Title: Characterizing remotely sensed CH_4 through Biogenic and Anthropogenic flux source attribution: an ecosystem embedding approach.

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Focal Areas:
This work critically contributes to four core challenges associated with CH_4 monitoring and prediction: 1) The development of a flexible modeling framework for upscaling biogenic CH_4 flux predictions, 2) the improvement of existing inventory and emissions factor-based oil and gas (O&G) sector production models, 3) implementation of state of the art AI for the uncertainty aware and climate responsive scaling of both anthropogenic and biogenic CH_4 sources, and 4) their incorporation into a top-down detection and source attribution remote sensing framework.

Science & Technological Challenges/Barriers to Progress:
This research program is multifaceted, with separate bottom-up and top-down research challenges. At its core is the comparison of models with observations, using instrumented research sites as a source of measurements. Both biogeochemical and O&G-centric models have data fusion and forecasting challenges, made more complex when paired with the requirement that the models are scaled spatially and interrogated using remote sensing CH_4 platforms.

Biogenic focus: Significant effort has been made over the past decade to understand the mechanisms driving the generation and release of biogenic CH_4 from the land surface, especially in regions considered particularly sensitive to changes in climate like the Arctic. Site-specific validation studies have linked physical processes at the surface/subsurface level with local CH_4 flux measurements (e.g., chamber, flux tower), but remaining challenges include:

- Lack of closure between bottom-up and top-down CH_4 emissions measurements, insufficient measurements at the flux tower scale and in the shoulder seasons
- Complexity of the processes involved not lending themselves to scaling (due to computational cost or lack of ability to constrain models)
- An absence of a flexible framework to forward model across ecotypes or future ecotype transitions honoring uncertainty in future changes to Arctic permafrost

Narrative and Rationale:

Monitoring and predicting CH_4 emissions is an emerging challenge in the global biosphere-atmosphere flux community, the success of which will have significant impacts on our ability to constrain associated uncertainty and propose steps to mitigate, runaway climatic change. CH_4 is produced through biogenic (natural) and anthropogenic (human-caused) sources, and any attempts to characterize CH_4 remotely cannot inherently discriminate between the two sources. However, biogenic and anthropogenic mechanisms of CH_4 fluxes have very different abiotic drivers, with substantially variable responses to future climates and policy intervention efforts. For instance, biogenic CH_4 fluxes are ecotype-dependent and are controlled to varying degrees by surface temperature, moisture content, precipitation, leaf area index, lateral subsurface fluxes, organic matter composition, and soil physical properties, among other factors.

Anthropogenic sources of CH_4 flux are dominated by O&G infrastructure, with complex and poorly constrained understanding of how CH_4 emission from O&G varies as a function of atmospheric conditions, and hardware state variables (e.g., component type, time since installation, time since maintenance, etc). Current bottom up modeling approaches subsume these mechanistic relationships using emissions factors, and scaling spatially as a function of component composition, resulting in massive and poorly constrained uncertainties that are static with respect to climate. Our research here directly contributes to improved estimates and scaling of these anthropogenic fluxes, through direct observations made using eddy covariance.

CH_4 flux measurements collected across networks of eddy covariance flux tower sites, are a massively underleveraged source of direct ground-atmosphere fluxes of CH_4, that can be described as a function of biotic and anthropogenic state variables, in response to changes in abiotic drivers. These CH_4 flux response functions will play a critical role in scaling local measurements to landscape and regional scales.

Our integrated CH_4 monitoring and decision framework combines bottom up estimates of CH_4 emission from biogenic and anthropogenic sources with top down measurements from satellites and aerial platforms, using eddy covariance as a systems integration lens. Specifically, are using sequence transformers used for language modeling to create an ecosystem embedding model for the terrestrial fluxes of carbon, water and energy in a general way, with specific inclusion of terrestrial sources of CH_4. This ecosystem embedding approach combines learns the relationship between abiotic drivers and CH_4 flux, as a function of remotely retrievable state variables of the system. By describing these state variables specifically in terms of anthropogenic parameters (e.g, O&G infrastructure databases) and biogenic parameters (e.g, vegetation type, leaf area index), we can dramatically improve our ability to generate bottom-up emissions estimates, with direct biogenic or anthropogenic source attribution. Ultimately, this capability is designed to operate in concert with space-borne and aerial gridded estimates of CH_4 concentration, and will permit the decomposition of an arbitrary grid cell into components that are due to anthropogenic and biogenic contributions.

Focusing here on our biogenic modeling contributions, we plan to use physics constrained machine learning to inform the transformer architecture's characterization of biogenic CH_4 fluxes. Specifically, we are incorporating a bio-geophysical CH_4 production model into a component of ecosystem embedding transformer objective function.

Ultimately, our combined source specific bottom up modeling approach will augment top down monitoring efforts by allowing researchers to ask questions about consensus between measurements and models, and most critically, to understand how terrestrial CH_4 production is changing as a function natural and human caused activities – a distinction that is central to managing and mitigating climate change.