Greenhouse Gas Emissions from New York State Septic Systems

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Abstract

Onsite septic systems are a practical way to treat wastewater in rural or less-densely populated areas of New York State. Water pollution has always been a concern with these systems; we sought to determine whether septic systems have the potential to contribute to air pollution as well through the release of greenhouse gases (GHGs). We measured the flux of CH\textsubscript{4}, CO\textsubscript{2}, and N\textsubscript{2}O from the soil over the leach field and sand filter, and from the roof outlet vent. These are the most likely locations for gas emissions during normal operation of the septic system. We found that the majority of all septic system gas emissions are released from the roof vent. However, our comparisons of the gas fluxes from these locations suggest that biological processes in the soil, especially the soil over the leach field, can influence the type and quantity of gas that is released from the system. The total vent, sand filter, and leach field GHG emissions were 0.12, 0.045, and 0.046 tonne CO\textsubscript{2}e capita\textsuperscript{-1} year\textsuperscript{-1}, respectively. This represents a fraction of the total carbon footprint of an individual living in the US, and thus air pollution from septic systems is likely not significant.

Three Summary Points of Interest

\begin{itemize}
  \item This is the first time GHG emissions have been reported from over the leach field of the septic system.
  \item As currently implemented, septic systems are likely not a large contributor to greenhouse gas emissions.
  \item Continuation of this work is planned to determine the microbial communities and activity level in the soil over septic system components, particularly the leach field.
\end{itemize}

Keywords

Septic system, Greenhouse gas, Methane, Carbon dioxide, Nitrous oxide, Wastewater, Sewage
Introduction

In 2011, roughly 20% of US households used onsite septic systems as their primary means of sewage disposal (US Census, 2011). This method of decentralized wastewater treatment is recognized by the EPA as having numerous public health, environmental, and economic benefits for local communities compared to traditional wastewater treatment plants (WWTPs), while achieving comparable treatment levels (US EPA, 2012, 2014). However, it is still unclear whether this solution could contribute to greenhouse gas (GHG) emissions.

In New York State (NYS), the use of septic systems mirrors the national picture. The 1990 US Census indicated that, similar to the national usage rate, about 20% of NYS homes relied on septic systems for sewage disposal (Cornell University Cooperative Extension, 2013). Furthermore, septic systems are more prevalent in rural and other less-densely populated areas of the state, while urban centers are likely to utilize centralized WWTPs (Cornell University Cooperative Extension, 2013). It is believed that reliance on septic systems will increase in the future in NYS, again following a national trend away from building new or expanding on existing WWTPs, and increasing development at impractical distances from WWTPs (NYS Department of Health, 2012).

A septic system typically consists of two main in-ground components: (1) the septic tank, which retains both dense, settled sludge and less dense, flocculent waste from incoming wastewater and (2) the soil dispersal system (or leach field), which discharges the partially treated water from the septic tank to the surrounding soil (Leverenz, Tchobanoglous, & Darby, 2010). To further improve the quality of discharged water, newer septic systems may have a sand filter between the tank and the leach field (US EPA, 2002). A series of vents and clean-out ports comprise the aboveground portion of the septic system (Figure 1).

The US Environmental Protection Agency estimated that in 2013, methane (CH$_4$) and nitrous oxide (N$_2$O) emissions from domestic wastewater treatment in the US were 9.2 and 4.9 MMT CO$_2$ Eq, respectively (2015). These estimates were based on theoretical calculations of CH$_4$ production from Biochemical Oxygen Demand and N$_2$O production from the amount of influent nitrogen (N) (US EPA, 2015). Very few field measurements have been made of the GHG emissions from septic systems.

To date, measurements of GHG emissions from septic systems have primarily been made from the sewage surface in the septic tank (Table 1). Diaz-Valbuena et al. (2011) also measured the GHG emissions from the clean-out port located between the septic tank and the house (Table 1) and report that GHG emissions from the clean-out port between the septic tank and the leach field and from the soil above the leach field were negligible.

To our knowledge, no previous research has reported GHG emissions from the roof outlet vent or from the soils over the leach field, even though these are the two most likely sources of GHG emissions during the normal operation of the septic system. It is rare for septic tanks to be vented to the atmosphere through pipes installed in the tanks themselves (Leverenz et al. 2010). Instead, gases produced inside the tank are released to the atmosphere through a vent located on the roof of the house. Furthermore, the periodic wetting and drying of the leach field soils may result in conditions that promote the production of CH$_4$ and N$_2$O through microbial processes that occur under conditions of oxygen limitation (Smith et al., 2003; Tate, 2015). Measurements of emissions from these two locations (leach field and roof vent) are therefore critical to accurately estimating the GHG emission potential from onsite septic systems.

![Figure 1. Diagram of a typical septic system. Adapted from Diaz-Valbuena et al. 2011.](image)

This report was prepared for the New York State Water Resources Institute (WRI) and the Hudson River Estuary program of the New York State Department of Environmental Conservation, with support from the NYS Environmental Protection Fund.
The objectives of this study were to: (1) determine the GHG (\(\text{CH}_4\), \(\text{CO}_2\), and \(\text{N}_2\text{O}\)) emissions from the soil over septic system leach fields, (2) determine the GHG emissions from the septic system roof vent, and (3) compare the magnitude of emissions from the soil over the leach field to those from the roof vent to determine the greatest source of emissions for each gas considered.

Results & Discussion

Gas emissions from the soil

We were able to detect \(\text{CH}_4\), \(\text{CO}_2\), and \(\text{N}_2\text{O}\) emissions from over the control soil, leach field, and sand filter at all sites. At seven of the nine sites (Sites 2 – 8), all \(\text{CH}_4\) ground emissions fell within a similar range of -0.11 to 0.16 g capita\(^{-1}\) day\(^{-1}\) (Figure 2a). Two sites (Sites 1 and 9) had more variable \(\text{CH}_4\) ground emissions, which generally were higher than the emissions from Sites 2 – 8 (Figure 3a); these sites were eliminated from the analysis of \(\text{CH}_4\) emissions as outliers. Similarly, all \(\text{CO}_2\) ground emissions from Sites 2 – 9 fell within the range of -140 to 450 g capita\(^{-1}\) day\(^{-1}\) (Figure 2b), while emissions from Site 1 were consistently higher (Figure 3b). Therefore, Site 1 was also considered an outlier for the \(\text{CO}_2\) emissions analysis. All \(\text{N}_2\text{O}\) ground emissions ranged from -0.012 to 0.17 g capita\(^{-1}\) day\(^{-1}\) (Figure 2c).

One of the more notable results of this study, in that it departs from the findings of previous work (i.e. Diaz-Valbuena et al. 2011), is that \(\text{N}_2\text{O}\) fluxes from over the leach field were significantly greater than fluxes from the control soil (\(p < 0.001\); Table 2; Figure 4c). This difference can likely be explained by differing bacterial communities at the two study locations, differing environmental conditions, or a combination of the two factors.

The production and consumption of \(\text{N}_2\text{O}\) in soil is influenced by a variety of biological and physical factors. \(\text{N}_2\text{O}\) can be produced through two microbial processes (Smith et al. 2003): 1) the nitrification of ammonium to nitrite and subsequently nitrate (Figure 5a), and 2) denitrification of nitrate to \(\text{N}_2\text{O}\) and subsequently \(\text{N}_2\) (Figure 5b). The production of \(\text{N}_2\text{O}\) through both of these processes increases as oxygen availability decreases, as caused by increasing soil water-filled pore space (Smith et al. 2003). Our model appears to capture this trend, as \(\text{N}_2\text{O}\) fluxes were positively correlated with VWC (\(p = 0.007\); Table 2).

\(\text{NOR}\) is the enzyme responsible for the reduction of \(\text{N}_2\text{O}\) to \(\text{N}_2\) during denitrification. \(\text{NOR}\) is sensitive to salinity, and thus \(\text{N}_2\text{O}\) reduction decreases as salinity increases (Menyailo et al. 1997). This is consistent with our model, where \(\text{N}_2\text{O}\) fluxes increased as conductivity increased (\(p < 0.001\); Table 2). In light of the interplay between the physical and biological characteristics of the site that might be suggested by these results, we again emphasize the need to determine the microbial activity level and community composition over buried components of the septic system when seeking to understand GHG emissions from these systems.

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**Table 1. Summary of previous GHG emission measurements taken from the sewage surface of septic tanks. Adapted from Diaz-Valbuena et al., 2011.**

<table>
<thead>
<tr>
<th>Study</th>
<th>Year</th>
<th>(\text{CH}_4) emissions (g CH(_4) capita(^{-1}) day(^{-1}))</th>
<th>(\text{CO}_2) emissions (g CO(_2) capita(^{-1}) day(^{-1}))</th>
<th>(\text{N}_2\text{O}) emissions (g N(_2\text{O}) capita(^{-1}) day(^{-1}))</th>
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<tbody>
<tr>
<td>Kinnicutt et al.</td>
<td>1910</td>
<td>10.1</td>
<td>N.R.(^1)</td>
<td>N.R.</td>
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<tr>
<td>Winneberger</td>
<td>1984</td>
<td>8-11</td>
<td>5-6</td>
<td>N.R.</td>
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<tr>
<td>Diaz-Valbuena (septic tank)</td>
<td>2010</td>
<td>11.0 ((\sigma = 2.2))(^2)</td>
<td>33.3 ((\sigma = 2.7))(^2)</td>
<td>0.005 ((\sigma = 4.3))(^2)</td>
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<tr>
<td>Diaz-Valbuena (clean-out port)</td>
<td>2010</td>
<td>10.7 ((\sigma = 1.7))(^2)</td>
<td>335 ((\sigma = 2.1))(^2)</td>
<td>0.2 ((\sigma = 3.6))(^2)</td>
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</table>

\(^1\) N.R. = not reported. \(^2\) Represent the geometric mean and standard deviation of all measurements.

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Figure 2. Distribution of (a) CH₄, (b) CO₂, and (c) N₂O gas emissions from over control soil, the leach field, and sand filter at each of the nine sites. The CH₄ emissions data are omitted for Sites 1 and 9, and CO₂ emissions data are omitted for Site 1. This is due to much higher emissions at the sites for these specific gases.

Figure 3. Distribution of (a) CH₄ emissions at Site 1 and 9, and (b) CO₂ emissions at Site 1 from over control soil, the leach field, and sand filter. These sites had much higher emissions for the specific gases than the other sites in this study. For comparison, the range of the ground emissions at the other (a) seven and (b) eight sites is shown using dashed lines.
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Table 2. Estimates, degrees of freedom and p values for the CH₄, CO₂, and N₂O soil flux models. While all possible two-way interactions were explored for all models, only significant interactions are shown. N.S. = not significant.

<table>
<thead>
<tr>
<th>Treatment, Leach field</th>
<th>Treatment, Sand filter</th>
<th>Temperature</th>
<th>Conductivity</th>
<th>VWC</th>
<th>Cond.:VWC</th>
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<tr>
<td>CH₄</td>
<td>N.S.</td>
<td>N.S.</td>
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<td>0.001</td>
<td>N.S.</td>
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<td></td>
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<td></td>
<td>df = 16.678, p = 0.0474</td>
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<td>CO₂</td>
<td>N.S.</td>
<td>-57.182,</td>
<td>7.585,</td>
<td>0.085</td>
<td>-0.367,</td>
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<td></td>
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<td>df = 108.02, p = 0.002</td>
<td>df = 97.05, p = 0.014</td>
<td>df = 159.74, p = &lt;0.001</td>
<td>df = 156.57, p = &lt;0.001</td>
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<td></td>
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<td>4.231,</td>
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<td>df = 64.21, p = 0.001</td>
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<td>-16.365,</td>
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<td>df = 21.86, p = 0.001</td>
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<td>766.39,</td>
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<td>df = 23.35, p = &lt;0.001</td>
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<td>0.017</td>
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<td>df = -0.069,</td>
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<td>0.085</td>
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<td>df = 3.304, p = &lt;0.001</td>
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<td>0.007</td>
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<td>df = 0.085, p = &lt;0.001</td>
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<tr>
<td>N₂O</td>
<td>df = 159.74, p = &lt;0.001</td>
<td>df = 118.10, p = &lt;0.001</td>
<td>df = 133.62, p = &lt;0.001</td>
<td>df = 132.19,</td>
<td>df = &lt;0.001</td>
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<td>3.304</td>
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<td>df = &lt;0.001</td>
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<td>df = 0.069,</td>
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Our model suggests that both CH₄ and CO₂ emissions from soil over the leach field were similar to those from control soil (p > 0.05; Table 2; Figures 4a and 4c). CO₂ fluxes from over the sand filter were significantly less than fluxes from the control soil (p = 0.002; Table 2; Figure 4b); CO₂ was the only gas with a significantly different flux rate from over the sand filter than over the control soil (Figure 4). We found CO₂ emissions to be lower over the sand filter than over control soil. This is possibly due to a replacement of a portion of soil volume that would have contained active, respiring roots and microbes with a relatively inert volume of sand. CO₂ emissions from respiration in the soil and vegetation are the primary sources of this gas to the atmosphere (Smith et al. 2003).

Gas emissions from the roof vent

All sites had CH₄, CO₂, and N₂O emissions from the roof vent (Figure 6). At Sites 8 and 9, we were unable to confirm which vent was connected to the septic system; these sites were omitted from the analysis.

Figure 4. The distribution of the differences between the mean soil flux for each treatment type (leach field and sand filter) and the mean soil flux from the control. Differences were calculated for each combination of site and sampling campaign. The gas types are (a) CH₄, (b) CO₂, and (c) N₂O. An asterisk indicates that, for the given gas type, there was a significant difference between the gas flux over the control soil and the gas flux over the particular treatment type.

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Comparison of soil and vent emissions

In general, roof vent emissions were higher than the ground emissions for all gas types and at all sites. CH$_4$ fluxes out of the roof vent were significantly greater than fluxes from over the septic system (V = 231, p < 0.001). The median ratio of roof vent to septic soil flux was 74:1 for CH$_4$ (Figure 7a). This ratio is almost ten times greater than the next greatest median vent to soil flux ratio, which was 7.6:1 for N$_2$O (Figure 7c), indicating a large production of CH$_4$ by the septic system that was not evident in our measurements of CH$_4$ fluxes over septic soil, which were not significantly different from over control soil (Figure 4a). Furthermore, the flux of N$_2$O from the leach field was significantly greater than the flux from the control soil (Figure 4c), raising the question of what was differentially limiting the flux of these two gases from the soil. Two possible explanations involve either the increased consumption or decreased production of methane by methanotrophs and methogens, respectively. Both of these biological processes also align with our observations of increasing soil CH$_4$ fluxes with increasing VWC (p = 0.047; Table 2), as methanotrophs are aerobic bacteria while methanogens are anaerobic (Tate 2015). Future work could characterize the bacterial community, and particularly the activity levels of methanogens and methanotrophs, in the soil over the septic system, and whether this differs from nearby control soil.
gas from the roof vent than the soil. Negative ratios indicate the soil was acting as a sink for the given gas.

There was no significant difference between CO$_2$ fluxes over the septic system and out of the vent ($V = 143$, $p = 0.165$). However, the median ratio of CO$_2$ flux from the roof vent to the soil over the septic system was 1.4:1 for CO$_2$ (Figure 7b), indicating slightly larger fluxes from the roof vent. This difference is likely due to diffusion limiting the escape of CO$_2$ through the soil.

**Policy Implications**

The NYS Department of Health (2012) recommends that onsite septic systems only be used in cases where wastewater treatment by a municipal WWTP is not practical. The primary pollution concerns surrounding the use of septic systems are contamination of surface and ground waters with untreated wastewater, or the production of obnoxious odors (NYS Department of Health 2012). In this work, we considered another possible source of pollution: GHG emissions resulting from normal septic system operation.

This research demonstrates that GHG emissions from different portions of domestic septic systems are variable. The total vent, sand filter, and leach field GHG emissions were 0.12, 0.045 and 0.046 tonne CO$_2$e capita$^{-1}$ year$^{-1}$, respectively (Table 3). This represents a small fraction of the total carbon footprint of an individual in the US, estimated to be 22.22 tonne CO$_2$e capita$^{-1}$ year$^{-1}$ (United Nations 2010). These results suggest that current NYS septic system policy is correct in not considering air pollution by GHGs as a potential risk associated with septic systems.

**Methods**

Eight Central New York households utilizing a septic system volunteered to participate in the study. One of the households had two separate septic systems serving different buildings, making nine septic system sites in...
Greenhouse Gas Emissions from New York State Septic Systems

Table 3. GHG emissions from each septic system component, reported in g capita\(^{-1}\) day\(^{-1}\) (first value) and tonne CO\(_2\)e capita\(^{-1}\) year\(^{-1}\) (second value). Estimates are based on the geometric mean of the emissions from all sites included in the analysis.

<table>
<thead>
<tr>
<th></th>
<th>Roof</th>
<th>Sand filter</th>
<th>Leach field</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>g/capita/day</td>
<td>tonne CO(_2)e capita(^{-1}) year(^{-1})</td>
<td>g/capita/day</td>
</tr>
<tr>
<td>CH(_4)</td>
<td>11</td>
<td>6.2E-02</td>
<td>0.0072</td>
</tr>
<tr>
<td>CO(_2)</td>
<td>160</td>
<td>4.8E-02</td>
<td>120</td>
</tr>
<tr>
<td>N(_2)O</td>
<td>0.12</td>
<td>1.3E-02</td>
<td>0.0060</td>
</tr>
</tbody>
</table>

Total. Between June and August 2014, measurements were taken at each site a minimum of three times.

Soil gas flux sampling

Gas flux chambers were used to measure the flux of CH\(_4\), CO\(_2\), and N\(_2\)O from the soil. The chambers were constructed following the methods of Molodovskaya et al. (2011). In brief, each chamber consisted of two parts: (1) a 30 cm opaque, plastic cylindrical collar with a 5 cm wide gasket (size 12H, Dykema Rubber Band Co., McKees Rocks, PA) and (2) a 3.5 gallon opaque, plastic removable cover (Paragon Mfg., Melrose Park, IL). At the top of each cover were two rubber septa: one to allow for the insertion of a sampling syringe and one to allow for installation of a pressure equilibration vent tube. The dimensions and configuration of the vent tube were calculated following Hutchinson and Mosier (1981), and were constructed using an aluminum pipe and flexible plastic tubing.

The chamber collars were installed in the soil to a depth of 3 to 5 cm on the day of sampling. At each site, three collars were installed over either the leach field or the sand filter, and three collars were installed over a section of the site upslope of the septic tank system, which served as a control.

Gas samples were taken from each chamber over a 30 min period immediately following the placement of the cover on the collar. Samples were collected by inserting a 20 mL syringe in the rubber septum at 0, 10, 20, and 30 minutes. The frequency and total duration of sampling were determined based on the chamber dimensions, following the recommendations from Rochette and Ericksen-Hamel (2008). For each sample, 20 mL of air were drawn from the chamber and five milliliters of air were expelled outside the chamber to flush the syringe needle before storing the remaining 15 mL sample in a 10 mL evacuated serum sample bottle.

Vent gas flux sampling

The gas escaping from the roof outlet vent was sampled using a 1 L syringe with a 97 cm length of plastic tubing. The tubing was lowered into the vent and 200 mL of air was withdrawn and expelled outside the vent to flush the tube. Subsequently, another 600 mL of air was withdrawn, 100 mL expelled, and the remaining 500 mL of air stored in a one liter multi-layer foil gas sampling bag (Restek Corporation, Bellefonte, PA). Later, five-15 mL aliquots were withdrawn from the bag and stored in 10 mL evacuated serum sample bottles using the same 20 mL syringe procedure used for the chamber samples.

At the time of vent sampling, a 39 cm length of PVC pipe was attached to the top of the 7.6 cm diameter roof vent. The pipe was then capped and a hotwire anemometer (VWR, Radnor, PA) was immediately inserted into a hole (1.3 cm diameter) drilled 8.5 cm above the base of the pipe. The reading from the anemometer was used to estimate the slowest possible air velocity escaping from the vent.

Gas analysis

CH\(_4\) and N\(_2\)O concentrations were analyzed on a gas chromatograph (Model 6890N GC/ECD, Agilent Technologies Inc., Santa Clara, CA) using a flame ionization detector and an electron capture detector, respectively. CO\(_2\) concentrations were analyzed on a LI-
6200 Portable Photosynthesis System attached to an LI-6250 CO₂ Analyzer (LI-COR, Lincoln, NE).

Soil gas fluxes were calculated by plotting the concentration of gas versus time. A linear regression line was fit to this data, and the slope was taken as the rate of gas flux. Vent gas fluxes were calculated by multiplying the gas concentrations by the area of the vent and the measured air velocity. All fluxes were ultimately converted into a mass flux of gas per capita (g capita⁻¹ day⁻¹) using the ideal gas law and information about the number of residents in each household.

Other parameters

During each gas sampling campaign, the soil temperature, conductivity, and volumetric water content (VWC) was measured immediately adjacent to each chamber. Each measurement was taken in triplicate and averaged. All homeowners were surveyed to determine the number of individuals in their household.

Statistical analysis

All statistical analyses were performed with R version 3.0.2 (R Core Team).

To address the question of whether the soil over components of the septic system (leach field or sand filter) had different gas fluxes than control soil, a linear mixed effects (LME) model was used. A maximal model was fit for each of the three types of gas fluxes (CH₄, CO₂, N₂O) with the following fixed effects: treatment (a categorical variable equal to leach field, sand filter, or control), soil temperature, conductivity, and volumetric water content. Site was used as the random effect. The N₂O flux measurements were log-transformed to satisfy normality conditions. Outliers were removed through inspection of the resulting plot of fitted values versus residuals. A minimal model was reached through successive removal of non-significant fixed factors.

To address the question of whether gas fluxes out of the roof vent were significantly different from fluxes out of the soil over the septic system, a Wilcoxon signed-rank test was used. The data did not meet the assumption of normality required to use a paired t-test. The nominal variables were treatment (septic or control) and site. The measurement variable was flux per capita.

Outreach Comments

Describe outreach efforts you have conducted, plan to conduct, or wish to suggest -
If government/community groups were contacted, please provide information, as it helps the Hudson River Estuary Program in its coordination efforts with local agencies

Student Training

Two undergraduate students, one Master of Engineering student, and one PhD student were involved with this project.

Additional final reports related to water resource infrastructure research are available at
http://wri.eas.cornell.edu/grants

References


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US EPA. (2012). *Decentralized Wastewater Treatment Can Be Green and Sustainable* (pp. 1–2).


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