

DEVELOPMENT OF COMPACT SENSING TECHNOLOGY FOR CONTINUOUS REAL-TIME MONITORING OF ENTERIC METHANE

Anna Shneidman

Summary

Enteric fermentation by cattle is a major source of agricultural methane emissions, creating a need for practical and scalable methods to measure emissions at the individual-animal and herd levels. Current approaches often rely on specialized instrumentation, controlled environments, or labor-intensive measurements that limit their use in routine farm operations. Gas Recognition and Analysis using Zonal Ear Tags (GRAZE-Tags) is being developed as a low-cost, lightweight methane sensing platform designed for deployment directly on animals or within barns. GRAZE-Tags combine bio-inspired chemical sensing with machine learning to detect and quantify methane in complex, variable environments.

Since the project started in 2024, the research team has focused on translating their previously developed bioinspired sensing approach into a practical, field-deployable sensor of enteric methane. The team built a fully integrated hardware prototype, which has recently been deployed in an ongoing field study. The resulting technology has the potential to enable continuous, distributed measurement of enteric methane emissions without specialized measurement infrastructure, providing data at the individual-animal and herd levels to support research and management strategies for reducing agricultural methane emissions.

Background and Motivation

Methane monitoring in agricultural settings remains a significant technological challenge. Growing regulatory, environmental, and market pressures are driving the need to quantify and reduce livestock methane emissions,¹⁻³ yet existing measurement technologies present substantial barriers to routine, large-scale deployment. These barriers include high cost, limited throughput, disruption of natural animal behavior, specialized infrastructure, and labor-intensive sampling.⁴

Respiration chambers are the current gold standard in bovine methane measurement, offering precise, quantitative methane data. However, they are expensive, require isolation of animals from their natural environment, and have extremely low throughput. GreenFeed systems⁵ offer somewhat lower cost and easier deployment but share a critical limitation of low throughput and interfering with the cow's natural behavior and activities. The sulfur hexafluoride (SF₆) tracer technique entails insertion of gas-releasing capsules into the animal and frequent manual sampling, providing improved scalability, but is invasive, labor-intensive, prone to contamination, and lacks real-time feedback.⁴



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The aim of the research team at Harvard's School of Engineering and Applied Sciences (HSEAS) has been to develop Gas Recognition and Analysis using Zonal Ear Tags (GRAZE-Tags), a compact, low-cost, autonomous technology capable of generating frequent, ground-level measurements of methane concentrations directly from animals in their natural environment (Figure 1).⁶⁻⁹ The technology builds on the team's previously validated volatile organic compound (VOC) electronic nose (e-nose) sensing platform that incorporates bioinspired strategies and machine learning.^{10,11}

The research and development are led by Haritosh Patel, a postdoctoral fellow in the [Bioinspired Engineering Research Group](#) at HSEAS, headed by Professor Joanna Aizenberg. Support from the EQT Foundation and Harvard Salata Institute's Methane Research Cluster has enabled the team to focus their technology on enteric methane emissions, allowing them, over the past two years, to 1) validate the need for sensing enteric methane on the level of individual livestock, 2) push the hardware and software forward, 3) secure concrete opportunities for field studies and collaboration, 4) develop a bigger-picture understanding regarding the need and policies surrounding enteric methane, and 5) provide mentorship to the next generation of scientists and engineers.

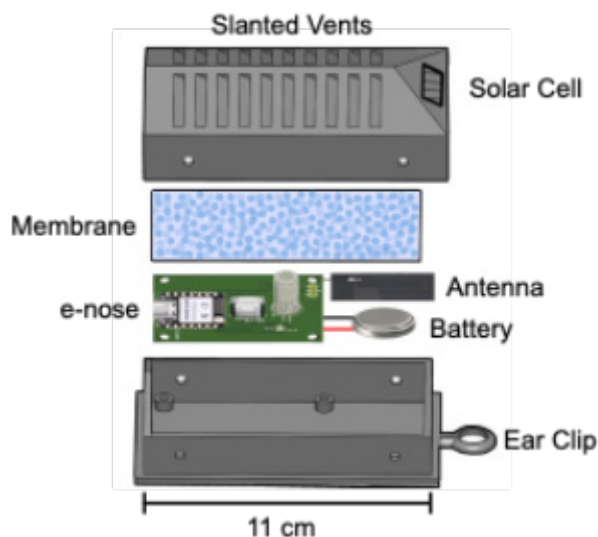


Figure 1. GRAZE-Tags schematic, exploded view.

Implications of Compact Ground-Level Methane Sensing Capabilities

The development of a compact, affordable methane sensor capable of high-frequency measurements at the ground level could substantially expand the ability to measure, understand, and manage agricultural methane emissions. By enabling repeated measurements from freely moving animals, GRAZE-Tags could help researchers and producers determine whether implemented interventions — such as feed additives, dietary changes, animal-management practices, and emerging biological interventions — reduce methane production under real-world conditions. This would greatly extend the scale and duration of studies compared to current approaches, which are typically limited to 10–50 animals at a time and require labor-intensive periodic sampling over a narrow timeframe rather than providing continuous measurements.¹²

GRAZE-Tags, in contrast, could be distributed across entire herds, allowing high resolution continuous tracking of methane emissions from a large number of individuals over months or even years. Researchers would be able to identify variation among animals and track the persistence of the

intervention's effects over time. Such measurements could ultimately support more data-driven optimization of feed and management strategies while maintaining animal productivity.

GRAZE-Tags further carries meaningful implications for how methane policy is designed and enforced. In fact, state and federal policy have begun to recognize the need for scalable approaches to enteric-methane measurement.¹³ The bipartisan Enteric Methane Innovation Tools for Lower Emissions and Sustainable Stock (EMIT LESS) Act of 2024, although not enacted, proposed expanding US Department of Agriculture (USDA) research and testing capacity for methane-reducing products and practices and providing voluntary conservation incentives for their adoption.¹⁴ EMIT LESS is being recommended for inclusion in the 2026 Farm Bill, a legislative package consisting of 10 bipartisan bills currently or previously recommended in Congress.¹⁵ In parallel, USDA continues to invest in greenhouse-gas measurement infrastructure through its Greenhouse Gas Research Network, which includes an enteric-methane research component focused on beef and dairy production in both confined and grazing systems.¹⁶

California provides a leading example of state-level investment in livestock methane mitigation.¹³ Approved in 2016, Senate Bill 1383 established a target to reduce methane emissions from the dairy and livestock sector by 40% below 2013 levels by 2030.^{13,17} In January 2026, the California Air Resources Board (CARB) initiated an information-gathering process to inform implementation of SB 1383, including soliciting information on methane emissions data, mitigation strategies, the effectiveness and feasibility of those strategies, and potential regulatory approaches.¹⁸ Current programs administered by the California Department of Food and Agriculture (CDFA), including the Alternative Manure Management Program, Dairy Digester Research and Development Program, and Dairy Plus Program, provide financial support for dairy and livestock operations to implement methane-reducing technologies and practices.¹⁹ In 2026, California continued this investment, including \$34 million made available through the Dairy Plus Program.²⁰ While these programs have focused primarily on manure-derived methane, they demonstrate a growing policy and investment environment around quantifying and reducing agricultural methane emissions.

The European Union is also establishing increasingly rigorous frameworks for methane measurement and emissions reduction. Regulation (EU) 2024/1787, which entered into force in 2024, establishes mandatory measurement, reporting, verification, and mitigation requirements for methane emissions from the fossil-fuel sector and extends elements of the framework to imported fossil fuels.²¹ Although the regulation does not currently cover agricultural methane, it reflects a broader shift toward measurement-based methane governance and development of standardized, verifiable emissions data. In parallel, the EU is evaluating additional approaches to address livestock emissions, particularly from cattle, including potential measures affecting imported livestock products. Together, these developments suggest a growing future need for reliable, scalable methods to quantify methane emissions across agricultural supply chains.

Beyond agriculture, GRAZE-Tags could have applications wherever methane must be detected across distributed or difficult-to-monitor environments. Potential applications include detection and localization of methane leaks in oil and gas infrastructure, landfills, wastewater facilities, and other methane-emitting sites. GRAZE-Tags can also provide a complementary perspective to remote satellite measurements, such as Carbon Mapper Coalition's Tanger-1 and Tanger-2 satellites.^{22,23} Ground-level measurements help validate and interpret remotely-detected emissions.

GRAZE-Tags Design

In order to optimize the research team's VOC sensing platform specifically for methane detection in open-air agricultural contexts, commercially available metal oxide semiconductor (MOS) sensing elements were chosen as the basis for GRAZE-Tags because of their small size, low cost, low power requirements, and availability in compact, commercially manufactured packages. As MOS elements are notoriously nonselective (each responds to a collection of gases, rather than specifically to a single gas), GRAZE-Tags has an electronic nose (e-nose) format, wherein multiple MOSs with differing response profiles are integrated together on a printed circuit board (PCB). The precise composition of the gaseous input is then determined from the pattern of signal outputs (changes in electrical resistance) from the collection of MOS sensing elements, which typically requires sophisticated data processing and, increasingly, machine learning algorithms.²⁴⁻²⁶

The research team defined key performance metrics for the individual MOS elements as well as for the integrated sensing device, such as the weight and dimensions applicable to implementation as an ear tag or distributed stationary devices within a barn or other relevant setting; ability to perform continuous methane monitoring with high selectivity — even in the presence of interferent gases like CO₂, acetone, and other VOCs found in and around farms;^{27, 28} and robustness to environmental variations and challenges, such as changes in temperature and humidity, and exposure to dust and rain.

Sensor Array Designed to Quantify Methane and Differentiate from Other Gases

To start, a broad range of commercially available MOS sensing elements were assessed for their suitability for methane detection in the concentration range relevant to enteric emissions (50–1,000 ppm). The evaluations were conducted using a purpose-built laboratory setup, which allows for the delivery of precise quantities of methane and other gases, as well as controllably varying the humidity level. The team focused on key performance metrics of the MOS elements, including sensitivity (strength of the sensor's response to methane), limit of detection (minimum detectable concentration), signal-to-noise ratio (SNR), response/recovery time, cross-sensitivity to interferents, and signal variations as a function of environmental conditions. Some of the key results of these evaluations are summarized in Figure 2.

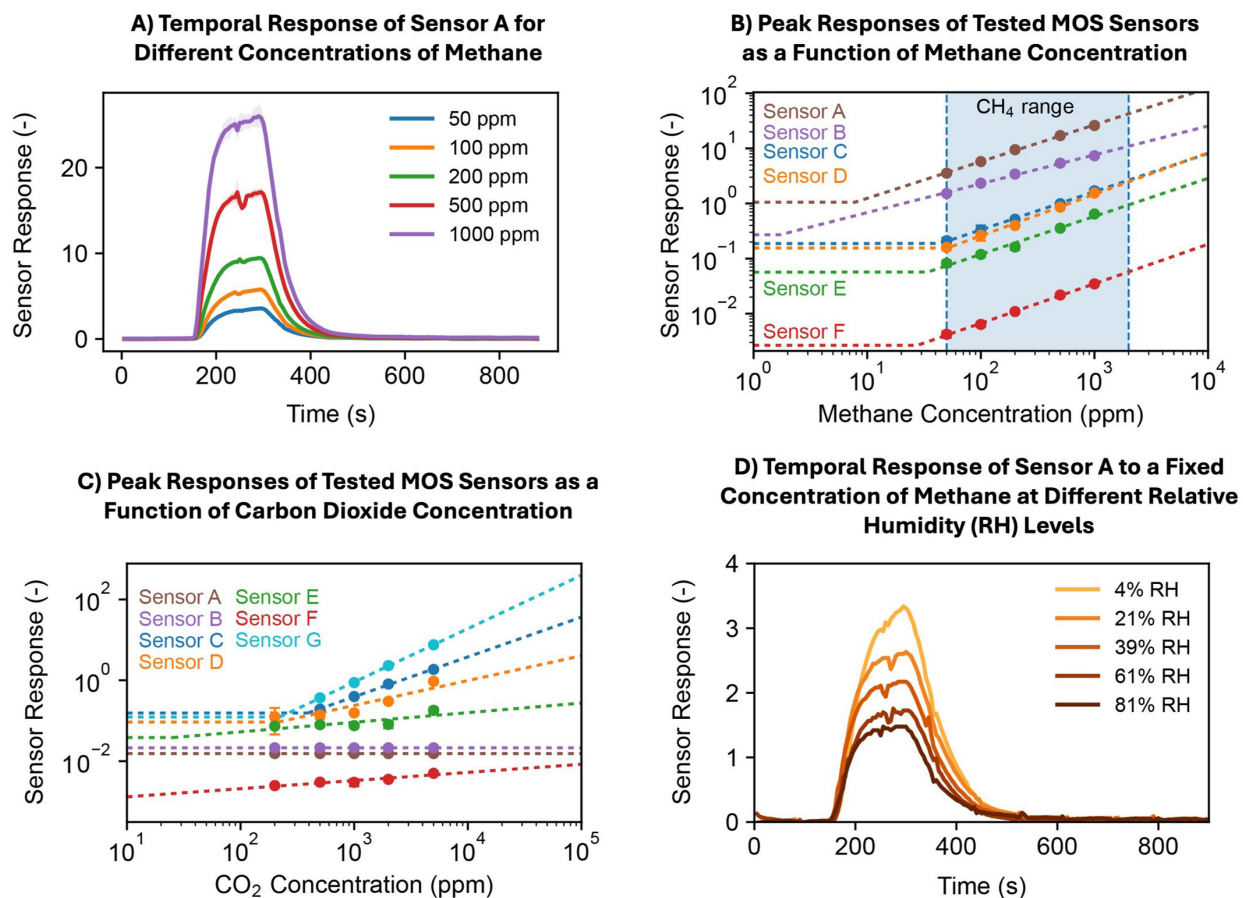


Figure 2. The MOS sensing platform that forms the basis of GRAZE-Tags: A) demonstrates that methane concentration can be distinguished from sensor output; B) indicates that all tested MOS sensing elements can sense methane at the relevant concentrations, with Sensors A and B providing the highest signal, and lowest limits of detection; the flat dashed lines indicate noise level of the corresponding sensor; C) determines that the responses of Sensors A and B to carbon dioxide are negligible (flat line as a function of changing concentration), and D) demonstrates that humidity changes the signal in a predictable manner.

Based on these studies, the team established the underlying hardware configuration (Figure 3), consisting of three sensing elements: 1) a filtered metal oxide sensor with high specificity for methane, owing to its built-in chemical filter layer that minimizes response to other common VOCs (see Figure 4 for a comparison to its unfiltered counterpart); 2) a general VOC sensor with relatively low sensitivity to methane, enabling interferent tracking and supporting signal deconvolution in multi-gas conditions; and 3) a non-dispersive infrared (NDIR) CO₂ sensor that does not respond to VOCs (including methane), since CO₂ is the other primary gas emitted by cattle; the latter also provides temperature and humidity readings, which will be important for contextualizing emissions relative to environmental conditions.

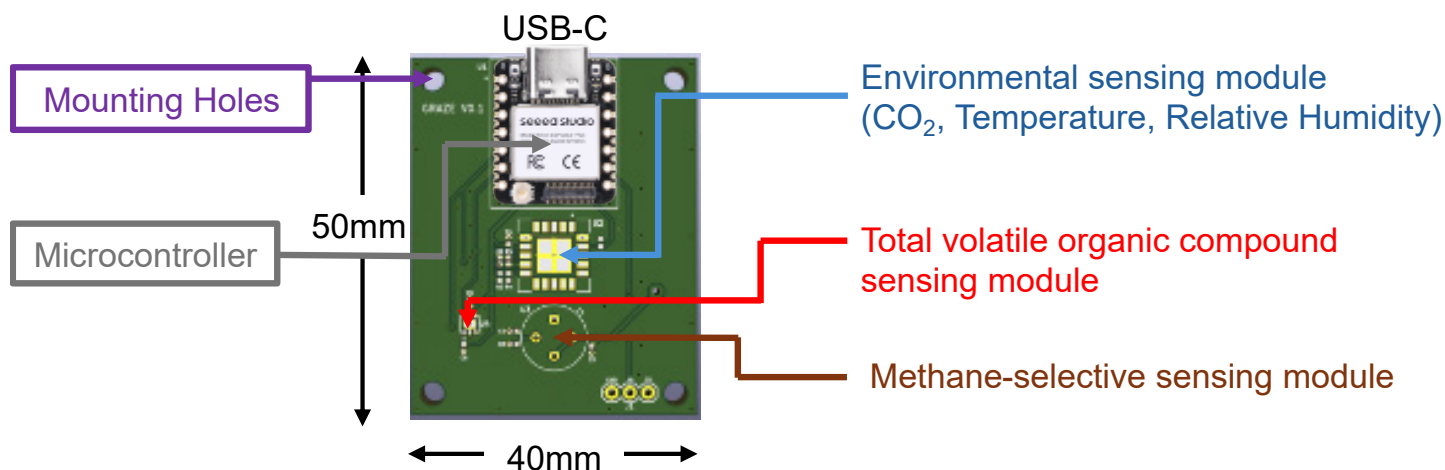


Figure 3. The MOS sensing platform that forms the basis of GRAZE-Tags.

Enclosure Designed to be Lightweight and Protect the Electronics

The enclosure was designed for durability, performance, and ease of use. Comparable in size to commercial GPS cattle tags, the GRAZE-Tag enclosure features slanted aerodynamic vents and a porous, hydrophobic IP67-rated PTFE membrane (shown in Figure 1). This structure allows for free gas exchange while protecting against dust, moisture, and debris — a critical requirement for field deployment in a farm environment. The system is intended to be wireless, solar-powered, and engineered for multi-season deployment with minimal maintenance and labor, enabling scalable, hands-off operation across large herds.

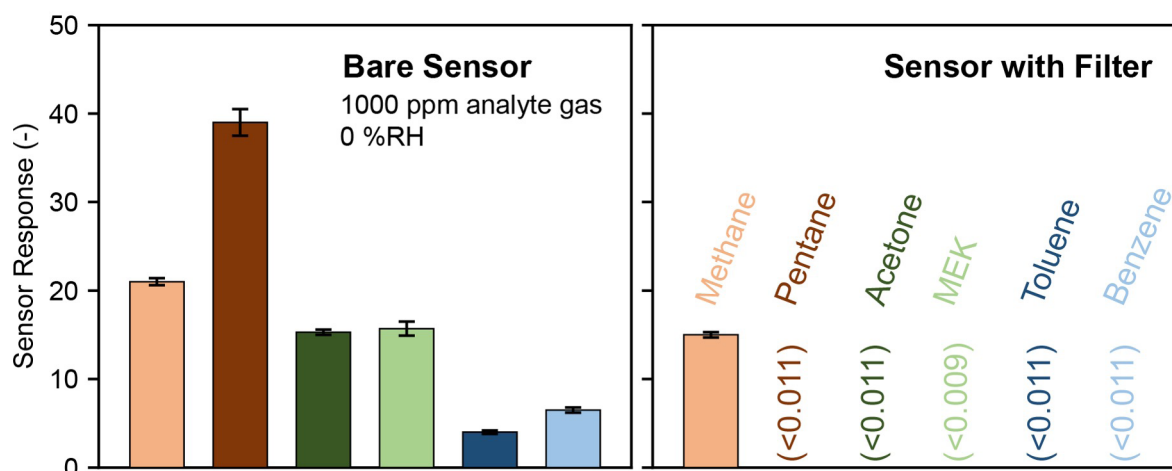


Figure 4. Responses recorded from the unfiltered and filtered versions of the methane sensor implemented in GRAZE-Tags.

Field Studies for GRAZE-Tags Validation

Once laboratory-based studies had established the essential device capabilities — ability to detect methane at relevant concentrations and to account for interferences and the environment — the team looked to validate GRAZE-Tags in a real-world environment. As a first step, it has been critical to demonstrate that GRAZE-Tags reports comparable quantitative methane concentrations to an industry-accepted standard. The research team thus contacted Professor Ermias Kebreab, an expert in agricultural greenhouse gas emissions and head of the [Animal Nutrition and Environment Modeling](#)

Applications Laboratory (ANEMAL) at the University of California at Davis (UC Davis). The ANEMAL lab routinely implements GreenFeed systems to quantify enteric methane production.²⁹ GreenFeed is an automated feeder that includes a hood that encloses an animal's head and a fan to collect the exhaled breath, allowing for quantification of methane with less logistical complexity and behavior disruption than respiration chambers.⁵

A kickoff meeting between the collaborating teams provided input and guidance regarding device requirements, field study schedule and logistics, and GRAZE-Tag device placement strategies for deployment. It was determined that the first set of field studies would not involve tagging cow ears, as several engineering developments are ongoing (see next section). Rather, GRAZE-Tag devices would be placed in close proximity to GreenFeed systems to provide synchronized collocation measurements. As per standard practice, each cow had an RFID tag scanned by the GreenFeed system and assigned to the data, allowing for attribution of recorded methane measurements to specific individuals.

While attending the State of the Science Summit at UC Davis in June 2026,³⁰ the team installed two GRAZE-Tag devices alongside a GreenFeed system to collect data in conjunction with ANEMAL Lab studies of feeds or feed additives that reduce bovine methane emissions. The placement of more than one GRAZE-Tag allowed the team to determine consistency between devices, or, in case of failure of one device, ensure robust data collection. Paulo de Meo Filho, a UC Davis postdoctoral scholar, and senior farm crew mechanics Mike Amato and Chris Beach, helped to install the GRAZE-Tag devices and set up the trial. This involved ensuring the GRAZE-Tag devices were secured and could not be dislodged by cows, did not interfere with the GreenFeed measurements, and were able to send data wirelessly. The latter allowed the Harvard team to track the device measurements remotely.

The initial results are promising, with both GRAZE-Tags fully functioning. As reported in Figure 5, the continuous data collected by GrazeTags indicated spikes in methane production at the same time intervals as those recorded by the GreenFeed system in which they were enclosed (note that the GRAZE-Tags MOS sensing element exhibits a lower resistance, i.e. higher conductance, in the presence of methane, corresponding to a dip in the plot).

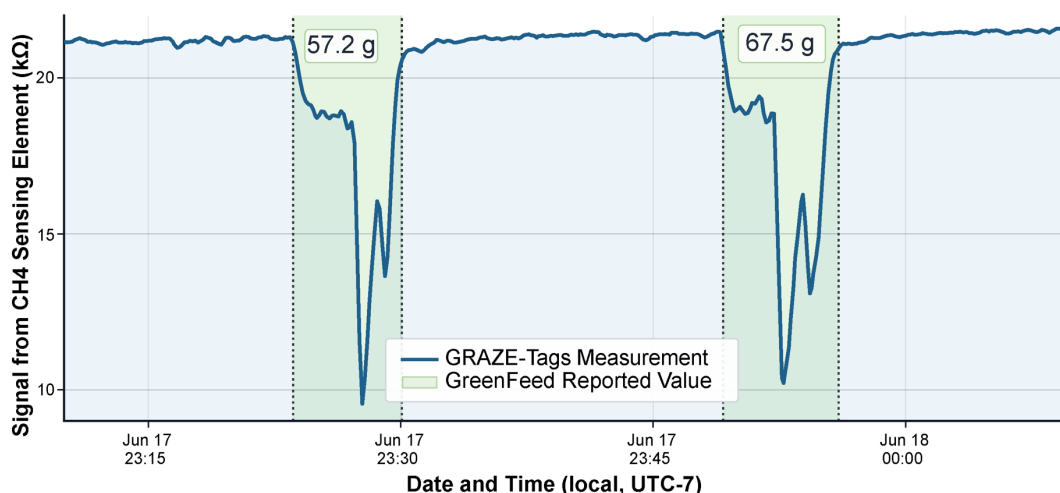


Figure 5. Data recorded at UC Davis field site.

Next Steps Required for Real-World Implementation

While the first integrated GRAZE-Tag prototype has been successfully developed and deployed in an initial field study, several engineering and validation steps remain before the technology can be implemented reliably at scale. The next phase of development will focus on improving hardware wearability and robustness to environmental conditions (such as rain); developing methods to interpret methane signals under realistic airflow conditions; validating performance on freely moving animals; and establishing the manufacturing and commercial infrastructure required for deployment.

Hardware Stress-Testing and Miniaturization

The next generation of GRAZE-Tags must be sufficiently compact, lightweight, rugged, and energy-efficient for long-term deployment on cattle. This requires systematic stress-testing under the environmental conditions encountered in real agricultural settings, including rain, humidity, condensation, dust, mud, temperature fluctuations, and mechanical impacts associated with animal movement.

A set of experiments have been planned to measure water ingress and retention, including characterization of how moisture interacts with the sensing chamber, protective membranes, and airflow pathways. The results will be used to optimize the enclosure and sensing architecture while preserving adequate gas exchange and sensor response. The team will also evaluate mechanical durability under repeated motion and impact and assess sensor performance following prolonged environmental exposure.

Further miniaturization is required to reduce the overall dimensions and weight of the device to levels appropriate for routine deployment on animals. This includes optimization of the electronics, sensor array, enclosure, and battery. Battery capacity and power consumption will be evaluated together to establish an operating lifetime appropriate for continuous field deployment, while minimizing the frequency of maintenance or recharging. The team is also considering installing GRAZE-Tags in barns or on posts throughout the field, as a less demanding alternative. Besides alleviating weight constraints, such installations would also reduce the incidence of cows jostling their own or another animal's ear tag.

Airflow Simulations for Measurement Interpretation

A central challenge for animal-mounted methane sensing is determining how a measured methane signal relates to emissions from the tagged animal in a dynamic environment. Methane released by one animal can be transported by local airflow and mixed with emissions from neighboring animals, creating complex and highly variable concentration patterns at the sensor.

To address this challenge, the team has begun developing methane dispersion modeling and computational airflow simulations to characterize how emissions move around individual animals and through groups of animals under different behavioral and environmental conditions, including animal orientation and clustering, and wind speed, respectively. These simulations will be coupled with empirical measurements to establish relationships between methane source location, airflow conditions, animal-related factors (such as proximity, age, weight, and health), and the signal observed by the GRAZE-Tag.

These data will inform the development of bioinspired signal-processing and machine-learning algorithms capable of identifying characteristic temporal and spatial patterns associated with an individual animal's emissions. Rather than relying solely on absolute methane concentration, the system will use the dynamics of the methane signal, environmental conditions, animal proximity, and airflow to distinguish emissions originating from the tagged animal from background methane and neighboring sources. Continued integration of simulation and experimental data will improve model robustness across different herd densities, wind conditions, animal orientations, and barn or pasture environments. Ultimately, this work will establish a computational framework for translating the raw sensor response into a meaningful estimate of methane emissions at the individual-animal level.

In-Field or In-Barn Validation with Freely Moving Cows

The next critical step is validation under realistic operating conditions. Following initial prototype testing, GRAZE-Tags will be evaluated on freely moving cows over extended periods, rather than under controlled or stationary conditions. These studies will assess sensor performance during grazing, feeding, resting, walking, and interactions with other animals.

Field experiments will examine the effects of animal behavior, orientation, proximity to neighboring animals, wind and airflow, temperature, humidity, and other environmental variables on methane measurements, complementary to the computational fluid dynamics described above. Measurements from GRAZE-Tags will be compared against established reference methods, where feasible, to quantify accuracy, repeatability, sensitivity, and the ability to resolve differences among individual animals.

Longitudinal measurements will be particularly important for demonstrating the value of GRAZE-Tags for methane-reduction research. Repeated measurements of the same animals over days or weeks could enable researchers to evaluate changes in methane emissions associated with diet, feed additives, animal health, genetics, or other mitigation strategies while reducing reliance on intermittent, labor-intensive measurement campaigns.

Towards Commercialization

In parallel with technical development, future work requires establishing the pathway from prototype to commercial product. This will include customer discovery and acquisition, with continued engagement with livestock producers, agricultural researchers, feed and animal-health companies, and organizations developing methane-reduction technologies. Early customers and research partners will help define the most valuable use cases, deployment models, data products, and service offerings.

Manufacturing and scale-up will be addressed through design-for-manufacturing, component sourcing, assembly, quality control, and development of a reproducible calibration process. The system will need to transition from individually assembled research prototypes to a standardized product that can be manufactured consistently and economically at larger volumes.

The commercialization strategy will also consider partnerships with established agricultural technology, livestock equipment, sensor, and data-platform companies. Such partnerships could accelerate distribution and integration into existing farm-management systems while reducing the infrastructure required for direct market entry.

Team Overview

Joanna Aizenberg (Principle Investigator [PI]), Venkatesh Murthy (Collaborating PI), Haritosh Patel (Team lead), Jack Alvarenga (Research Scientist), Anna Shneidman (Research Scientist), Owen Gibbs (Student Intern), Ethan Ye (Student Intern), Nicholas Lee (Student Intern), and Jeniton Augustinpillai (Student Intern).

Publications and News

The device design and its methane sensitivity and selectivity are presented in H. Patel, O. Gibbs, *et al.*, “Highly Selective Enteric Methane Monitoring Through Modular Sensor-Filter Assembly” (Ref. 5), as well as in two news articles, “Recognition and Analysis of Livestock Methane Using Zonal Ear Tags” (Ref. 7) and “Sniffing Out Cow Burps with an Electronic Nose” (Ref. 8). The initiation of field studies and deployment of the integrated device are discussed in “Field Study: Catching Cow Burps in Real Time” (Ref. 9). Figures 1–4 are adapted with permission from Ref. 5.

Acknowledgements

Harvard Initiative on Reducing Global Methane Emissions, a research cluster of the Salata Institute for Climate and Sustainability (Institutional support and funder); EQT Foundation (funder).

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30. 2026 *State of the Science Summit: Reducing Methane from Animal Agriculture*, June 16–18, 2026, Davis, CA. <https://caes.ucdavis.edu/news/events/FeedSummit>

About the Program

The Harvard Methane Initiative seeks meaningful and sustained progress in reducing global emissions of this very important greenhouse gas — through research and effective engagement with policymakers and key stakeholders. This Initiative is supported by the [Salata Institute for Climate and Sustainability](#) at Harvard University. The Harvard Methane Initiative and other Research Clusters supported by the Salata Institute comprise interdisciplinary teams of researchers from across Harvard's schools, whose varied expertise is required to address the complexity of the climate-related problems that they seek to solve. [Robert N. Stavins](#), A.J. Meyer Professor of Energy and Economic Development at Harvard Kennedy School, directs the Harvard Methane Initiative. The findings, views, and conclusions in this publication are those of the authors alone.