations.

Fig. 3 | GHG emission rates during paired-pile management experiments.

a–f. Emissions of CO₂ (**a,b**), CH₄ (**c,d**) and N₂O (**e,f**) are standardized (reported as a percentage of initial waste C or N), accounting for pile characteristics, to enable comparisons across composting Stages 1 and 2 (Stage 3 was negligible) and management options (colouring), for the cover (**a,c,e**) and lining (**b,d,f**) experiments. The pile means (points), overall medians (centre lines), first and third quartiles (vertical box limits), ranges (whiskers) and outliers are displayed. Significant treatment effects are denoted by asterisks (in **d**, ****P* < 0.001, *t* = -3.847; in **e**, ***P* < 0.01, *t* = 2.603).

IPCC EFs for the composting of urban (~1.5% CH₄-C and ~1.9% N₂O-N) and animal wastes (~1.75% CH₄-C and 0.5–1.0% N₂O-N; ref. ¹⁷) or more recent empirical estimates for a range of feedstocks (1.6% CH₄-C and 1.3% N₂O-N; ref. ²³), suggesting that a simple substitution of other EFs for source-separated faeces may overestimate

GHG emissions. We propose that urine diversion, the high bulking-agent-to-waste ratio (~2:1) and the fibre content of faeces may result in a drier and more recalcitrant compost feedstock that shifts the pile towards aerobic conditions. This is also supported by the stability of the compost product (Supplementary Table 3), despite a relatively low feedstock biodegradability (22.5% CO₂-C emission); however, more research will help elucidate the mechanism.

Combining the EF_C and EF_N (Table 1), we estimate an average global warming potential (GWP) of 0.46 ± 0.08 kg of CO₂-equivalent (CO₂e) per kilogram of biological oxygen demand (BOD), which is much lower than the GWP of other waste fates (Table 1): approximately 4-fold lower than direct environmental discharges, 20-fold lower than stagnant (open) sewers and 27-fold lower than wet pit latrines. Overall, composting produced 0.95 ± 0.1 kg CO₂e kg⁻¹ BOD, with 52% from climate-neutral CO₂ emissions, 15% from CH₄ and 34% from N₂O. Deeper cover material increased the GWP (0.23 ± 0.12 kg CO₂e kg⁻¹ BOD) via enhanced N₂O, more than permeable soil lining decreased the GWP (0.12 ± 0.06 kg CO₂e kg⁻¹ BOD) via reduced CH₄.

Upscaling composting emissions reductions

By substituting EFs for composting with those of typical waste fates (pit latrines and direct discharge; Table 1), we estimate the climate change mitigation potential via changes in GHG emissions, from local to global scales. In the composting fate, we consider other sanitation-cycle GHG sources and sinks from transport, urine and soil compost amendments (Methods). Briefly, transport emissions (0.15 kg CO₂e kg⁻¹ BOD) could be offset by a conservative range of soil carbon sequestration rates (−0.05 to −0.34 kg CO₂e kg⁻¹ BOD), whereas N₂O emissions from urine were not negligible (0.54 kg CO₂e kg⁻¹ BOD).

After accounting for the full sanitation cycle (including avoided emissions), the climate change mitigation potential of off-site composting is 8.6 kg CO₂e kg⁻¹ BOD, in agreement with negative life-cycle emissions reported for a circular manure and green waste composting system in California²⁵. Upscaling across global slum populations, the climate mitigation potential ranges from 0.0126 Tg CO₂e yr⁻¹ for a single city or municipality to 126 Tg CO₂e yr⁻¹ for the current global slum population (Fig. 4), reducing GHG emissions by 92%. The global mitigation potential is due to a 99% reduction in CH₄ emissions from 4.03 to 0.06 Tg CH₄ yr⁻¹ and an increase in N₂O emissions from 1 to 32 Gg N₂O yr⁻¹. Our typical waste fate CH₄ emissions estimate is therefore congruent with the 2.3–6.6 Tg CH₄ yr⁻¹ range⁸ previously reported for the ~1.77 billion global pit latrine users³.

Table 1 | Cumulative GHG emissions as a percentage of initial waste C and N, EFs for CH₄ (EF_C) and N₂O (EF_N) and global warming potential (GWP) of combined emissions for waste fates typical of informal settlements lacking centralized wastewater treatment infrastructure

Waste fate	CO ₂ -C (%)	CH ₄ -C (%)	N ₂ O-N (%)	EF _C kg CH ₄ kg ⁻¹ BOD	EF _N kg N ₂ O kg ⁻¹ waste N	GWP kg CO ₂ e kg ⁻¹ BOD
Off-site composting	23	0.5	1.5	0.004	0.024	0.46
	21–24	0.2–0.7	0.8–1.9	0.002–0.006	0.013–0.03	0.23–0.6
Environmental discharge	—	10	0.3	0.06	0.005	2
Lagoon (shallow)	—	20	0	0.12	0	3.6
Stagnant sewer	—	50	0	0.3	0	9
Dry pit latrine	—	50	0	0.3	0	9
Septic system	—	50	0	0.3	0	9
Wet pit latrine	—	71	0	0.42	0	12.6
Lagoon (deep)	—	81	0	0.48	0	14.4

EFs for off-site composting are the overall averages (top) and the management option ranges (bottom) of cumulative emissions, calculated as the sum of Stage 1–3 emissions. The other data are IPCC EFs¹²³¹.

Fig. 4 | Local- to global-scale climate change mitigation potentials at different levels of waste diversion to composting. Calculations integrate both CH_4 and N_2O forcing effects and assume that Haiti's consumption and excreta biogeochemistry, and Cap-Haïtien's waste fates, are representative of informal urban settlements globally. Darker shading corresponds to greater GHG mitigation ($\text{Tg CO}_2\text{e yr}^{-1}$).

Sanitation biogeochemical cycles

Circular sanitation systems may offer synergistic solutions to multiple Sustainable Development Goals^{6,26}; however, few data exist to evaluate the potential impacts on biogeochemical processes. Recent top-down studies have explored potential global nutrient recovery from urine and faeces², as well as sanitation intersections with ecosystem services, including climate regulation²⁷, whereas we explore climate mitigation potential from the bottom up, using empirical data from new sanitation systems. Here we find that the mitigation of sanitation GHGs is possible using off-site composting of human waste due to large CH_4 reductions that outweigh smaller N_2O increases. At local scales, we estimate a GHG mitigation effect of 126 kg CO_2e per capita per year for slum residents whose waste is composted, which may provide a revenue stream for sanitation services via offset credits²⁸. At the global scale, we estimate that the implementation of human waste composting for the 1 billion people who live in slums could mitigate 13–44% of CH_4 emissions from the sanitation sector¹¹.

Slow development in the provision of safely managed sanitation may reflect scientific deficiencies in our understanding of the biogeochemistry of human waste. Biogeochemical cycling in sanitation systems may have been overlooked due to the relatively small magnitude of global human waste production ($\sim 100 \text{ Tg C yr}^{-1}$; refs. 1,2) compared with other biosphere processes, such as gross primary productivity ($\sim 120 \text{ Pg C yr}^{-1}$; ref. 29), as well as the reluctance to break cultural taboos³⁰. However, we believe that the biogeochemistry of sanitation is important to study because: (1) excreta flux is growing due to its inherent coupling with population and consumption growth, (2) untreated excreta is hazardous to human health and is increasingly concentrated within vulnerable slum populations due to urbanization, and (3) circular design applied to sanitation can lead to environmental improvements by reconceiving excreta as a resource. More data are needed to build an empirical foundation for bottom-up modelling of the biogeochemistry of sanitation, including information on the sizes of relevant pools and fluxes, and their interactions with environmental systems across local to global scales.

Online content

Any methods, additional references, Nature Research reporting summaries, source data, extended data, supplementary information,

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Methods

Study site and region. The study was conducted at a human waste composting facility (Mouchinèt; 19°40'38.9" N, 72°06'49.3" W) operated by the non-governmental organization Sustainable Organic Integrated Livelihoods (SOIL; www.oursoil.org). The site is located 17 km southeast of Cap-Haïtien in the North Department of Haiti. The meteorological conditions in northern Haiti reflect a tropical monsoon climate with average daytime temperatures during the study ranging from 26.1 ± 2.8 °C in February to 31.2 ± 2.3 °C in September, consistently high daytime humidity (>70%), and a bimodal precipitation distribution with peaks in rainfall occurring around March and October (Supplementary Fig. 1; SOIL Meteorological Station). The greater Cap-Haïtien area has a population of approximately 274,000 with 45% younger than 18 years old³². The residents are vulnerable to preventable, diarrhea-related mortality, with greater than tenfold increases in mortality rates reported for a Cap-Haïtien slum during the peak of the 2010–2011 Haitian cholera epidemic³³.

SOIL thermophilic composting. SOIL began operating in Cap-Haïtien in October 2012 and provides CBS services to slum residents via EkoLakay and EkoMobil programmes. EkoLakay uses urine diversion toilets that separate liquid and solid waste, and coarsely ground sugarcane bagasse (hereafter, bagasse) to cover waste after each use. EkoLakay services small (20 l) composting toilets in ~1,000 private households, while larger non-urine-diversion composting toilets (60 l) are serviced via the EkoMobil programme. The toilet containers reach capacity, are collected approximately weekly and are brought to the centralized compost facility using pickup trucks, flatbed trucks and motorized tricycles. In the 2016–2017 fiscal year, concurrent to this study, 443 tonnes (t) of wet material was collected and transported to the Mouchinèt composting facility from EkoLakay and 25 t (6%) from EkoMobil.

SOIL's CBS sanitation collection service is paired with off-site composting treatment, which is an established means of reducing pathogen levels in human faecal material. Thermophilic (>55 °C) compost temperatures have been shown to lead to *Ascaris* egg inactivation after approximately 6 weeks, while *E. coli* is reduced to undetectable levels after 16 weeks³⁰. The microbial community is transformed from one of predominantly human faecal bacterial populations to one resembling compost produced from other feedstocks, such as animal manure²¹.

At Cap-Haïtien, three compost stages are used to produce sanitary compost and reflect SOIL's current best practices. Static aerobic compost bins are used for the first 10–15 weeks (Stage 1) of composting while the material is still pathogenic. The bins measure approximately 4 m × 2 m × 2 m and are constructed of wooden shipping pallets packed with bagasse (a carbon-rich bulking agent) with a cement floor lining. The small urine diversion toilets typically provide a composting feedstock of faeces and bagasse, but the large toilets, and misuse of the small toilets, can introduce urine. Therefore, the bins are installed with a PVC pipe to drain excess fluid into an adjacent subsurface tank and ensure that the piles are dry enough to reach thermophilic conditions¹⁸. When the bins are being filled, they are first lined with ~30 cm of bagasse, then filled with feedstock directly from a combination of 20 l and 60 l containers at a ratio of 14:1 to make the moisture conditions consistent. A bagasse-to-waste ratio of approximately 2:1 is used. Finally, the piles are capped with a 10 cm layer of bagasse to block insect vectors, avoid wind dispersal of the material and retain heat¹⁸, and the containers are washed and reused. After eight to ten weeks, the bin is emptied onto an inset cement floor (Stage 2), which is turned every two weeks for approximately eight weeks. The greatest volume reduction of the material occurs in this second turned stage. Finally, the material is left to cure for two to four months in windrows (Stage 3) before being sieved and bagged as sellable compost. The final compost analyses conducted by A&L Great Lakes Laboratories indicate a highly mature compost product (Solvita = 8), a final C:N of 7.8:1 and a total organic C content of 23.5% (SOIL, personal communication; the full dataset is in Supplementary Table 3).

Experimental design. In a 2014 survey⁹, we observed lower GHG emissions on an area basis from SOIL's composting than from other waste disposal fates in Haiti. We identified the need to report CO₂, CH₄ and N₂O emissions for the composting of human waste in scalable IPCC units (mass basis). To achieve this, in the present study, we undertook comprehensive measurements of gas exchange over the three composting stages, replicating in space and time. We used a grid-based spatial sampling design for gas flux chamber placement in Stage 1 piles, a stratified random design for Stage 2 and a random sampling design for Stage 3. In preliminary work⁹, we found that a four-by-three grid ($n = 12$) of chambers placed on both cement-lined and soil-lined Stage 1 piles showed strong trends towards higher CO₂ and CH₄ and lower N₂O emissions rates at the centres of the piles (Supplementary Fig. 4). Random sampling is not justified when surfaces feature non-random spatial patterning because it can lead to biased estimates if hot spots are unsampled. We therefore continued the highly replicated ($n = 12$) grid-based sampling from the preliminary work into the present study, to increase the likelihood that the pile spatial gradients were captured and were weighted in proportion to their respective pile surface areas in the pile mean calculations. The distributions of CO₂ and CH₄ emissions during the sampling campaign for this study validated our use of this sampling design (Supplementary Fig. 5). For Stage 2, we found that using a four-by-two grid-based sampling design, one and three days after pile turning, did not reveal consistent spatial gradients to justify grid-based

sampling as in Stage 1 (Supplementary Fig. 6). However, as Stage 2 piles are long and narrow, we avoided randomly clumped measurements by placing chambers ($n = 3$) approximately evenly along the length of the pile and approximately halfway up the face of the pile. For Stage 3, preliminary work indicated that gas emission rates would be low and less variable. We therefore used simple random sampling within each pile ($n = 3$) and focused sampling resources on the larger and more variable fluxes in Stages 1 and 2. The preliminary work also indicated that the greatest temporal flux dynamics would be observed in Stage 1; therefore, sampling was more frequent (weekly) during Stage 1 and less frequent (bi-weekly) during Stage 2 (Supplementary Tables 1 and 2), while piles of different ages were randomly selected in Stage 3 as a substitute for temporal replication.

We also investigated the effects of two management options (cover material depth and pile lining permeability) that may mitigate GHG emissions from the static thermophilic stage. We used paired treatment and control compost bins for each experiment, in which the business-as-usual practice was designated as the control. In the cover experiment, we compared a compost bin capped during Stage 1 with the standard 10 cm of bagasse¹⁸ with a bin capped with approximately double that (~20 cm), and the additional surficial bagasse was incorporated when turning the pile in Stage 2. In the lining experiment, we compared a Stage 1 bin lined with an impermeable cement floor and fitted with a PVC drain, with an unlined bin with a permeable soil floor and without the PVC drain. The Stage 2 floors were also lined and unlined, respectively. Paired bins were filled at the same time (Supplementary Table 1), or as close as possible, and paired experimental comparisons were repeated three times (hereafter, rounds), between November 2016 and August 2017, providing a time-for-space substitution in replication.

Gas flux and material sampling. Gas samples for static and turned phase GHG fluxes were collected using non-steady-state (static) flux chambers. The chambers were constructed from 20 l buckets with the bases removed. The chambers were installed 5–10 cm deep in the pile material. The chamber lids were outfitted with a ¼-inch bulkhead fitting that acted as a septum port to allow 30 ml gas samples to be withdrawn using a needle and syringe. A short length of narrow-gauge stainless-steel tubing was inserted into the lid to minimize sampling-induced pressure changes within the chamber. Finally, an additional ¼-inch hole was drilled and fitted with a removable plastic cap to allow for beginning- and end-of-incubation temperature measurements.

For each flux measurement, the lids were placed on the chamber bases, and 30 ml headspace samples were collected at five time points (0, 5, 10, 20 and 30 min) and were stored at positive pressure in pre-evacuated 20 ml vials (Wheaton) capped with thick rubber septa (GeoMicrobial). The internal chamber dimensions were measured to calculate chamber volume, and initial ambient and final internal chamber temperatures were measured with calibrated portable thermometers (Davis Instruments). The compost temperature was recorded manually in each pile at both 15 and 45 cm, at the corner, edge and centre of the pile, and turned pile dimensions were recorded to estimate the pile material volume and mass each week. We also quantified gas fluxes from six windrows (final composting stage) using pre-weighed 1 l plastic tubs with removable lids that were fitted with rubber septa. The tubs were half-filled with windrow material, reburied in the pile surface while the gas samples were collected (as above) and weighed to calculate the material mass afterwards.

Material subsamples were collected in triplicate at 30, 60 and >90 cm from the exposed face of each static pile immediately before it was turned into the second phase for estimates of the initial material moisture and CN content and from windrow tubs for the final material values. Volumetric samples were also collected by pressing a plastic tube into the compost material at the same depths in the pile face and weighing quantitatively for dry bulk density, corrected for moisture content. The dry bagasse bulk density was measured by weighing gently compacted bagasse in 20 l containers ($n = 4$) and adjusting for bagasse moisture.

Temperature and oxygen sensors. In the third round of the study (Supplementary Table 1), temperature and oxygen concentrations were measured in the experimental piles at two depths (15 cm and 45 cm) and three pile locations (corner, edge and middle) to understand the biogeochemical effects of the treatments. The cover experiment piles were installed with rugged Campbell Scientific 108-10-PT temperature probes (range, −5 to 95 °C), while the lining experiment piles were installed with galvanic-cell oxygen sensors (Apogee Instruments) that use a thermistor for temperature measurement. The oxygen sensor output was calibrated with readings under oxygen-free air (flushing jars with dinitrogen gas) and in ambient air conditions at the compost site.

Laboratory analyses. The gravimetric moisture was determined by oven-drying the subsamples for 24 h at 105 °C. The mass content of C and N was determined on an elemental analyser (Cotek Analytical Technologies) at the University of Hawaii at Hilo Analytical Laboratory. The gas samples were analysed for concentrations of CO₂, N₂O and CH₄ on a gas chromatograph outfitted with a thermal conductivity detector, an electron capture detector and a flame ionization detector (Schimadzu Analyzer 5000-A at the University of California, Merced, and Schimadzu GC-2014 at the University of Hawaii at Mānoa). The instrument was calibrated with a standard curve for CH₄ (1, 2, 5, 10, 500 and 5,000 ppm(v)), CO₂ (0.04, 0.1,

0.2, 0.5 and 2 ppm(v), 5%) and N₂O (0.4, 1.01, 2, 5, 10 and 20 ppm(v)). The responses were linear for CO₂ and CH₄, and nonlinear (asymptotic) for N₂O. High (0.5 or 2%) and low (5 ppm(v)) CH₄ standards were run alternately every tenth sample.

Flux calculations. Gas fluxes (grams of CO₂-C, CH₄-C or N₂O-N per square metre per day) were calculated using:

$$\text{GHG flux} = S \times \frac{PV}{RT} \times \frac{Ms}{A_{\text{sc}}} \times 10^{-6} \quad (1)$$

where S is the slope coefficient of a linear fit to the change over time in the chamber gas concentration (ppm(v) s⁻¹); P , V and T are the air pressure (kPa), internal volume (m³) and average temperature (in K) of the chamber, respectively; R is the ideal gas constant (8.1314 J mol⁻¹ K⁻¹); s is seconds per day; A_{sc} is the cross-sectional area of the chamber (m²); and M is the mass of C or N (g) per mole of GHG. Due to the high fluxes of all gases, Stage 1 fluxes were valid when the linear fit $R^2 > 0.95$. The final time point was sometimes excluded to improve poor fits, or the linear component of a second-order polynomial fit was taken. Zero fluxes were identified (and not excluded) with both low R^2 and a very small (<50%) concentration change between the first and last time points. Flux uncertainty was estimated as the mean $\pm$ one standard error of the pile observations and was added in quadrature where necessary. The cumulative pile fluxes were calculated by scaling the mean pile fluxes spatially, from the chamber area to the measured pile horizontal surface area (9.03 m² for Stage 1 and 12.9 m² for Stage 2), and temporally by pile duration. Slight differences in stage lengths were accounted for during scaling and are treated as typical variation associated with composting.

Statistical tests. The flux data followed a positive skewed distribution in Stage 1 due to the gridded sampling (few high fluxes); however, the mean pile fluxes for each sampling date were normally distributed and therefore not transformed for analysis. The first four weeks of data were excluded from the statistical analyses (but not from the cumulative emissions) in the lining experiment and the first and seventh weeks were excluded from the cover experiment due to asynchronous sampling across the respective treatments and controls. Two linear mixed-effects models were implemented with the `lme` function in the `nlme` package (v.3.1; ref. ³⁴) in R (v.3.5.2; ref. ³⁵) to determine the statistical significance (two-sided) of Stage 1 treatment differences among the two paired pile experiments. The treatment was a fixed effect, and the sampling round was a random effect (cover, d.f. = 32; lining experiment, d.f. = 46). Significant treatment effects in Stage 2 were determined with simple linear regression (two-sided) using the `lm` function in the R `stats` package (cover, d.f. = 17; lining, d.f. = 8).

Scalable fluxes and EFs. The cumulative pile fluxes, expressed on a unit-area (m²) basis, were converted into scalable values (kilograms of CO₂-C, CH₄-C or N₂O-N per kilogram of treated waste C or N). Waste C and N were estimated from the total drum and bucket volume used to create each pile (23–27 m³), adjusted for the average pile dry bulk density (0.13 g cm⁻³) and C (~40%) and N (~3%) content. The pile dry bulk density was calculated from the mean dry weight of the volumetric cores (collected as described above), the faeces bulk density from only mid-pile cores, and the bagasse bulk density from filled 201 containers, adjusted for moisture. The initial pile mass was reduced by a scaling factor, to account for the addition of the bulking agent (bagasse) to the faeces. The scaling factor (0.5) was estimated with a simple mixing model, using the bulk density of the settled (compressed) bulking agent (0.08 g cm⁻³), the faeces (0.18 g cm⁻³) and the final combined pile material (0.13 g cm⁻³), reflecting a bagasse-to-waste volume ratio of 2:1. As bulking agents are likely to be recalcitrant fibrous material with low decomposability, it is important to remove their contribution to the pile mass to avoid diluting the waste EFs. In this study, by removing the bagasse mass contribution entirely, we conservatively attribute all emissions as arising from faeces. We chose this approach in the absence of any bagasse decomposition data. The EF_C values were rescaled into IPCC units (kg CH₄ kg⁻¹ BOD) using a BOD:TOC ratio of 1.68:1 and the CH₄:CH₄-C molar mass ratio³⁶. The EF_N values were rescaled using the N₂O:N₂O-N molar mass ratio. We calculated separate EFs for each of the four management options in the two paired-pile experiments. We report the mean of those EFs as the overall average for SOILs off-site composting treatment process, and the minimum and maximum of those EFs as a range that reflects primarily the range of conditions imposed by the different management options but also, to a lesser extent, the inherent pile-to-pile variability of the composting system.

Sanitation cycle emissions. Although the focus of this study was to determine the EFs for composting treatment of human waste, we also approximate GHG emissions from three potentially important sanitation cycle components associated with off-site composting: collection and transport system, indirect urine N₂O emissions, and soil carbon sequestration. Off-site composting requires considerably more transportation than on-site containment or treatment systems, such as pit latrines. We used 2019 transportation data for SOILs operation including vehicle type, distance driven, gas mileage and annual gas consumption. We used these data with the *IPCC Guidelines for National Greenhouse Gas Inventories, Volume 3: Mobile Combustion*¹⁷ to estimate total

transportation emissions of CO₂ of 10.7 t CO₂e yr⁻¹. Converting the total collected wet material in 2019 (492 t yr⁻¹) to the mass of waste C (42.7 t C yr⁻¹) indicates transportation CO₂-C emissions of 6.8% waste C, adding ~32% to the GWP for off-site composting (GWP + transportation = 0.61 kg CO₂e kg⁻¹ BOD). Off-site composting may also cause indirect N₂O emissions (IN) after soil deposition of volatilized ammonia (NH₃), pile leaching into soils (when not lined with cement) and the environmental disposal of urine from source-separating toilets. We assume that 20% of the initial waste N (~8 kg per pile) is lost via NH₃ volatilization during composting³⁷, and we conservatively assume that it all eventually deposits to soils. We also assume that 80% of N is excreted in urine rather than faeces³⁸, amounting to a further ~200 kg N per pile deposited to soil from users or via pile leaching. The *IPCC Guidelines for National Greenhouse Gas Inventories, Chapter 4: Agriculture, Forestry, and Other Land Use*¹⁷ Tier 1 EF for N₂O emitted following N deposited as urea is 1%, indicating indirect N₂O-N emissions of 0.042 kg N₂O per kilogram of waste N, adding 0.54 kg CO₂e kg⁻¹ BOD to the GWP (+117%) for off-site composting. Urea fertilizer can be displaced by the N content of the final compost (~32 kg per pile), offsetting some IN; however, in Haiti, mineral fertilizer use is very low, so we assume zero displacement (GWP + transportation + IN = 1.15 kg CO₂e kg⁻¹ BOD). Finally, there is considerable potential for compost to sequester C in agricultural and forest soils, though there is no data for compost application in Haiti. A one-time application of compost to grazing lands in California demonstrated sequestered C rates of ~0.5 to ~3.3 t Cha⁻¹ yr⁻¹ (refs. ^{39,40}), and we consider these rates conservative due to the degradation of Haitian soils⁴¹. We compute C sequestration rates equivalent to 2.4–15.8% of waste C, or ~0.05 to ~0.34 kg CO₂e kg⁻¹ BOD (GWP + transportation + IN + sequestered C = 0.81–1.1 kg CO₂e kg⁻¹ BOD).

Scaling GWP. To calculate the GWP of emissions from typical and composting waste fates, we used conversion factors of 34 kg CO₂e per kg CH₄, and 298 kg CO₂e per kg N₂O (ref. ⁴²). We acknowledge recent work⁴³ indicating that higher GWP values are more accurate for sustained (non-pulse) ecosystem emissions, but we prioritized comparability with other emissions inventories that use IPCC values. To scale by the population size utilizing composting, we used a BOD production rate of 40 g per capita per day⁴⁴, a protein consumption/excretion rate of 44.108 g per capita per day, and a protein N content of 0.16 kg N per kilogram of protein. We did not scale for non-faecal N sources as is done for household organic waste calculations¹⁷. These values are country-specific for Haiti; however, we assume that they are typical of urban slum residents internationally for the global upscaling estimates. A more detailed inventory was beyond the scope of this study. The waste BOD and N mass values were used in combination with the default EF_C (0.6 kg CH₄ kg⁻¹ BOD) and EF_N (0.005 kg N₂O kg⁻¹ BOD_N), adjusted by CH₄ and N₂O correction factors for dry pit latrines (0.5 and 0) and direct discharge (0.1 and 1; ref. ¹⁷). The values have remained unchanged in the 2019 IPCC update to the wastewater treatment chapter⁴¹. We also assume that waste is being redirected from a 90:10 split of pit latrines and direct discharge on the basis of a recent Inter-American Development Bank report for Cap-Haïtien that found that ~12% of waste was directly disposed into the environment via open defecation, while ~87% was deposited in a pit latrine before being disposed, untreated⁴⁵. To scale indirect N₂O emissions, we assumed that 80% of N is excreted in urine³⁸.

Reporting Summary. Further information on research design is available in the Nature Research Reporting Summary linked to this article.

Data availability

The datasets generated and/or analysed during the current study are available from the corresponding author on reasonable request. Source Data for Figs. 2 and 3 are provided with the paper.

Code availability

The code for the figures and analysis in the current study are available from the corresponding author on reasonable request.

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Author contributions

G.M. and R.R. designed the study and wrote the manuscript. J.J. assisted with the sample collection and site logistics and contributed to the manuscript writing. J.J.F. contributed to the site logistics and organized the sample collection. S.K. contributed to the study design and manuscript writing.

Competing interests

The authors declare no competing interests.

Additional information

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Correspondence and requests for materials should be addressed to G.M.

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Software and code

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Data collection

Gas concentration data used to compute fluxes were obtained with Shimadzu's GCsolution. Compost pile sensors were programmed and data were retrieved using Campbell Scientific LoggerNet 4 software.

Data analysis

Linear mixed-effects models were implemented with the lme function in the nlme package (v3.1; Pinheiro et al. 2019) and linear regression models were implemented with the lm function in the stats package in R (v.3.5.2; R Core Team 2019 (www.R-project.org)).

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Study description	This study used gas flux chamber measurements to quantify cumulative greenhouse gas emissions of carbon dioxide, methane, and nitrous oxide during the human waste composting operation of a Haitian sanitation service. Paired-pile (treatment and control) experiments were used to test the effects of pile management options on emissions. Cumulative composting emissions, and the potential for mitigation of emissions from typical waste fates, were upscaled from local to global slum population scales using an IPCC emissions inventory approach.
Research sample	The dataset used to compute cumulative composting emissions consists of over 8,000 gas concentration samples, collected from November 2016 to October 2017. Samples were collected from non steady-state flux chambers installed over or within compost piles during different operational stages and were used to compute over 1,000 flux measurements of carbon dioxide, methane, and nitrous oxide. Cumulative fluxes for each stage, and in sum, were computed based upon pile dimensions and duration. Emissions factors were computed by normalizing cumulative fluxes by the mass of initial waste biological oxygen demand, in proportion to measured total organic carbon content.
Sampling strategy	Sampling strategy varied between composting stages. We used a model-dependent sampling design in stage one due to consistent spatial patterning of fluxes and temporal trends (Ryals et al. 2019). Pile surfaces were segmented on a four-by-three grid (n = 12) and installed with permanent chambers that were sampled weekly. We used a spatially stratified random sample for stage two due to the lack of a spatial pattern. We divided piles into three length-wise sections, with one weekly to bi-weekly measurement per section (n = 3). We used a spatially and temporally random sampling design for stage three due to lower flux variability and made triplicate flux measurements across piles of different ages from May to October 2017.
Data collection	<p>Gas samples for stage one and two GHG fluxes were collected using non-steady-state flux chambers. Chambers were constructed from 20 L buckets with bases removed. Chambers were installed 5-10 cm deep in pile material and lids were outfitted with a ¼-inch bulkhead fitting that acted as a septum port to allow 30 ml gas samples to be withdrawn using a needle and syringe.</p> <p>For each stage one and two flux measurement, lids were placed on chamber bases, 30 ml headspace samples collected at five time points (0, 5, 10, 20, 30 min) and were stored at positive pressure in pre-evacuated 20 ml vials (Wheaton, USA) capped with thick rubber septa (GeoMicrobial, UK). Internal chamber dimensions were measured to calculate each chamber volume along with initial ambient, and final internal, chamber temperatures measured with calibrated portable thermometers (Davis Instruments, IL, USA). Compost temperature was recorded manually in each pile at both 15 and 45 cm, at the corner, edge, and center of the pile and turned pile dimensions were recorded to estimate pile material volume and mass each week. For stage three gas fluxes, we used pre-weighed 1 L plastic tubs with removable lids that were fitted with rubber septa. Tubs were half-filled with windrow material, reburied in the pile surface while gas samples were collected, and weighed to calculate material mass afterwards. SOIL hired local agronomy students as composting interns who collected the samples and recorded the data by hand on printed sheets.</p>
Timing and spatial scale	Stage one sampling was repeated three times from November 2016 to August 2017. Each round lasted approximately 3 months and samples were collected weekly, capturing the annual range in meteorological conditions. Stage two sampling was performed once from August 2017 to October 2017, following the final round pile material from stage one, with weekly to bi-weekly sampling.
Data exclusions	Gas flux data were excluded below a coefficient of determination threshold. The first 4 weeks of data were excluded from statistical analyses in the lining experiment and 1st and 7th weeks were excluded from the cover experiment due asynchronous sampling across the respective treatment and controls.
Reproducibility	The composting operation we studied is an exemplary sanitation service that uses a published three-stage waste treatment method that can be readily replicated by other researchers or services (Preneta et al. 2013). Greenhouse emission data cover four paired-piles that were sampled in three rounds during a 10-month period and paired treatment and control piles were initiated within two weeks of each other and built using a similar ratio of large and small waste containers. The overall averages and uncertainties therefore encompass a range of ambient tropical meteorology, and typical operational variation in pile composition and duration. The high spatial density of sampling that used a model-dependent grid design minimized uncertainty in flux estimates to approximately 6%.
Randomization	Randomization was only applicable during stage two and three sample collection. In stage two, chamber location on the pile was randomized within three length-wise strata due to a lack of a consistent spatial pattern in prior observations (Ryals et al. 2019) and in stage three, the choice of the pile, affecting pile maturity, and the location of the sampling was randomized. A model-dependent sampling design was used in stage one with consistent sampling across a spatial grid, rather than randomized sampling.
Blinding	This is not relevant to this study because we made empirical measurements of greenhouse gas emissions during the composting of human waste.
Did the study involve field work?	☒ Yes ☐ No

Field work, collection and transport

Field conditions	Meteorological conditions in Northern Haiti reflect a humid tropical climate with average daytime temperatures during the study ranging from 26.1 ± 2.8 °C in February to 31.2 ± 2.3 °C in September, consistently high daytime humidity (> 70%), and a bimodal precipitation distribution with peaks in rainfall occurring around March and October. Due to a lack of existing local data, a
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meteorological station was constructed at the composting facility.

Location	The study was conducted at a human waste composting facility (Mouchinèt: 19°40'38.9"N, 339 72°06'49.3"W) operated by SOIL. The site is located 17 km southeast of Cap-Haïtien in the North Department of Haiti.
Access and import/export	SOIL provided transport locally between Cap-Haitien to the off-site Mouchinette composting facility. Personal protective clothing and boots were provided to all contributors as part of standard protocol. Gas samples, and approximately 50 gram compost samples, were returned from Haiti to Hawaii, U.S., sealed in checked air baggage and declared to U.S. Customs and Border Protection as ambient air and soil samples, respectively.
Disturbance	Plank boardwalks were used to avoid compression of the compost piles during above-pile gas flux sampling. Minor disturbance of the superficial cover material and underlying waste/compost occurred during chamber base and sensor installation. Accessing the composting site involved no disturbance of the surrounding ecosystems.

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Methods

n/a	Involved in the study
☒	☐ ChIP-seq
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