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# Liquid manure storage temperature is affected by storage design and management practices—A modelling assessment

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ABSTRACT

A numerical model was used to predict effects of different liquid manure storage designs and management practices on manure temperature ($T_m$). Manure storage designs included various tank diameters, proportion of the storage above-ground, addition of a roof, and floating covers (synthetic or straw). Manure management practices included the frequency of manure removal, manure agitation, and the depth of manure remaining after removal. Results showed that smaller diameter tanks with a greater depth had lower peak $T_m$. There was no appreciable effect on $T_m$ from constructing a storage tank above-ground *vs* in-ground. Adding a roof decreased peak $T_m$ for spring manure removal, but not autumn removal. Floating synthetic covers with high solar absorptivity (i.e. dark colour) greatly increased peak $T_m$, whereas straw covers had the opposite effect—decreasing peak $T_m$. Removing manure twice per year (spring and autumn) or once annually in spring led to shallower manure depth in summer and greater peak $T_m$; in contrast, once annual autumn removal had greater depth and lower peak $T_m$ in summer. Manure agitation during the warm season increased peak $T_m$ substantially for autumn manure removal, and slightly for spring removal. Leaving less manure in storage after spring removal led to a more rapid increase in $T_m$ and a higher peak $T_m$ in summer. Overall, the study highlights that manure storage design and management practices can greatly affect $T_m$, with peak $T_m$ being increased or decreased up to 8°C in some scenarios. These findings emphasize that $T_m$ is dynamic and that air temperature is an overly simplistic surrogate for $T_m$. Thus, it is important that studies examining greenhouse gas emissions from liquid manure also measure manure temperature. Insights from the study may guide future research linking liquid manure storage design and management to $T_m$ and related effects on greenhouse gases such as methane.

## 1. Introduction

To minimize global temperature rise, mitigating greenhouse gas (GHG) emissions needs to occur (IPCC, 2007). The livestock sector is a relatively large source for GHG emissions, representing ~18% of global emissions (Stehfest et al., 2009). Within the agricultural sector, livestock production contributes ~40% of all anthropogenic methane ($CH_4$) emissions (Key and Tallard, 2012). Livestock manure storages are a significant source of GHG emissions and a need exists to develop beneficial management practices to reduce emissions. Emissions of $CH_4$ are a greater concern with liquid-based than solid-based manure systems (Dong et al., 2006). Within liquid manure systems, emissions of $CH_4$ typically contributes more than 95% of the total GHG emissions on a $CO_2$-equivalent basis (Le Riche et al., 2016). There have been numerous studies investigating the GHG emission rates from liquid manure storage systems (Amon et al., 2006; Chianese et al., 2009; Kulling et al., 2003; Massé et al., 2008; Sommer et al., 2007; Umetsu et al., 2005; VanderZaag et al., 2014; Wood et al., 2014). In a review of field-based studies, Owen and Silver (2015) reported that modeled $CH_4$ emissions underestimated measured emissions for liquid manure and anaerobic lagoons. This points to the need for improved liquid manure emission models.

To model emissions from liquid manure requires accurately modeling manure temperature ($T_m$) because the rate of $CH_4$ generation from liquid manure is highly temperature dependent. Laboratory studies have modeled $CH_4$ production using an Arrhenius relationship (Elsgaard et al., 2016). As an exponential function, seemingly small differences in $T_m$ have a large impact on the rate of $CH_4$ production. For example, an increase in $T_m$ from 15 to 20°C would increase the $CH_4$ production rate from cattle slurry by 81% (based on Elsgaard et al. (2016)). An additional increase in $T_m$ to 25°C would further increase production by 77%. Similarly, the Intergovernmental Panel on Climate

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Change guidelines for estimating $CH_4$ emissions from liquid manure storages recommend using a climate factor based on a van't Hoff-Arrhenius relationship to account for the temperature effect (Dong et al., 2006; Mangino et al., 2001).

As $T_m$ is a crucial driver of GHG emissions (especially for $CH_4$), it is valuable to predict the effect of management practices and storage design on $T_m$. Although studies have measured $T_m$ within manure storages (Amon et al., 2001; Arrus et al., 2006; Bluteau et al., 2009), there is a general lack of knowledge about the effects of management practices and manure storage design on $T_m$. Due to this knowledge gap, emission models use $T_a$ as a surrogate for $T_m$. However, on-farm studies have shown that $T_m$ does not simply track $T_a$; rather, at times $T_m$ is less than $T_a$, and at other times $T_m$ exceeds $T_a$ substantially (Baldé et al., 2016). The temporal dynamics of $T_m$ are particularly important because the volume of manure stored is also dynamic. This was highlighted by Baldé et al. (2016) who observed the impact on elevated $CH_4$ emissions when both manure volume and manure temperature peaked in the autumn. In contrast, a model based on $T_a$ would underestimate $CH_4$ emissions because peak $T_a$ occurred in the summer, months before the peak manure volume.

The design dimensions of a storage tank are expected to affect $T_m$ as manure depth is an important factor in the heat transfer characteristics (Rennie et al., 2017). Studies have suggested a smaller surface area to volume ratio for liquid manure storages can reduce $NH_3$ emissions (Nicholson et al., 2002). Furthermore, the addition of a roof structure over a storage tank can reduce the intercepted precipitation to be stored (Turnbull et al., 1977). A roofed storage would require a lower design volume and could therefore be constructed with a smaller surface to volume ratio for the same design depth (i.e. smaller design diameter).

Several types of floating covers are available that have the potential to decrease emissions (VanderZaag et al., 2008). Floating synthetic covers have been investigated (Bluteau et al., 2009; VanderZaag et al., 2010). These covers can be permeable or impermeable, with varying degrees of insulation. Clay granule floating covers have been used to study the effects on $NH_3$ and GHG emissions (Misselbrook et al., 2016). Floating straw covers have been used to reduce odour (Blanes-Vidal et al., 2009; Clanton et al., 2001, 1999; VanderZaag et al., 2008; Xue et al., 1999), $CH_4$ and $NH_3$ emissions (VanderZaag et al., 2009), and total GHG emissions (Laguë et al., 2005). The mechanism for reducing $CH_4$ emissions is not well understood. It is commonly thought to be due to biological methane oxidation in the cover by methanotrophs, but this mechanism has been shown to be limited (Nielsen et al., 2013). Thus, it is of interest to know whether floating covers affect liquid manure temperature. Effects on temperature might be of equal or greater importance than the effects on methanotrophs. Timing of manure removal has been shown to affect GHG emissions (Baldé et al., 2016). Late summer or early autumn manure removal can reduce $CH_4$ emissions compared to spring removal (Baldé et al., 2016). The quantity of manure removed has also been shown to affect $CH_4$ emissions due to the remaining manure serving as an inoculum (Massé et al., 2016, 2008; Wood et al., 2014).

Manure agitation/aeration has been observed to alter $CH_4$ emissions (Amon et al., 2006; Calvet et al., 2017; VanderZaag et al., 2014). While these methods enhance $O_2$ diffusion into the slurry, mixing manure could also affect the heat transfer characteristics by disrupting established thermal gradients.

As manure storage GHG emissions depend on several parameters it is difficult to reproduce real-world conditions in controlled experiments. It is therefore beneficial to use models to simulate the effects of storage design and storage management on $T_m$. Using this approach provides insight into management strategies that can lead to reduced $T_m$ and consequently lower GHG emissions.

We previously developed a 3-D mathematical model to describe the heat transfer phenomena in liquid manure storages and the model was validated using experimental data (Rennie et al., 2017). The current study focusses on using the model to predict the effect of different storage design and management practices that could affect $T_m$ within liquid manure storages ultimately leading to possible $CH_4$ emission reductions.

## 2. Materials and methods

### 2.1. Model overview

The numerical model used in this study has been presented and validated by Rennie et al. (2017) using data from on an open-top liquid manure tank near Ottawa, ON, Canada. A sensitivity analysis on some input parameters (manure depth, incoming $T_m$, wind-speed, solar absorptivity, manure emissivity, manure solids, and soil thermal conductivity) was performed and model uncertainties and limitations were discussed (Rennie et al., 2017). An overview of the model is given below to provide the basic framework and key parameters.

The model uses the basic heat conduction equation to estimate $T_m$ within liquid storages, with boundary conditions that account for heat transfer with surrounding soil, short and long-wave radiation, convective heat transfer, evaporation, and the effect of incoming fresh manure. The model was developed for a range of liquid manure storages including concrete storages (above-ground or in-ground storages) and earthen lagoons. The model was solved using a numerical method. For this study, the model was set to calculate $T_m$ at 600 points throughout the liquid manure storage on a 5 min timestep, and data output was on an hourly average basis. Average hourly $T_m$ was calculated from these 600 locations, representing the spatial average of the liquid manure.

Solar radiation was estimated using a model based on geographical location (latitude), day of year (DOY), time of day, and was adjusted for local cloud cover. Details on the solar radiation model are provided in Rennie et al. (2017). Long-wave radiation exchange with the atmosphere is based on the Stefan-Boltzmann equation with atmospheric emissivity ($\varepsilon$) estimated from humidity. Convective heat transfer from the manure surface was calculated with an empirical heat convection equation (Incropera and DeWitt, 1996) with wind-speed and $T_a$ as inputs. Evaporative losses from the manure surface, leading to latent cooling, were a function of the water vapour pressure deficit.

Heat transfer to the soil through the floor of the tank was based on a model used for heat losses from building basements (ASHRAE, 1997) and assumes a constant soil thermal conductivity and soil temperature equal to the average annual $T_a$ at 3 m depth. Heat conduction losses through the manure tank walls were estimated using a model developed for basements. The model required the soil thermal conductivity and an estimate of the length of the heat flow path lines.

The model considers the effects of manure freezing during the winter months, with the latent heat of fusion of water used to simulate a heat sink/source during the freezing/thawing process. Other effects during winter conditions, such as the thermal insulation of snow cover or the change in surface albedo due to snow, were not considered. Additionally, the effects of surface crusting were not considered in the model.

The model was not validated for roofed storages or for floating covers. For these cases, model parameters were adjusted to best reflect the addition of a roofed storage or a floating cover. This did not result in fundamental changes to the model and are consistent with the governing heat and mass transfer phenomena. Parameters were based on experimental data or literature values, as outlined in Sections 2.3.3–2.3.5.

### 2.2. Model inputs

The model required several inputs dependent on the local environmental parameters or the characteristics of the manure storage (tank dimensions, manure properties, incoming $T_m$). For this study, environmental conditions were from the same location as the model