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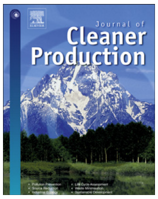

Greenhouse gas fluxes from human waste management pathways in Haiti

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ABSTRACT

The lack of safely managed sanitation services is a major global public health and ecological sustainability challenge. Ecological sanitation (EcoSan) technologies designed to close the “poop loop” through the capture, treatment, and beneficial reuse of human feces can meet this interconnected challenge. EcoSan has the potential to mitigate climate change through the reduction of greenhouse gas (GHG) emissions, yet the climate impacts of EcoSan are poorly understood. We measured GHG emissions (carbon dioxide, CO_2; methane, CH_4; and nitrous oxide, N_2O) from two EcoSan operations in Haiti, as well as two anaerobic waste stabilization ponds and a grass field where sewage is known to be illegally deposited. Carbon dioxide was the major constituent of total GHG emissions from both EcoSan systems. Nitrous oxide emissions were similar across both EcoSan systems, however CH_4 emissions were significantly higher in the system with moister pile conditions. Highest CH_4 fluxes were observed during the first two months of composting in both EcoSan systems. In a paired-comparison, we found that piles with a soil lining had four-fold lower CH_4 emissions and three-fold lower N_2O emissions compared to piles with a cement lining. Overall climate-forcing effects of emissions from EcoSan were favorable relative to waste stabilization ponds and unmanaged disposal on grass fields. In contrast to EcoSan, CH_4 emissions dominated net emissions from waste stabilization ponds, accounting for 94% of net emissions, and N_2O emissions were negligible. Methane emissions from waste stabilization ponds were up to 250 times higher than those from EcoSan compost piles. The grass field had a significantly higher CH_4 flux than EcoSan, and the highest N_2O flux rate observed. Our data suggest that EcoSan systems can contribute to climate change mitigation by reducing GHG emissions relative to alternative sanitation pathways, and EcoSan management conditions can be optimized to minimize emissions.

1. Introduction

Broken nutrient and carbon cycles in food systems waste vast quantities of organic resources and contribute to climate change, food insecurity, and soil degradation. Closing these cycles may contribute to global greenhouse gas (GHG) reduction goals (Lal et al., 2011), improve the resiliency of agroecosystems (Schipanski et al., 2016), and advance sustainable development goals (Kanter et al., 2016). The capture and transformation of human excrement, in particular, represents an enormous and largely untapped resource stream. An estimated 4.1 billion people do not have access to a sanitation system that includes waste treatment (Baum et al., 2013), including 892 million people still practicing open defecation (WHO/UNICEF, 2017). The release of organic matter and nutrients embedded in untreated feces and urine into the environment impairs water quality and emits GHGs, resulting in public health concerns.

Ecological Sanitation (EcoSan) is a strategy for improving access to sanitation and full cycle treatment of human waste. EcoSan is

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implemented throughout the world (GIZ, 2012), and is particularly important in areas where water access, financial resources, and infrastructure are limited (Langergraber and Muellegger, 2005). There are several models of EcoSan, with technologies ranging from constructed wetlands to composting toilets and scales ranging from simple household installations to complex decentralized systems (Nelson and Murray, 2008; Hu et al., 2016). Regardless of implementation, all EcoSan systems share the common objective of the closed-loop management of human waste and a systemic philosophy that connects sanitation and agriculture (Langergraber and Muellegger, 2005). Here, we consider EcoSan implementations that combine container-based toilets for capture and transport of waste, with aerobic, thermophilic composting for the treatment process to sanitize human feces and produce an organic soil amendment (Kramer et al., 2011; Tilmans et al., 2015).

EcoSan offers potential solutions to critical sustainability challenges in the nexus of sanitation, water, health, and agriculture (Simha and Ganesapillai, 2017). In particular, EcoSan may solve three important sustainability challenges by (1) providing safely managed sanitation for presently underserved communities and reducing the spread of intestinal-born pathogens, (2) returning nutrients and organic matter to degraded agricultural soils, and (3) mitigating climate change by reducing GHG emissions compared to alternative waste disposal methods, bioenergy production, and/or promoting soil carbon sequestration in agricultural ecosystems. EcoSan currently makes up a minor fraction of global sanitation services. Current social challenges (e.g. users' perception of excreta for resource recovery (Naughton et al., 2018)) and technical challenges (e.g. scaling up operations without increasing contamination risks) exist to its widespread implementation. However, as population expands in rapidly urbanizing cities and as water availability declines, cost-effective EcoSan operations, such as container-based implementations we consider here (WWC, 2018), may grow to serve a larger proportion of the global population (Russel et al., 2015; Tilmans et al., 2015).

Quantitative data are required to critically evaluate the potential of EcoSan to address these sustainability goals. Here, we focus on the goal of reducing GHG emissions because emissions from EcoSan composting technologies are an important, yet unknown, variable in their overall sustainability. Greenhouse gas emissions vary widely among waste treatment technologies, depending on the biogeochemical conditions, operating conditions, and associated collection and discharge systems (Prendez and Lara-Gonzalez, 2008; Benetto et al., 2009). Wastewater treatment plants are globally significant contributors to GHG emissions (IPCC, 2006). Several sources provide estimates of CH_4, N_2O, and CO_2 emissions from wastewater treatment plants, including national inventories, primary literature, and life cycle assessments (Doorn et al., 2006; Rodriguez-Garcia et al., 2012; Campos et al., 2016; Parravicini et al., 2016). Fluxes of CH_4 and N_2O are biologically-produced, and therefore fluxes can be reduced by technologies that remove or stabilize carbon and nitrogen during the waste treatment process (Campos et al., 2016). Systems that use anaerobic digestion of sludge tend to be a major source of CH_4 emissions (Parravicini et al., 2016) though some anaerobic digestion systems aim to contain and burn emitted CH_4 for energy production (Spinosa et al., 2011). In contrast, GHG emissions data from EcoSan and other non-sewered sanitation systems are sparsely available in primary literature and monitoring inventories.

Greenhouse gas emissions from non-sewered sanitation systems, including pit latrines, septic systems, and container-based toilets, are poorly constrained due to their decentralized locations and high level of operational variability (Doorn and Liles, 1999; Diaz-Valbuena et al., 2011). Direct measurements of CH_4 and N_2O from septic systems are few and have differed from modeled emissions factors (Diaz-Valbuena et al., 2011). A recent analysis of pit latrines concluded that globally, pit latrines accounted for 1% of anthropogenic CH_4 emissions (Reid et al., 2014). The relatively large contribution of pit latrines to global CH_4 sources can be attributed to the global extent of pit latrine use – approximately one-quarter of the global population – as well as the wet and unventilated conditions that drive anaerobic CH_4 production.

EcoSan relies on aerobic conditions to treat waste and has the potential to considerably reduce the GHG footprint of waste management (Pardo et al., 2015). In aerobic thermophilic composting, CH_4 emissions are typically low because of the presence of oxygen. However, anaerobic microsites created by uneven distribution of water in pores and hot spots of labile carbon can create conditions leading to CH_4 emissions (Hao et al., 2004). The use of bulking agents and pile turning can be used to reduce the occurrence of anaerobic CH_4-producing conditions and, when effective, carbon emissions from composting are in the form of CO_2, which is considered to be climate-neutral because of its biogenic origin (Brown et al., 2008). Composting can, however, produce biogeochemical conditions prime for N_2O emissions through nitrification or denitrification, including large sources of reactive nitrogen, dynamic and spatially varying levels of oxygen, and labile carbon sources. Quantifying the magnitude and balance of CH_4 and N_2O emissions in a given sanitation system is critical as the two gases have 100-year global warming potential values of 34 and 298, respectively (Myhre et al., 2013). EcoSan systems utilizing aerobic, thermophilic composting are promising because they may mitigate GHG emissions from the waste and agricultural sectors, however these emissions reductions have not yet been quantified. Further, measurements of GHG emissions from management of solid organic wastes are especially limited from tropical climates (Pardo et al., 2015), where implementation of EcoSan solutions are likely to be greatest.

To our knowledge, no direct measurements of GHG emissions exist from EcoSan systems that deploy container-based toilets and thermophilic composting of human excrement. Our primary objective was to characterize and quantify the GHG emissions resulting from the aerobic composting of human waste in EcoSan settings. We considered two operations that employed similar compost practices, but differed in the physical infrastructure that could alter biogeochemical conditions mediating GHG dynamics. We also compared the GHG footprint of EcoSan with alternative waste management pathways present in the region, including waste stabilization ponds and unmanaged disposal on grass fields. Finally, we undertook an investigation of the effects of compost management options that help reduce EcoSan GHG emissions.

2. Material and methods

2.1. Field sites

Greenhouse gas fluxes were measured from three sanitation pathways in Haiti: two waste stabilization ponds, two EcoSan operations, and a grass field where the illegal disposal of sewage was observed (Fig. 1). The waste stabilization ponds were located in Croix ed Bouquets near Port-au-Prince, Haiti and operated by the Haitian government agency, Direction Nationale de l'Eau Potable et de l'Assannissement (DINEPA). Ponds consisted of uncovered concrete basins with effluent pipes connected to secondary overflow ponds. Two ponds were included in the sampling: a pond that received mostly septic tank waste (hereafter referred to as "Pond 1"), and another that received mostly pit latrine waste (hereafter referred to as "Pond 2"). Solid sludge was scraped out occasionally and stockpiled on-site. Solid and liquid waste from septic tanks and pit latrines were transported to the site and emptied into the waste

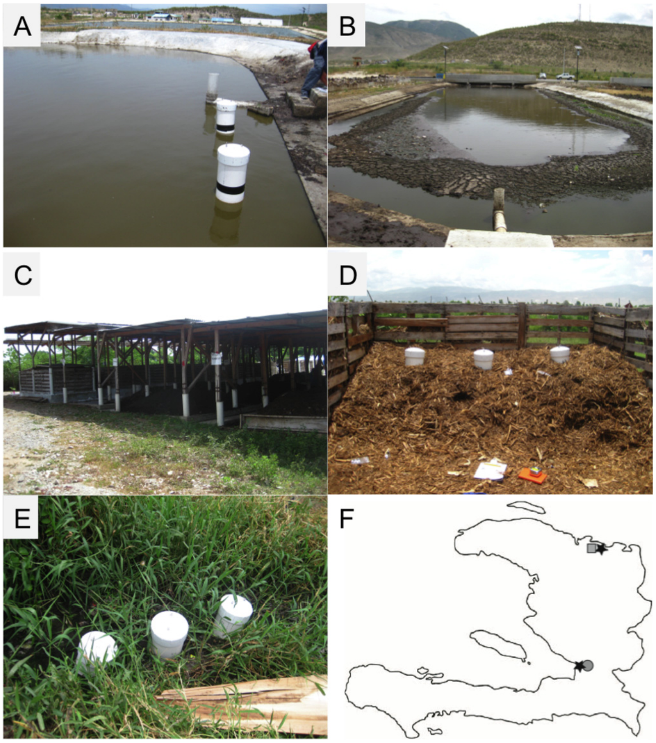

Fig. 1. Greenhouse gas sampling locations representing three alternative pathways of waste treatment. (A) Pond 1 waste stabilization pond primarily received liquid and solid waste from septic tanks. (B) Pond 2 waste stabilization pond primarily received semi-solid waste from pit latrines. Both EcoSan operations employed similar composting practices but different infrastructure, with roofing and cement lined floors at Compost CH (C) and no roof or flooring at Compost PAP (D). (E) Grass fields are also used as locations for illegal emptying of pit latrines and septic tanks. Gas flux chambers visible in panels A, D, and E consisted of PVC collars and caps, with a sample port and pressure vent. (F) All sampling locations are indicated on a map of Haiti, where stars represent EcoSan operations, the circle represents the waste stabilization ponds, and the square represents the grass field where untreated human waste was disposed.

stabilization ponds. The waste stabilization ponds represent the primary pathway of centralized waste treatment as advanced municipal wastewater treatment technologies are not present in the country.

The EcoSan compost facilities were located in Port-au-Prince, Haiti (18°38′29.99″ N, 72°17′46.42″ W) and Cap Haitiën, Haiti (19°40′30.20″ N, 72°06′49.07″ W). The sites received approximately 65 MT yr^{-1} and 440 MT yr^{-1} of human waste, respectively. Eighteen and 54 L container-based toilets were collected from households and communities, respectively, in each of the regions. Container-based toilets separated urine and feces into different compartments. Coarsely ground sugarcane bagasse was added throughout use to prevent flies and reduce odor. Urine was disposed of on-site, and only solid material was transported to the compost facilities. Both facilities used a similar aerobic composting process consisting of a static thermophilic stage, followed by pile turning and maturation in windrows. At the Cap-Haitiën operation, hereafter referred to as “Compost CH,” the ground was lined with cement to prevent leaching and an aluminum roof covered the area. Roofs and cement-lined floors were absent at the Port-au-Prince EcoSan operation, hereafter referred to as “Compost PAP”. During the initial thermophilic stage, approximately 2700 kg (~21 m^3) of fresh material from container-based toilets was added to a ~27 m^3 bin (ca. 4.5 × 3 × 2 m) consisting of air-permeable walls and an open top (unpublished data). Coarsely ground sugarcane bagasse was used as a bulking agent (3:1 feces to bagasse) to create interstitial air spaces within the pile and as a 15 cm deep covering material. The material remained in the bin for about two months or until confirmation of *Eschericia coli* elimination, during which time it underwent static, thermophilic composting, reaching a peak minimum temperature of 50 °C for at least 7 days (Kramer et al., 2011). Following the thermophilic stage, the material was removed from the bin onto a flat surface, formed into windrows (approximately 5 m × 4 m x 1.3 m) and aerated by weekly manual turning for two to three months. Finally, matured compost was then sieved and bagged for use as a composted soil amendment.

The third waste disposal pathway was an unmanaged grass field near Quartier Moren, Haiti (hereafter referred to as “Grass Field”). Unregulated emptying of septic and pit latrine waste is not uncommon and has been observed here for at least five years and within a few months of sampling. While the frequency and magnitude of waste disposal in the grass field was unknown, there was apparent build up of organic material that resembled a moist, viscous sludge several inches to feet deep.

2.2. *Greenhouse gas sampling*

Greenhouse gases were measured once at each site within seven days in July 2014. Fluxes of CO_2, CH_4, and N_2O were measured using vented static flux chambers (Keller and Reiners, 1994) constructed of 25.4 cm diameter Schedule 80 PVC collars and chamber tops. 1.5 m tall collars were placed carefully in the semi-solid sludge in the waste stabilization ponds, approximately 1 m from the edge. Chamber tops were connected to collars after 1 h to minimize disturbance effects. Four areas were sampled in Pond 1, and six areas were sampled in Pond 2. Gas samples collected within ponds were treated as replicates and used to determine mean fluxes from each pond. Six 0.3 m tall collars were placed randomly in the Grass Field and allowed to settle for 1 h before the chamber tops were connected.

Gas measurements were also made within and across compost piles of different stages. While sampling was conducted at each site at one time point, compost piles exist along a gradient of ages from freshly collected waste to mature compost. This design allows us to effectively substituting space for time to determine mean flux from each EcoSan system over the entire composting process. At Compost PAP, eight piles ranging from <1, 1, 2, 4, 6, 8, 10, and 13 months were sampled, with six static flux chambers randomly placed in each pile. At Compost CH, six piles ranging from <1, 3, 4, 5, and 12 months old were sampled, with three static flux chambers randomly placed in each pile. Linear interpolation between age classes was used to calculate the net GHG emissions from EcoSan compost operations. Mean GHG emissions were determined by weighting fluxes by age of the pile.

Gas samples (30 mL) were collected from the static flux chamber headspace at 0, 5, 10, 20, and 30- minute intervals, immediately transferred to evacuated 20-mL Wheaton glass vials outfitted with 1-inch butyl septa. Samples were transported to the Cary Institute of Ecosystem Science in Millbrook, New York for analysis on a gas chromatograph (Schimadzu model 14A). Methane concentrations were analyzed using a flame ionization detector. An electron capture detector was used to analyze N_2O concentration, and CO_2 concentrations were analyzed using a thermal capture detector. Samples with concentrations exceeding the maximum detection limit on the gas chromatograph were diluted at 1:10 or 1:100 with N_2. Fluxes were calculated using an iterative exponential curve-fitting approach (Matthias et al., 1978).

2.3. *EcoSan compost management experiments*

To explore how compost management impacts GHG emissions, we established an additional experiment at the Compost CH site in

August 2016. First, to test the effects of pile lining permeability, we measured GHG emissions using the procedure described above from a bin with a soil floor (unlined) and from a bin with a cement floor and a blocked PVC overflow pipe (lined), which were filled at approximately the same time. Second, to test the effects of pile turning, we measured GHG emissions one and three days after unlined bin material was turned for the first time, and compared emissions to those before turning. Twelve fluxes spaced evenly on a four x three grid were measured for each bin in the first stage to explore spatial variability of GHG emissions within the pile. Six fluxes were measured per pile in the second turned stage, spaced on a three x two grid (see SI). The grid design also allowed us to explore the effects of pile structure and geometry on GHG emissions in greater detail.

2.4. Statistical analysis

One-way analyses of variance (ANOVA) followed by Tukey-Kramer means comparison tests were used to identify statistically significant effects of waste treatment pathway on mean CO_2, CH_4, and N_2O fluxes. Treatment fluxes sampled across waste pathways were calculated as the mean and standard error of replicate samples collected within each system ($n = 6$ for Compost PAP for each pile, $n = 3$ for Compost CH for each pile, $n = 4$ for Pond 1, $n = 6$ for Pond 2, and $n = 6$ for Grass Field). Standard errors were propagated when considering mean GHG fluxes throughout the entire compost process at the EcoSan sites. For the compost management experiments, fluxes are represented as the mean and standard error of sample replicates ($n = 12$ for the unlined and lined static piles, $n = 6$ for the turned piles from the second stage of composting). Fluxes of each gas species were considered separately and in combination using units of CO_2-equivalents, using the 100-year global warming potential of 298 for N_2O and 34 for CH_4. Gas flux data were log-transformed to meet assumptions for ANOVA. Data are reported either as mean values±one standard error. Statistical significance was determined as $P < 0.05$ unless otherwise noted.

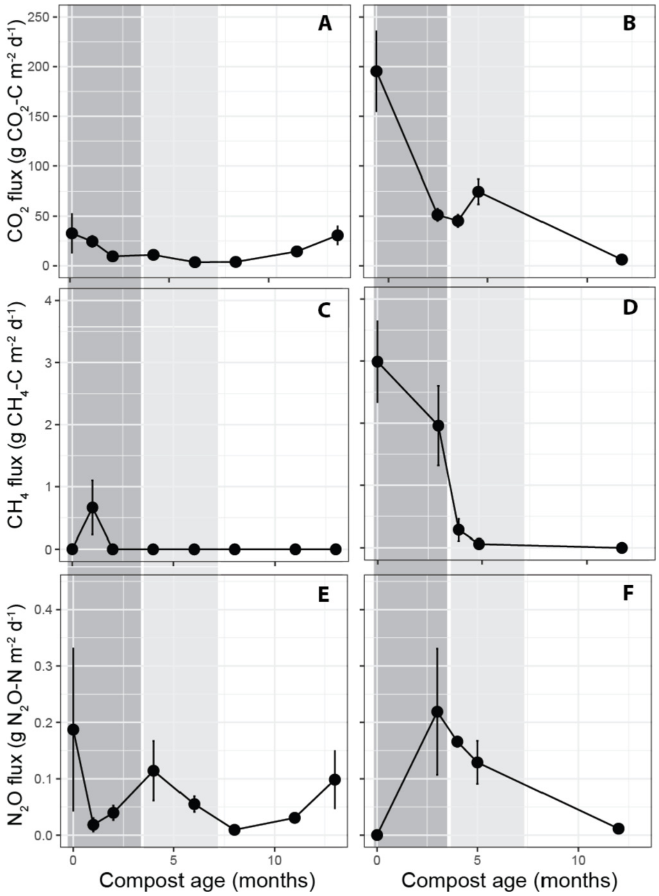

Fig. 2. Fluxes of CO_2, CH_4, and N_2O throughout the compost process at Compost PAP (A, C, E, respectively) and Compost CH (B, D, F, respectively). Shading denotes the three stages of composting: static, thermophilic stage (dark gray), pile turning stage (light gray), and maturation (white). Values are mean ± 1 standard error.

3. Results

3.1. Greenhouse gas emissions from EcoSan settings

Greenhouse gas fluxes throughout the main stages of the composting process varied significantly ($p = 0.02$ for CO_2, $p < 0.0001$ for CH_4, and $p = 0.10$ for N_2O at Compost PAP; $p = 0.0002$ for CO_2, $p < 0.0001$ for CH_4, and $p = 0.10$ for N_2O at Compost CH; Fig. 2). At both sites, CH_4 fluxes were highest during the static, thermophilic stage. Mean methane fluxes reached a maximum of 2.99 g CH_4-C m^{-2} d^{-1} at Compost CH and 0.66 g CH_4-C m^{-2} d^{-1} at Compost PAP. Methane fluxes declined significantly but remained elevated during the pile turning phase at Compost CH, ranging from 0.06 to 0.28 g CH_4-C m^{-2} d^{-1}, and declined to 0.01 g CH_4-C m^{-2} d^{-1} during the maturation phase. Overall CH_4 fluxes were significantly lower at Compost PAP during the turning and maturation phases, ranging from 0.0001 to 0.0003 g CH_4-C m^{-2} d^{-1}. Nitrous oxide fluxes at Compost PAP were highest in the first month of the initial thermophilic phase (0.19 g N_2O-N m^{-2} d^{-1}), and peaked again at the beginning of the turning phase (0.11 g N_2O-N m^{-2} d^{-1}). In contrast, N_2O fluxes at Compost CH were negligible during the thermophilic stage, and quickly rose upon turning, ranging from 0.13 to 0.22 g N_2O-N m^{-2} d^{-1}. Carbon dioxide fluxes peaked during the thermophilic stage (32.6 and 195 g CO_2-C m^{-2} d^{-1} at Compost PAP and Compost CH, respectively), and tended to follow similar overall temporal patterns as N_2O.

Considering the 100-year global warming potential of each GHG, CO_2 dominated the cumulative GHG emissions from Compost PAP, accounting for 62.6% of net CO_2-eq emissions (Table 1). Nitrous oxide made up about one-third of the net flux, with CH_4 accounting for the remaining 5%. In contrast, CH_4 and CO_2 constituted the bulk of the flux from Compost CH, with N_2O only accounting for 9.5%.

3.2. Comparison of GHG emissions from waste treatment pathways

Rates of GHGs emissions from the EcoSan operations differed significantly. Mean CO_2 and CH_4 were significantly lower at Compost PAP compared to Compost CH ($p < 0.0001$ for CO_2, $p < 0.0001$ for CH_4; Fig. 3). Mean N_2O fluxes were not significantly different between the EcoSan operations ($p = 0.88$).

The highest CH_4 fluxes were observed from waste stabilization Pond 2, and were 3.3–248 times greater than those observed at Compost CH and Compost PAP, respectively (Fig. 3). Methane fluxes from Pond 1, Grass Field, and Compost CH were not statistically significantly different from each other, but were significantly greater than Compost PAP. Nitrous oxide emissions from the two waste stabilization ponds were undetectable to very low (Fig. 3). In contrast, N_2O emissions from the compost treatments ranged from 0.06 ± 0.01 to 0.14 ± 0.04 ng N cm^{-2} h^{-1}. The Grass Field, however, resulted in high, albeit variable, N_2O fluxes, with a mean of 0.32 ± 0.14 ng N cm^{-2} h^{-1}.

Overall GHG emissions, expressed in CO_2-eq using a 100-year global warming potential, were highest from Pond 2 and lowest from Compost PAP (Fig. 4). Net GHG emissions were not significantly different among Compost CH, Pond 1, and Grass Field when

Table 1
Relative contribution of each gas to net GHG fluxes, expressed in CO_2-eq using a 100-year global warming potential.

Site	Waste Treatment	% CO_2	% CH_4	% N_2O
Compost PAP	aerobic composting, without roof or floor	62.6	5.1	32.4
Compost CH	aerobic composting, with roof and floor	42.6	47.9	9.5
Pond 1	stabilization pond	8.6	91.4	0.0
Pond 2	stabilization pond	3.8	96.2	0.0
Grass Field	illegal disposal	11.6	66.5	21.9

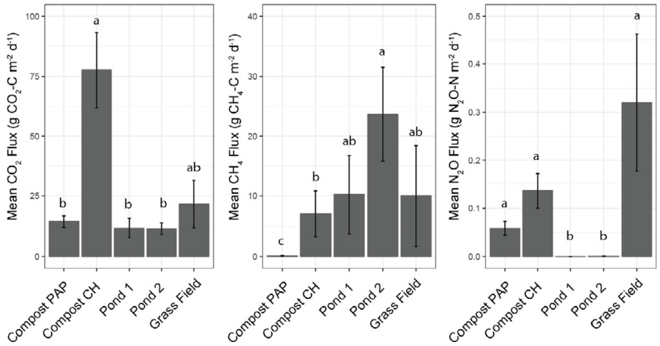

Fig. 3. Mean CO_2 (a), CH_4 (b), and N_2O (c) fluxes from five waste treatment pathways. Bars are means, and errors bars are ±1 standard error. Letters denote statistical significance at $P < 0.05$.

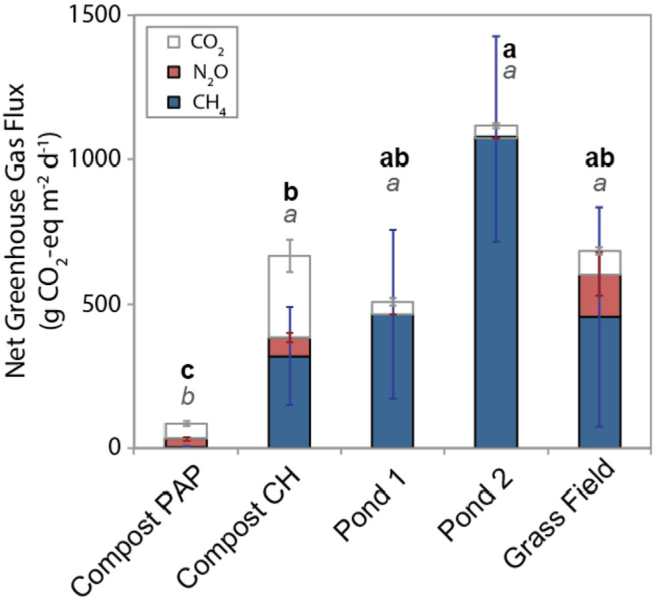

Fig. 4. Net GHG emissions (in CO_2-eq m^{-2} d^{-1}, using a 100-year global warming potential) from five waste pathways in Haiti. Bars are means, and errors bars are ±1 standard error. Italicized letters denote statistical significance at $P < 0.05$ considering the cumulative contribution of CO_2, CH_4, and N_2O. Bold letter denote statistical significance at $P < 0.05$ considering the cumulative contribution of CH_4 and N_2O.

considering all three gases. However, total N_2O and CH_4 emissions were significantly less from Compost CH because CO_2 represented a large portion of its flux. On average, CH_4 dominated the net GHG emissions from the waste stabilization ponds, accounting for 94 ± 2.4% of total emissions. Methane also dominated the net flux from Grass Field, accounting for 66.5% of total emissions (Table 1). Nitrous oxide occurred in greater proportions from the Grass Field and compost treatments compared to the waste stabilization ponds.

3.3. *Greenhouse gas mitigation options within EcoSan operations*

We found pile lining permeability and pile turning significantly altered GHG emissions during EcoSan composting (Table 2). A permeable soil lining lowered GHG emissions with pile CH_4 and N_2O emissions four and three-fold lower, respectively, in the unlined pile compared to the cement lined pile. Emissions also followed spatial patterns within the piles with CH_4 emissions generally increasing from corners and edges to the center of the pile, with the opposite trend observed for N_2O. Finally, substantial changes were observed in all GHGs after pile turning: CO_2 and N_2O emissions approximately doubled while CH_4 emissions dropped almost to zero.

4. Discussion

4.1. *Greenhouse gas emissions from waste management pathways*

We found that composting human fecal matter resulted in significantly lower overall GHG emissions than those observed from waste stabilization ponds and the illegal disposal of human waste on unmanaged grass fields. In EcoSan systems, CO_2 was a major constituent of the overall GHG footprint, making up 42–62% of net CO_2-eq emissions. In contrast, CO_2 made up only 12% from grass fields used for dumping of untreated waste and 4–9% of the net CO_2-eq emissions from waste stabilization ponds, suggesting that the ponds are not completely anaerobic. The difference in CO_2 loss is likely driven by differences in oxygen availability among the waste treatment pathways. Composting systems enhance aerobic conditions that stimulate the microbial oxidation of organic carbon to CO_2 (Pardo et al., 2015), whereas biological treatment systems with oxygen-depleted conditions stimulate methanogenesis and production of CH_4 (Narihiro and Sekiguchi, 2007). Carbon dioxide produced from the decomposition of human waste is of biogenic origin, and therefore not considered a net source of GHG emissions from a climate change perspective (IPCC, 2006).

Conditions that evenly aerated compost piles, such as forced aerated and pile turning, tend to maximize CO_2 production relative to CH_4 and N_2O (Pardo et al., 2015). However, compost piles tend to have high levels of biogeochemical heterogeneity due to within-pile spatial variations in organic compounds, physical size and structure of material, oxygen diffusivity, density, porosity, and moisture content. Therefore, compost pile management can play a strong role in altering biogeochemical conditions that effect the composition of GHG fluxes (Brown et al., 2008). In the two EcoSan systems that we studied, we saw significantly higher CH_4 fluxes from Compost CH, where static piles sat atop a concrete floor during the thermophilic phase. The presence of the floor likely built up moisture in the pile and increased the probability of anaerobic microsites. Methane emissions from Compost CH rapidly declined after the first two to three months, when piles were moved into the actively turned stage. In contrast, compost piles at Compost PAP were constructed atop compacted soil and without a roof covering, allowing for infiltration of leachate and higher rates of evaporation. As a result, CH_4 production made up only 5% of net GHG emissions

Table 2
Effects of compost management experiments on mean (±1 SE) GHG emissions. Superscript letters denote significant differences within each experiment. No error range is reported for Pile Center sampling group because $n = 2$.

Experiment	Sampling	CO_2 (g C m^{-2} d^{-1})	CH_4 (g C m^{-2} d^{-1})	N_2O (g N m^{-2} d^{-1})
Drainage	Lined (L)	58.8 ± 5.8	16.1 ± 3.67	0.31 ± 0.05
	Unlined (UL)	48.9 ± 8.0	3.55 ± 1.76	0.13 ± 0.02
Pile Structure	Pile Corners (L)	40.5 ± 11.8	7.37 ± 2.62	0.42 ± 0.15
	Pile Edge (L)	64.3 ± 3.6	17.6 ± 1.52	0.29 ± 0.03
	Pile Center (L)	78.9	29.0	0.14
	Pile Corners (UL)	35.8 ± 7.1	2.10 ± 0.84	0.18 ± 0.04
	Pile Edge (UL)	41.5 ± 7.7	2.06 ± 1.11	0.10 ± 0.02
	Pile Center (UL)	97.0	10.9	0.11
Turning	1 day after turn (UL)	136.3 ± 20.0	0.04 ± 0.02	0.59 ± 0.06
	3 days after turn (UL)	111.3 ± 23.6	0.06 ± 0.04	0.22 ± 0.06

at Compost PAP and 48% of those from Compost CH. This finding suggests that aeration during the thermophilic phase of composting is critical in minimizing the GHG footprint of EcoSan systems.

Waste treatment ponds produced anaerobic conditions that generate high levels of CH_4 and very little CO_2 (Hernandez-Paniagua et al., 2014). The GHG contribution of waste stabilization ponds can be mitigated by the use of CH_4 gas capture and electricity generation (Konaté et al., 2013). Anaerobic digestion coupled to CH_4 capture has been used to treat livestock manure (Walker et al., 1985) and in some wastewater treatment plants for decades (Lettinga, 1995). However, many waste stabilization ponds throughout the world, including those sampled in this study, do not capture and reuse the CH_4 generated during waste treatment. Market barriers - including the initial financial investment costs CH_4 capture technology and electricity generation facilities - regulatory challenges, and lack of access to technology severely limit its widespread adoption in regions of the world that currently lack basic sanitation needs (Kumaran et al., 2016). Further, the efficiency of pathogen removal in waste stabilization ponds is highly variable (Verbyla et al., 2017), thereby limiting the effectiveness of waste stabilization ponds in regions of the world with limited technological and capital resources.

Nitrous oxide is produced during the microbial-mediated processes of nitrification and denitrification, and can be produced in conditions with high to low levels of oxygen (KFirestone and Davidson, 1989). Nitrification, the conversion of ammonium to nitrate through microbial oxidation, requires a source of ammonium and oxygen. During nitrification, N_2O can form by the nitrate reductase enzyme in anaerobic conditions. Denitrification, the reduction of nitrate to dinitrogen through a series of intermediates, requires a source of nitrate, organic carbon, and limited oxygen. Nitrous oxide can form as a result of incomplete denitrification to N_2. Human waste contains organic carbon and a range of organic and inorganic forms of nitrogen. Therefore, the oxygen conditions of a particular waste treatment pathway are a major control on N_2O fluxes. In the anaerobic waste stabilization ponds, N_2O was undetectable. In municipal wastewater treatment plants, measurements of N_2O vary widely and can be mitigated by technologies that remove total nitrogen (Parravicini et al., 2016). Grass fields where waste was illegally disposed exhibited high and spatially variable N_2O and CH_4 fluxes.

We observed a tradeoff between N_2O and CH_4 across sanitation pathways. Whereas waste stabilization ponds produced high levels of CH_4 and no N_2O, both EcoSan systems tended to have high fluxes of N_2O. Nitrous oxide in compost piles can be produced by both nitrification and denitrification processes present along oxygen, moisture and C:N gradients within the pile (Jiang et al., 2011). Reducing occurrences of anaerobic microsites could further limit N_2O production from EcoSan compost, however, N_2O production could still results from nitrification conditions. Despite this pollution swapping and taking into account the greater global warming potential of N_2O, the largest contributor to GHG emissions from these systems is still CH_4. Therefore, without systems in place to capture and oxidize CH_4, the aerobic EcoSan system is a favorable system relative to waste stabilization ponds and illegal disposal on grass fields with respect to its impact on the climate.

4.2. EcoSan compost management impacts on GHG emissions

The management of aerobic biogeochemical conditions in compost piles plays a key role in minimizing CH_4 and N_2O losses (Yuan et al., 2016). We observed large differences in CH_4 emissions, and consequently in overall GHG emissions, across the two EcoSan systems in our study, implying opportunities for improved management. We tested this explicitly with a targeted comparison of GHG emissions above two piles, one with a permeable soil lining and one with an impermeable cement lining, at the Compost CH site and with a second comparison of GHG emissions before and after turning pile material. We found that CH_4 emissions from the cement lined pile were approximately four times greater than from the soil lined pile, despite no significant temperature or CO_2 emission differences. This is evidence that higher CH_4 emissions were driven by a larger methanogenic fraction (Von Fischer and Hedin, 2007), expressed as the amount of CH_4 emitted per unit CO_2, in the lined pile, indicating a greater prevalence of anaerobic conditions due to higher pile moisture.

The cement-lined pile in the paired-pile experiment had no drainage mechanism and therefore likely represents a high end-member for wet pile conditions and high CH_4 emissions. Notably, the standard design (Kramer et al., 2011) for cement-lined piles at the Compost CH_4 site includes a lateral overflow PVC pipe, providing passive drainage, while at Compost PAP a soil lining is used without a PVC drain, and in both cases the CH_4 emissions observed were much lower. The very high CH_4 emissions from the undrained pile (Table 2) therefore likely reflect a very high moisture end-member for thermophilic composting.

For future EcoSan implementations there are important tradeoffs to consider in pile design. The advantages of a PVC drain and associated storage tank are that potentially pathogenic liquid is contained, can be recycled to maintain optimal pile moisture levels under drier conditions and, if sanitized, the nutrient content of the leachate can be recycled (Jarecki et al., 2005). In contrast, a soil floor costs less, but it is important to consider, and monitor for, the potential leaching of pathogens, nutrients that can causes algal blooms, and trace metals that could contaminate drinking water when using a permeable floor (Das and Kirkland, 2008). Future studies should further explore the quantity, composition, and timing of pile leaching, and assess the efficacy of soil as a filter to avoid contamination of groundwater alongside lowering GHG emissions.

Though use of a permeable soil floor and/or PVC overflow drain showed potential to reduce EcoSan composting GHG emissions, the effects of turning the pile – even once – were even greater. Emissions of CH_4 dropped two orders of magnitude, approaching zero, within one day after turning and stayed comparably low through the third day. Piles in the EcoSan second stage are turned every 7–10 days (Kramer et al., 2011), therefore it is likely that CH_4 emissions remain low throughout this entire phase, as originally evidenced by the >3-month time points in the initial measurements at Compost CH and Compost PAP. From these results, it may appear to be beneficial from a climate forcing perspective to reduce the time spent in the first static phase, however this must be balanced by the need to safely manage the pathogen burden at this early treatment stage, especially if piles are turned using manual labor. Turning must only begin when pathogen abundance in the material has been reduced to a safe level, thus safeguarding the health of employees and local environment (Kramer et al., 2011). Furthermore, though not observed in this study, past work has also shown that pile turning can increase N losses. Significant spikes in ammonia and N_2O emissions follow mechanical turning of composting manure (Arriaga et al., 2017). It is therefore possible that within EcoSan composting there may be a trade-off between N_2O and CH_4 emissions between the initial static and later turned stages, similar to our observations across different sanitation pathways.

Our gridded sampling scheme also allowed us to test the hypothesis that aeration drives CH_4 emissions *within* piles. The results confirmed the utility of our model-based sampling design, with mean CH_4 emissions four to five times higher from pile centers than pile corners or edges, regardless of the general drainage characteristics of the pile. An alternative to early turning may be the use of additional engineering to further aerate the middle of large piles where, even under well-drained pile conditions, we observed steep increases in CH_4 emissions. One solution may be use of perforated PVC pipes for passive (or active) aeration of the pile at relatively low cost.

Thermophilic composting is most effective under aerobic conditions. Understanding how management can best support aerobic conditions provides a win-win opportunity to increase the operational efficiency composting for treating waste while reducing the associated GHG emissions (Onwosi et al., 2017). The preliminary comparisons in this study captured significant effects of pile lining permeability and pile turning on GHG emissions during thermophilic composting, and helped us interpret the longer-term dynamics of GHG emissions during composting. Although our targeted measurements identify two of the management controls of GHG differences (pile moisture and aeration during turning), robust estimates of emission factors for EcoSan composting requires a more comprehensive assessment of GHG dynamics, considering different management options, and with more extensive sampling throughout the composting operational stages. In sum these results support the potential for EcoSan composting to further reduce CH_4 and overall GHG emissions associated with waste containment and treatment if piles are carefully designed and effectively managed to support aerobic metabolism.

5. Conclusions

Models of sanitation that employ ecological principles are thought to be a sustainable alternative to conventional wastewater treatment. EcoSan compost technology is important for realizing the concept of cleaner production through GHG mitigation and for promoting a circular economy (Pan et al., 2015). We present the first direct measurements of GHG emissions from EcoSan systems that use an aerobic, thermophilic composting process to treat waste. We found that EcoSan systems were effective at minimizing GHG emissions compared to waste stabilization ponds and the illegal disposal of waste directly to the land. EcoSan may further contribute to climate change mitigation if compost products are applied to agricultural soils resulting in soil carbon sequestration (Ryals and Silver, 2013; Paustian et al., 2016).

Our results have important implications for the future of sustainable human waste management. The recovery, treatment, and reuse of nutrients and organic matter embedded in human waste has potential to mitigate climate change, reduce the spread of pathogens, and protect water sources from eutrophication. Currently, 32% of the global population rely on sanitation services that are considered less than basic needs, and only 39% of the global population has access to safely managed sanitation services that considers the full life cycle of this organic waste stream (WHO/UNICEF, 2017). EcoSan via the thermophilic composting of solid organic waste has been shown to be effective at eliminating pathogenic microorganisms (Piceno et al., 2017) and *Ascaris*, a parasitic nematode that causes intestinal disease (Berendes et al., 2015). It is also thought to be a cost-effective alternative to sewered systems or waste stabilization ponds, particularly in areas of the world where financial resources and infrastructure are limited (WWC, 2018). Here we show that EcoSan benefits the climate by producing less net GHG emissions compared to waste stabilization ponds, and that EcoSan compost management can be optimized to minimize emissions. These findings, in conjunction with associated social, economic, and other ecological impacts, are a valuable, and previous unknown, variable in assessing the overall sustainability of sanitation pathways.

Author contribution

RR designed and conducted the study and wrote the manuscript.

GM assisted with sample collection, data analysis, and manuscript writing.

SP contributed to the study design.

SK contributed to the study design, sampling, and site logistics.

Conflicts of interest

The authors have no conflicts of interest.

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