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A Physics-Based Framework for Accurate On-Farm Enteric Methane Sensing

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ABSTRACT: The accuracy of on-farm sensors remains a limiting factor in their use to verify efforts to reduce enteric methane emissions. These "sniffers", although scalable, measure gas concentration (ppm), which is poorly correlated with mass flux (g/day), because the dilution of enteric methane by turbulence is unmeasured. We develop a multiphysics framework that provides the first mechanistic connection from the biological source to the sensor reading. Our model combines a physiological mass balance of rumen gas production and mixing with a transient, buoyant puff model that captures the fluid dynamics of the emission event as it disperses into the near-field environment. Validated against field measurements of mass flux from emission events (a 9% error in mass prediction and a root-mean-square error of 0.4 mg/s), the model replicates the magnitude, fluctuations, and overall dispersion of mass flux using basic physiological variables and quantifies the "captured fraction" of mass by the device. This framework is a foundational tool for transforming low-cost sensor data into accurate measures of mass emission fluxes.

KEYWORDS: *enteric methane, on-farm sensing, greenhouse gas mitigation, high-throughput phenotyping*

INTRODUCTION

The agricultural sector is a significant source of greenhouse gas emissions,[1] mainly methane (CH_4) from enteric fermentation in ruminants. This digestive process accounts for 30% of global anthropogenic methane emissions,[2] with cattle being the largest contributor, responsible for 75% of these emissions.[3] One dairy cow can emit about 160 kg of CH_4 each year.[4] Because methane is potent but remains in the atmosphere for about 12 years,[5] reducing livestock emissions is a key strategy for slowing near-term global warming. Developing and rapidly validating mitigation methods—such as genetic selection for low-emission animals, dietary changes, and new feed additives—depends on accurate measurement of methane emissions from individual animals.[6] Without reliable high-throughput phenotyping, it is impossible to evaluate intervention effectiveness or advance breeding efforts. This has created a strong need for robust measurement tools that can scale to commercial farms, where interventions are applied. However, current measurement methods often trade accuracy for scalability.[7] The gold standard for measuring methane, the respiration chamber, is highly accurate but expensive and impractical for farm use (see the first method from the left in Figure 1).[8] The proprietary GreenFeed system is a practical in-field alternative that estimates mass flux by measuring gas concentrations.[6,9−11] The system correlates well with chamber data (r^2 = 0.92); however, calculating the total flux depends on the number of visits to the measuring stall, which limits the availability of continuous, real-time data. Moreover, it is not scalable on farms (see the second from the left in Figure 1). In contrast, inexpensive "sniffer" sensors are scalable but usually only measure concentration.[12] These readings are often unreliable because methane gets significantly diluted by the time it reaches the sensor (fourth from the left in Figure 1). Dilution can vary between 10- and 100-fold and is influenced by sources of unpredictable variability, such as background air currents, small head and muzzle movements, and changes in breathing patterns.[11,13] Because this dilution is both large and difficult to measure precisely, accurately calculating the emitted gas mass from concentration alone remains challenging (see fourth from the left in Figure 1). This bottleneck in methane measurements is not just a technical limitation; it also acts as a barrier that hampers the effectiveness of climate agreements like the Global Methane Pledge[14] and the ability of the global food industry to decarbonize its agricultural supply chains.[15] The challenge of accurately and scalably verifying emissions at the source means that national climate commitments lack solid data for verification, making it hard to prove mitigation efforts in real-world conditions.

This work directly addresses the measurement challenge by introducing a physics-based framework that enables low-cost, scalable sensors to produce the high-fidelity mass flux data required to enable action across these interconnected domains. The methane emitted by cattle during an eructation event forms a turbulent, transient, buoyant puff of gas that is subject to complex, random dilution by ambient air currents, temperature, relative humidity, pressure, and respiratory flows before it reaches a sensor. To mechanistically link the measured concentration to the true emission rate, this work develops a physics-based framework based on the primary hypothesis that the relationship between near-source methane concentration

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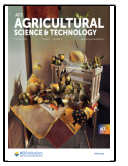

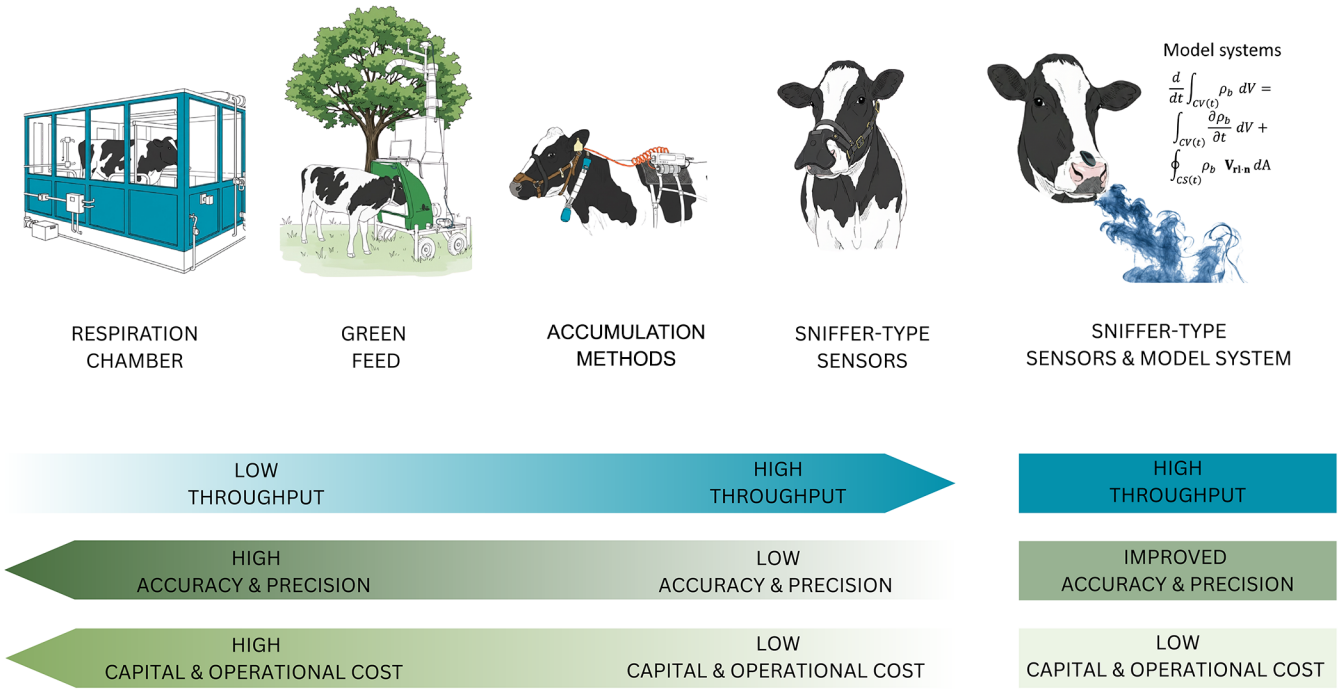

Figure 1. Methodologies for quantifying enteric methane emissions in ruminants.

and true mass flux can be mechanistically resolved by modeling the emission event as a system of interconnected control volumes and a transient buoyant puff, allowing for the reconstruction of mass flux with significantly greater accuracy than simple statistical correlations (see right in Figure 1). Using this model, we will also validate a second hypothesis: that the sensor's captured fraction is more sensitive to its spatiotemporal position relative to the puff's trajectory than its inherent sampling flow rate, predicting an exponential decay in capture fraction with increasing sensor distance versus a linear relationship with flow rate. Our results demonstrate that this framework, when initialized with key physiological parameters, accurately reproduces the mass-flux profile of an emission event. Moreover, spectral imaging of live animal respiration validates the puff model, which reveals that the emitted methane plume decays rapidly, making the sensor's capture efficiency highly sensitive to its precise location and timing. This approach provides the theoretical foundation necessary to move beyond simple statistical correlations, to mechanistically link the measured concentration from sniffer-like devices to the true emission rate, and to enable large-scale monitoring and phenotyping of animal agriculture.

METHODS

The hybrid, multiphysics framework designed to mechanistically link the physiological source of methane emission to the signal measured by a near-source sensor is composed of two distinct but coupled models: (1) a multicontrol-volume mass balance model representing the animal's digestive and respiratory systems, and (2) an integral model for a transient, buoyant puff that describes the complex fluid dynamics of the emitted gas in the near-field environment. By integrating these approaches, we can simulate the entire emission-to-sensor pathway, from methane generation in the rumen to its dynamic dispersion and subsequent capture. The physiological source term is modeled by applying the Reynolds Transport Theorem to a system of four interconnected control volumes (CVs), which represent the rumen, the lungs, the immediate environment, and the sampling device. This approach yields a system of coupled ordinary differential equations that govern the conservation of methane mass, allowing the calculation of time-varying concentrations and fluxes within and between each volume. To provide a more physically realistic description of the gas dispersion, the well-mixed environmental control volume is replaced by a transient buoyant puff model. An emission event is not a continuous jet but a finite release of gas with initial momentum and buoyancy. The puff model captures the complete life cycle of this gas cloud as it entrains ambient air, grows in size, and travels away from the source. The output from the control volume system (i.e., the total mass, momentum, and buoyancy released during an event) serves as the initial conditions for the puff model. The solution of the puff model provides the full spatiotemporal concentration field, which is then used to determine the concentration profile that a sensor would measure at any given location and time. A Monte Carlo simulation with 10,000 repetitions based on ±10% variation of input parameters provides a validation of the model's range and the propagation of its uncertainty.

The following section provides a description and summary of the governing equations for both the control volume system and the buoyant puff model (the detailed derivation can be found in the Supporting Information), and the code is provided in Muriel and Jaramillo-Botero.[16]

Experimental Setup for Methane and Flow Measurements

Experimental measurements were performed to characterize the fluid dynamics of methane release during cattle respiration and compare them to the model results. These measurements include one-dimensional laser and two-dimensional spectral measurements, as well as measurements of respiratory flow rate. We used a Crowcon LM2B03E-SBA commercial hand-held laser methane detector (LMD) with a 2 Hz sampling frequency. The LMD was pointed to one nostril of the animal and the distance from the device to said nostril was kept fixed by mounting the device on the snout (see the Supporting Information for details on the setup). A Sensirion flow sensor (SFM3003−300-CE) at 40 Hz measured the flow rate from one nostril, while the LMD detected methane on the other. Flow and concentration measurements were performed simultaneously to have a direct correlation between respiratory flow and mass flow. The accuracy of the concentration, distance, and flow measurements is 10, 5, and 2.5%, respectively. Propagating independent random errors using the Root-Sum-Square method results in a final accuracy of 11.5% for the mass flow rate. Spectral measurements were performed with the cooled FLIR Gx320

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camera during the respiration of free-ranging cattle. The camera has a thermal resolution of 320 × 240, a spectral range of 3.2 to 3.4 μm and a sensitivity of 9.6 ppm·m CH_4. The sampling frequency was set to 10 Hz, however, in this mode the camera cannot quantify the methane concentrations. Wavelet-based optical flow analysis[17] and Q-criterion[18] were used to reveal the flow characteristics. The latter provides a physical definition for a vortex, identifying it as a zone within a flow field where rotational forces dominate over deformational forces. This is quantified by comparing the magnitude of vorticity with the strain rate, a value derived from the second invariant of the velocity gradient tensor. The record lengths for flow and concentration varied from 25 to 80 min where the devices logged data continuously, and up to 30 s for spectral measurements.

We characterize all methane emissions in animal subjects in partnering barns with Javeriana University (i.e., Zebu breed in a low-tropic environment). A first group composed of ten females from 26 dairy animals was used for spectral measurements, with ages varying between 3 and 6 years and kept in a dry temperate environment at 1000 m above sea level (m.a.s.l.). A second group of six females out of a total of 40 dairy animals in the herd was used for flow and laser measurements, with ages between 4 to 7 and kept in a humid temperate environment at 1600 m.a.s.l. The measurements included two repetitions for 75% of the animals and covered early morning, midday, and afternoon. The animals in both groups are kept in a silvopastoral system (native woods and ornametal eucalyptus cinerea), where they graze freely from 6 am to 4 pm and return to a stable for the rest of the day. Before all measurements, the cattle followed a period of habituation with equipment and human handlers. The protocol consisted of 1 day of food reward after a period of 20 to 30 min of equipment use. Typical forages ingested include *Cynodon nlemfuensis* and *Brachiaria sp* species. The use of animals in this study was approved (Animal Usage Form 185−25) by the Institutional Animal Research Ethics Committee of Pontificia Universidad Javeriana, accredited by the Association for Assessment and Accreditation of Laboratory Animal Care. The project also complies with Colombian regulations that govern the ethical use of animals in scientific research.

Model 1: Methane Generation, Mixing, and Emission

The methane release system is made up of four control volumes (CV) shown in Figure 2. CV_1 is the stomach (rumen) where methane is produced, CV_4 is the lungs with cyclic respiration, CV_2 also named CV_{env} is a subvolume of the larger environmental volume (i.e., troposphere) and is therefore considered in thermodynamic equilibrium, and CV_3 is a sampling device near the nostrils. The methane-rich gas from CV_1 and the air from CV_4 mix in the mouth/nose enter CV_2.[19] For tractability, we assume instantaneous mixing in each control volume, acknowledging that this is an idealized condition and that, in reality, mixing will vary due to molecular and turbulent diffusion. The device CV_3 draws a fixed flow Q_f from CV_2 near the source for a limited time. The device does not have net accumulation (i.e., outflow equals inflow Q_f), similar to a sniffer method where air is continuously sampled near the animal's nostrils through a tube to a gas analyzer.[19] We assume that the pressure in each CV stays constant because outflow equals inflow, preventing pressure from building up. The stomach volume changes significantly as gas is produced and released, and the lung volume changes with breathing (inflation/deflation).

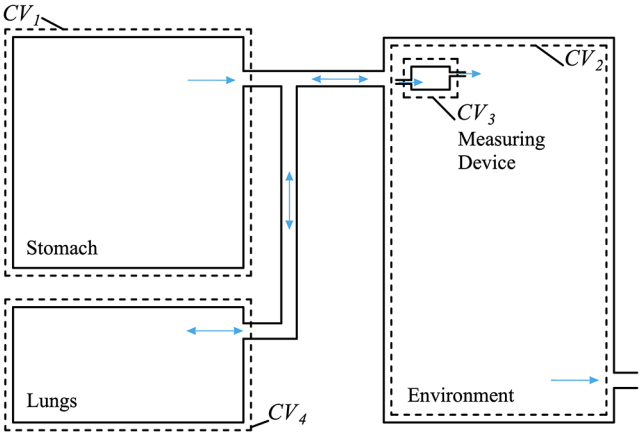

Figure 2. Control volume model representing the digestive and respiratory systems of cattle.

The rumen produces methane by fermentation, increasing its concentration within CV_1 over time, and is predominantly (~87%) expelled through eructation events.[19] We model a single emission event of duration Δt_1 (e.g., 30−40 s[20−23]). During this event, a time-varying volumetric flow $Q_1(t)$ carries methane out of CV_1. The flow $Q_1(t)$ is represented as a log-normal pulse to match the observed emission profiles. We denote the period of the breathing cycle as T_b (a cow's resting respiration is approximately 18−30 breaths per minute, so $T_b \approx$ 2−3 s). For simplicity, we may assume that lung flow follows Lekeux et al.[24,25] A small device near the nostril samples the air. Air is drawn at a fixed flow rate Q_f (e.g., ~1 L/min as in typical sniffer setups[19]) for a duration Δt_3. Table 1 defines the key variables for each control volume (with SI units, unless otherwise stated).

Table 1. List of Symbols, Definitions, and Units

symbol	definition	units
$V_1(t)$	Volume of rumen (CV_1), time-dependent	m^3
$V_4(t)$	Volume of lungs (CV_4), time-dependent	m^3
V_{env}	Volume of environment CV_2 (control volume size)	m^3
V_3	Internal volume of sampling device (CV_3)	m^3
$C_1(t)$	Methane concentration in rumen gas	kg CH_4/m^3
$C_4(t)$	Methane concentration in lung alveolar air	kg CH_4/m^3
$C_{env}(t)$	Methane concentration in environment (CV_2)	kg CH_4/m^3
$C_3(t)$	Methane concentration in device sample air	kg CH_4/m^3
$Q_1(t)$	Rumen gas volumetric outflow (emission event)	m^3/s
$Q_{lung,in}(t)$	Lung inhalation volumetric flow	m^3/s
$Q_{lung,ex}(t)$	Lung exhalation volumetric flow	m^3/s
$Q_{env,in}(t)$	Inflow to environment (CV_2) = $Q_{lung,ex} + Q_1$	m^3/s
$Q_{env,out}(t)$	Outflow from environment CV_2 (to ambient)	m^3/s
Q_f	Sampling flow into device CV_3	m^3/s
$R_{CH_4}(t)$ or $S_1(t)$	Methane generation rate in rumen	kg/s
Δt_1	Enteric release duration (event length)	s
Δt_3	Sampling duration for device	s
T_b	Breathing period (one inhale−exhale cycle)	s

Equations 1−4 constitute the system of mass conservation equations derived from the Reynolds Transport Theorem for our multi-CV system. Each equation corresponds to a control volume and equates the rate of change of methane mass inside to the net mass flux in/out plus any generation. These can be solved (analytically or numerically) given functions for $S_1(t)$, $Q_1(t)$, $Q_{lung}(t)$, etc.

$$\frac{d}{dt}(C_1V_1) = S_1(t) - Q_1(t)C_1(t) \tag{1}$$

$$\frac{d}{dt}(C_4V_4) = Q_{lung,in}(t)C_{env}(t) - Q_{lung,ex}(t)C_4(t) \tag{2}$$

$$\frac{d}{dt}(C_{env}V_{env}) = Q_1(t)C_{1,out}(t) + Q_{lung,ex}(t)C_4(t) - (Q_{env,out}(t) + Q_{lung,in}(t))C_{env}(t) \tag{3}$$

$$\frac{d}{dt}(C_3V_3) = Q_fC_{env}(t) - Q_fC_3(t) \tag{4}$$

The capture fraction of methane by the device is defined as

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$$\text{capture\%} - \frac{\int_{t_s}^{t_s+\Delta t_3} Q_f C_{\text{env}}(t)\mathrm{d}t}{\int_{t_0}^{t_0+\Delta t_1} Q_1(t)C_1(t)\mathrm{d}t} \times 100 \tag{5}$$

From eq 5, if V_{env} is small and Q_f is not too small relative to Q_1, and if the sampling covers the whole emission event, a significant fraction could be captured. However, in general $Q_f \ll Q_{\text{env,in}}$, so the captured fraction is only a few percent at best.[26] Therefore, many sniffer measurement devices capture a small subsample and must infer total emissions using statistical methods.

If the device sampling period Δt_3 covers the entire release ($t_s = t_0$ and $\Delta t_3 = \Delta t_1$) and if V_{env} is very small (near the source, minimal dilution) and if Q_f is, say, on the order of exhalation flow, then the fraction could approach a sizable value. More realistically, for large V_{env} (open air) and $Q_f \sim 1$ L/min versus cow exhalation of the order of 100 L/min, the fraction is small. We can incorporate the effect of the environment dilution by substituting an approximate solution for $C_{\text{env}}(t)$. If the emission event is short and the device captures during that window, a rough estimate assuming that there is no outflow loss during the capture (like a batch, which is not strictly true) is $C_{\text{env}} \approx \frac{M_{\text{released}}}{V_{\text{env}}}$ as an average. Then $M_{\text{captured}} \approx Q_f \Delta t_3 \frac{M_{\text{released}}}{V_{\text{env}}}$, thus, $\frac{M_{\text{captured}}}{M_{\text{released}}} \approx \frac{Q_f \Delta t_3}{V_{\text{env}}}$. Plugging typical numbers: $Q_f = 1 l/\text{min} = 1.67 \times 10^{-5}$ m^3/s, $\Delta t_3 = 30$ s, $V_{\text{env}} = 1$ m^3 (small volume around the head), gives a fraction of 5×10^{-4} or 0.05%. Nevertheless, the effectiveness of a sniffer method can also be described in other terms, such as the flow velocity at which the device captures relative to the ejection velocity, its ability to detect and measure concentration peaks and temporal variations observed in enteric emission events, and the sensor's characteristics, like specificity, sensitivity, and others. Here, we focus on assessing the mass fraction captured.

Model 2: Integral Model for a Transient Buoyant Puff

The exhalation of cattle is not a continuous steady stream, but a finite volume of gas released over a short time span. This type of flow is known as a puff or, when buoyancy is significant, a thermal.[27] A puff is driven by an initial impulse of momentum, whereas a thermal is driven by an initial release of buoyancy. A single bovine exhalation is a classic example of puffing. It has an initial momentum from the respiratory muscles and an initial buoyancy from its temperature and humidity. As it evolves, it behaves as a buoyant puff, a hybrid structure whose dynamics are initially momentum-dominated but become increasingly influenced by buoyancy over time (see Figure 3).

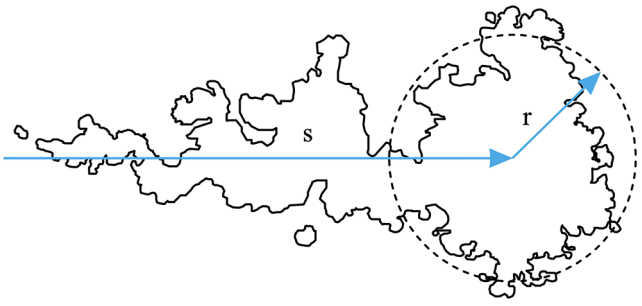

Figure 3. Representation of tracer release as a puff. Assuming a radially uniform puff at time t, the path-length is defined as s and the radius of the cross-section as r.

The life cycle of a turbulent puff can be described in distinct stages: the zone of flow establishment (ZFE), in the immediate vicinity of the source (the nostrils), is typically short, on the order of 5 to 12 source diameters.[28,29] Within this zone, dictated by the geometry of the nasal passages, the core velocity remains close to its initial value, as it transitions to a more universal, self-similar profile.[30] Beyond the ZFE, the puff enters a self-similar evolution phase, the zone of established flow (ZEF). It entrains ambient air, causing it to grow in size ($b(t)$) and its centerline velocity ($U_c(t)$) to decrease. The velocity profiles across the puff take on a characteristic shape, often well approximated by a Gaussian distribution. Eventually, viscous dissipation and continued entrainment cause the puff's momentum and buoyancy to be dispersed into the ambient fluid, and it ceases to exist as a coherent structure. A key feature of self-similar decay in the ZEF is that the centerline velocity of a pure momentum puff is predicted to decrease over time as $t^{-3/4}$.[31]

The mathematical formulation developed herein will focus on the dynamics of an assumed continuous gas phase. The passive scalar concentration, $C(\mathbf{x}, t)$, can be interpreted as the concentration of a gaseous tracer such as CH_4. We assume that the mean velocity and other scalar quantities (buoyancy, tracer concentration) have a self-similar Gaussian profile across any plane perpendicular to the puff's centerline. This assumption is supported by experimental data for jets and puffs,[28,32] and is suitable for integral models focused on bulk dynamics. It should be noted that this is a simplification of the more complex instantaneous flow field, which is inherently intermittent, and of analytical solutions to linearized equations, which can produce different functional forms such as the D-vortex.[33] Let s be the coordinate along the puff's curved centerline and r be the radial distance from the centerline. The profiles are $U(s, r) = U_c(s)\exp\left(-\frac{r^2}{b(s)^2}\right)$, $g'(s, r) = g'_c(s)\exp\left(-\frac{r^2}{\lambda^2 b(s)^2}\right)$, $\overline{C}(s, r) = C_c(s)\exp\left(-\frac{r^2}{\lambda^2 b(s)^2}\right)$ for mean velocity, buoyancy, and concentration, respectively. Here, $U_c(s)$, $g'_c(s)$, and $C_c(s)$ are the centerline values of velocity, buoyancy, and concentration, respectively. $b(s)$ is the characteristic radius of the velocity profile. The parameter λ is the turbulent Prandtl/Schmidt number, which is the ratio of the width of the scalar profile to the width of the velocity profile ($\lambda = b_{\text{scalar}}/b_{\text{velocity}}$). Typically, $\lambda > 1$ (a common value is $\approx 1.1 - 1.3$), indicating that scalars diffuse more widely than momentum in a turbulent flow.[34]

The following set of coupled ODEs and algebraic relations forms the complete integral model (full derivation is provided in the Supporting Information). It describes the evolution of the puff's radius b, centerline velocity U_c, centerline buoyancy g'_c, centerline concentration C_c, and trajectory angle θ as a function of distance s from the source. The entrainment to the system is given by

$$2U_c\frac{\mathrm{d}b}{\mathrm{d}s} + b\frac{\mathrm{d}U_c}{\mathrm{d}s} = 2\alpha U_c \tag{6}$$

where α is the entrainment coefficient, a dimensionless constant. For a round puff $\alpha \approx 0.25$.[35−37] The conservation of momentum is defined as

$$U_c\frac{\mathrm{d}b}{\mathrm{d}s} + b\frac{\mathrm{d}U_c}{\mathrm{d}s} = \frac{\lambda^2 b g'_c \sin(\theta)}{U_c} \tag{7}$$

with θ being the angle with respect to the horizontal and $g'_c = g\beta(T_c - T_a)$, with β being the thermal expansion coefficient, and T_c and T_a the centerline and ambient temperature. The conservation of Buoyancy Flux, assuming a neutral atmosphere, is given by

$$g'_c(s) = \frac{B_0}{b(s)^2 U_c(s)} \tag{8}$$

where B_0 is the initial buoyancy flux. Similarly, the flux of the passive scalar is conserved:

$$\frac{\pi\lambda^2}{(1+\lambda^2)} b^2 U_c C_c = \text{constant} = S_0 \tag{9}$$

where S_0 is the initial flux of the scalar. Finally, we need to relate the centerline coordinate s to the Cartesian coordinates (x, z) (horizontal and vertical)

$$\frac{\mathrm{d}x}{\mathrm{d}s} = \cos(\theta); \quad \frac{\mathrm{d}z}{\mathrm{d}s} = \sin(\theta) \tag{10}$$

The change in the trajectory angle θ is governed by the balance of momentum components. Differentiating the vector momentum equation yields the equation for curvature. This curvature equation

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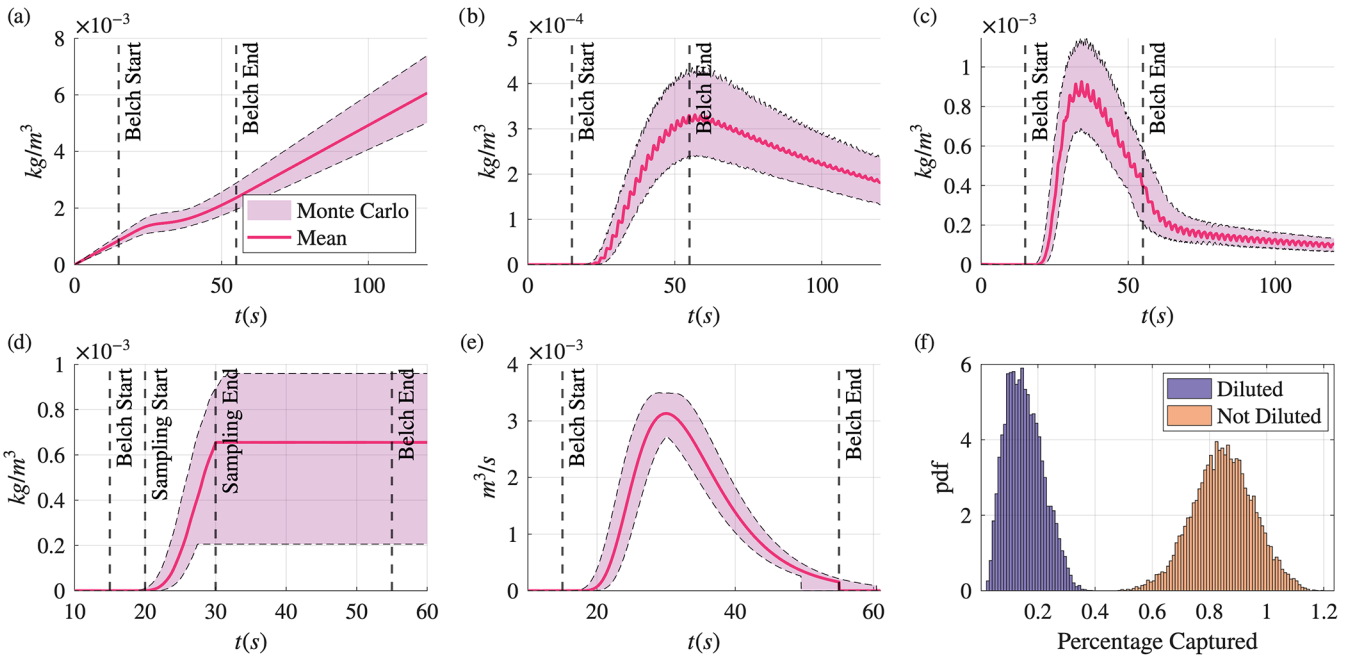

Figure 4. Monte Carlo simulation of methane transport in a modeled respiration system (10% variation of input parameters): concentration in the rumen (a), lungs (b), environment (c), and device (d), and emission event flow rate (e) and percentage of mass captured (f).

shows how the puff turns as momentum dissipates and buoyancy dominates

$$\frac{d\theta}{ds} = \frac{\lambda^2 g_c' \cos(\theta)}{U_c^2} \tag{11}$$

The formulation itself reveals a key physical process: the transition from momentum-driven to buoyancy-driven flow. Initially, near the source, U_c is large, and the momentum flux term ($b^2U_c^2$) dominates. The trajectory is nearly horizontal ($\theta \approx 0$). As the puff travels and entrains air, U_c decreases. The buoyancy term in the momentum eq ($2\lambda^2 b^2 g_c' \sin(\theta)$) becomes relatively more important, causing the trajectory to curve upward (θ increases). Further details of the models, the derivation of the spatiotemporal velocity and concentration fields, the coupling with Model 1, and the initial and boundary conditions are provided in the Supporting Information.

The captured fraction is now based on the local puff concentration at the sensor's coordinates (x_d, z_d).

$$\text{capture\%} = \frac{\int_{t_s}^{t_s+\Delta t_3} Q_f C_p(x_d, z_d, t)\,dt}{\int_{t_0}^{t_0+\Delta t_1} Q_1(t) C_1(t)\,dt} \times 100 \tag{12}$$

This formulation explicitly demonstrates that the capture efficiency is a strong function of both the sensor's spatial position (x_d, z_d) relative to the puff's buoyant trajectory and the temporal alignment of the sampling window (t_s, Δt_3) with the puff's passage time at that location. An optimal measurement requires precise spatiotemporal synchronization between the sensor and the emission event. Because $C_p(x_d, z_d, t)$ (puff concentration near the source) is typically much higher than $C_{env}(t)$ (diluted ambient concentration) for the same emission, we expect the capture fraction in this scenario to be significantly larger than in the well-mixed scenario.

The exact value from eq 12 can be computed if we know $C_p(x_d, r_d, t)$. If the device is essentially at the source ($x_d \to 0$, $r_d = 0$) and sampling throughout the emission event, it could approach the theoretical maximum: in the limit $x_d \to 0$, $C_p \to C_{mix}$ (the concentration of the undiluted rumen/lung mixture) and if the device is drawing directly from the nostrils. In that case, the capture fraction would be $Q_f/Q_{env,in}$ (since the device would be siphoning directly from the outflow). For example, if Q_f (1 L/min) and exhalation plus emission event flow $Q_{env,in}$ (say 100 L/min) were compared, that ratio is 1%. So 1% would be an upper bound if the sampling tube to capture a portion of the flow is directly in the nose. In practice, the device is near but does not capture the bulk flow, and does not necessarily operate during the whole enteric emission event, so capture percentage would be a fraction of that upper bound. The derivation above via concentration is a more general expression that is applicable to any placement of the device relative to the puff.

Implementation Parameters

We implement the system of equations representing the control volume with instant mixing in the environment and its coupling with the puff model. We provide the Matlab codes to run them independently and in a coupled manner. These codes are available in Muriel and Jaramillo-Botero.[16] The following variables used through the models are set to represent the physiology of an animal, but can be changed as required by the user.

The initial concentration of methane in the lungs and rumen is assumed to be zero and tracked throughout the simulation. The background methane concentration in the environment of a cattle farm is typically elevated compared to the general atmosphere. We set it to 3 ppm or 2×10^{-6} kg/m^3 at the standard atmosphere, temperature, and pressure. For context, the global atmospheric methane concentration is approximately 1.9 to 2.0 ppm,[38] and on-farm measurement reports vary from 2.8 to 5.6 ppm.[39,40] The daily methane production rate in cattle varies significantly based on numerous conditions. In general, a cow is expected to produce between 151 and 497 g/day depending on factors such as feed intake, diet composition and quality, production level, and whether the animal is in lactating state.[4,41−43] Therefore, we adopt a methane production rate of 5.7×10^{-6} kg/s corresponding to the expected high-end emissions.

The duration of an emission event is defined as the time between the increase and fall in the methane concentration of a baseline concentration. The dependency of concentration on time follows a log-normal distribution, as is shown in general cases of fluids that discharge into a quiescent environment.[44] This behavior can be seen in the literature[45] and is set to the value reported by Muriel et al.[20] of 40 s in a tropical environment. Moate et al.[46] reported the total capacity of the rumen and reticulum, which holds feed, fluid, and gas, is between 50 and 120 L. Therefore, we define the ruminal volume and the total volume of a gas released during an emission event as 100 and 50 L,

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