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Forum

Linking vegetation changes to Arctic methane efflux

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Arctic methane emissions are uncertain, impacting climate models. We propose combining vegetation data with machine learning to improve methane process predictions, offering more reliable insights. This approach can better inform global policies to reduce warming and address climate change effectively.

Methane efflux in the Arctic and the uncertainties in its estimation

The pan-Arctic region, defined as the area north of 60° latitude, is a critical zone for global soil carbon storage, accounting for approximately 50% of the world's soil carbon reserves [1]. However, recent studies indicate that this region is exceptionally sensitive to climate change, with a warming rate about four times that of the global average [2]. This rapid warming has led to extensive permafrost thawing, which releases methane (CH_4) stored in the permafrost and accelerates the microbial decomposition of soil organic carbon, resulting in increased CH_4 emissions [3,4]. Given that CH_4 has a global warming potential 25 to 30 times greater than that of carbon dioxide (CO), this will further intensify climate change [5]. Therefore, accurately quantifying CH_4 emissions from this area is crucial for developing global climate policies and effectively reducing CH_4 emissions [6–8].

Currently, annual net CH_4 emissions from the pan-Arctic region are estimated to range between 24 and 70 teragrams per year, exhibiting significant emission intensity and substantial interannual variability [5]. This uncertainty primarily arises from several key factors. First, the extreme environmental conditions in this region, coupled with a scarcity of observation stations, have resulted in very limited data collection on CH_4 efflux in the pan-Arctic area, making long-term and continuous monitoring a considerable challenge. Second, the pan-Arctic region encompasses diverse habitats, such as lakes, wetlands, forests, and tundra, each exhibiting complex differences and interactions in their roles as CH_4 sources and sinks [9,10]. Generally, well-drained terrestrial habitats, such as forests and tundra, are considered CH_4 sinks, while lakes and wetlands are viewed as CH_4 sources [6,8,11]. Additionally, the intensity of CH_4 sources and sinks is influenced by various environmental factors, including climate conditions, hydrology, vegetation cover, and soil characteristics [6]. The interplay of these ecological variables and their interactions collectively determines the variability of CH_4 efflux in the pan-Arctic region. However, there is currently a lack of a comprehensive model that can fully integrate these complex CH_4 source and sink processes while simultaneously considering multiple ecological variables and their interactions.

Vegetation types and CH_4 processes in the Arctic

In-depth research has shown that the sources and sinks of CH_4 are inherently interconnected, encompassing both the production and oxidation processes of CH_4 [5]. When CH_4 production exceeds oxidation in soil, the pan-Arctic region acts as a source; conversely, it behaves as a sink when oxidation predominates. Moreover, recent studies have found that CH_4 production and oxidation processes were significantly dependent on soil organic matter, which primarily originates from plant photosynthesis [6,8]. Therefore, vegetation dynamics – such as changes in vegetation types and plant productivity – play a crucial role in influencing CH_4 fluxes. Vegetation types are closely linked to habitat heterogeneity and each type exhibits distinct surface evapotranspiration and energy balance characteristics. Additionally, plants influence the formation of soil organic matter through root exudates and litter decomposition, both of which affect microbial activity related to CH_4 production and oxidation processes, thereby impacting CH_4 fluxes [6,8]. This indicates an urgent need for existing CH_4 process models to incorporate the contribution of plants to soil organic matter and account for variations in vegetation dynamics.

The rapid warming of the pan-Arctic region is gradually transforming tundra vegetation, shifting from low-growing plants to shrubs and trees. This change in vegetation will significantly alter both the quantity and quality of soil organic matter inputs and will also affect soil moisture and temperature conditions [12,13]. These changes, in turn, will influence the processes of CH_4 production and oxidation in the soil [5,8,11], ultimately altering the balance of CH_4 sources and sinks. Studies indicate that tree bark can oxidize substantial amounts of CH_4 [14], and as forests expand to higher latitudes [13], trees may become an important component of CH_4 sinks in the Arctic in the future (Figure 1). Therefore, accurately predicting future net CH_4 emissions requires a thorough analysis of vegetation dynamics and their impacts on soil sources and sinks under warming scenarios.

Meanwhile, some habitats with high CH_4 emissions deserve more attention. Particularly noteworthy is the unique soil type found in the dry regions of the pan-Arctic, known as 'Yedoma'. Composed of sediments and organic matter, Yedoma is primarily distributed across Siberia, the

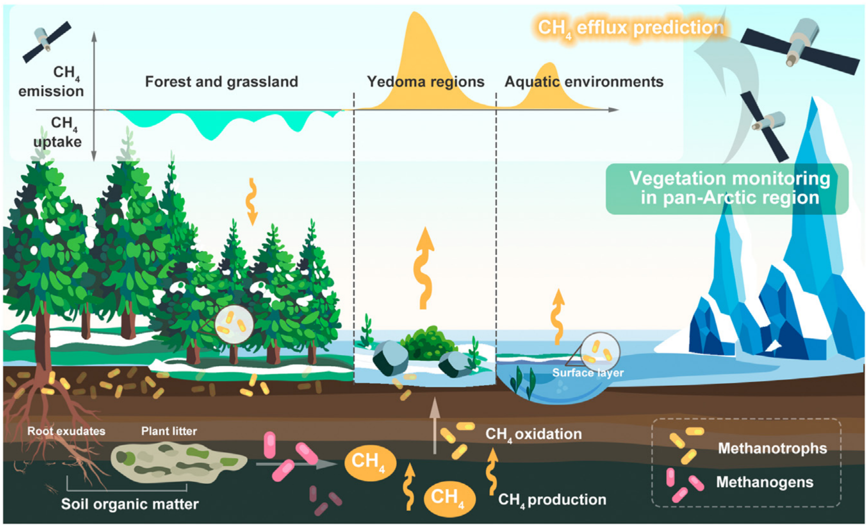

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Figure 1. Conceptual diagram of methane (CH_4) source–sink dynamics under different vegetation types in the pan-Arctic region. Various ecosystems exist in the Arctic, including forests, tundra, and lakes, yet the substrates for CH_4 production remain consistent: they are derived from soil organic matter, which originates from plant litter and root exudates. This organic matter is converted into CH_4 through the activity of methanogenic microorganisms. Before CH_4 is released into the atmosphere, several types of sources and sinks of CH_4 can be identified in the Arctic. The first type encompasses forest and grassland surface soils, which possess a significant capacity for CH_4 oxidation, often exceeding the amount of CH_4 produced, thereby functioning as a CH_4 sink by oxidizing atmospheric CH_4. The second type is found in Yedoma regions, where the CH_4 oxidation capacity of surface soils is less pronounced, allowing CH_4 to escape into the atmosphere and thereby acting as a CH_4 source. The third type relates to freshwater environments, such as lakes, where some of the CH_4 produced is oxidized by methanotroph at the water's surface, while the remaining portion is released into the atmosphere. These observations highlight that sources and sinks of CH_4 in the Arctic are closely linked to vegetation dynamics, which can oxidize atmospheric CH_4 as well. Additionally, satellite remote sensing provides essential data on surface vegetation dynamics, which can serve as inputs for machine learning models to dynamically estimate key subsurface CH_4 process parameters (e.g., maximum rates of methanogenesis and methanotrophy). This integration enhances the accuracy of regional CH_4 flux predictions. Therefore, it is crucial to incorporate vegetation dynamics into CH_4 process models for various Arctic ecosystems to improve the precision of future CH_4 emission forecasts under global change scenarios.

Russian Far East, Alaska, and the Yukon, and it paradoxically emits CH_4 year-round, with per-unit-area annual emissions exceeding those of pan-Arctic wetlands [15]. This phenomenon arises from its unique soil structure; the deep organic layer allows CH_4 production rates in the soil's depths to surpass oxidation rates at the surface, making it a significant CH_4 source [15]. Although Yedoma regions account for only 14% of the total area of Arctic permafrost, their CH_4 emissions comprise over 52% of the total net CH_4 emissions in the pan-Arctic region [11,15].

Thus, by monitoring vegetation dynamics, we can effectively delineate the distribution and extent of this unique soil type. This understanding will facilitate more comprehensive considerations of the region's distinctive characteristics – such as the deep organic layer and year-round emissions – in future predictions of CH_4 efflux in the pan-Arctic region. Such analyses will contribute to a more accurate assessment of CH_4 dynamics in this area and their implications for global climate change.

Linking vegetation changes to CH_4 efflux

Despite the existence of various CH_4 process models, current models overly simplify the coupling mechanisms between vegetation dynamics and the CH_4 source–sink balance, typically focusing only on CH_4 emissions from wetlands. There remains a lack of comprehensive consideration of the relationship between vegetation and CH_4 sources and sinks at a regional scale [5,8,11]. Therefore, future models should integrate vegetation dynamics into CH_4 process models, especially under scenarios of climate warming.

The construction of such complex process models relies on a thorough understanding of CH_4 efflux in the diverse habitats of the Arctic region, particularly within unique ecosystems such as Yedoma. Since CH_4 can be released not only from the soil but also through plants [5,15], traditional static chamber methods have limited observational coverage and fail to meet the demands of long-term, large-scale ecological monitoring. To effectively capture the dynamics of CH_4 in the pan-Arctic region, advanced monitoring technologies are essential. For instance, flux towers can provide continuous data on CH_4 efflux, while satellite observations can cover larger areas and deliver high-resolution spatial data (Table 1). The integration and advancement of these technologies will enhance the accuracy of CH_4 efflux measurements in the pan-Arctic region, thereby improving our understanding of CH_4 efflux characteristics across various ecosystems [7,9,15].

Firstly, satellite remote sensing enables the characterization of surface vegetation types, allowing researchers to determine the distribution and extent of specific soil types such as Yedoma. Additionally, continuous satellite observations provide valuable information on changes in vegetation productivity over time. When combined with continuously monitored CH_4 flux data, this integration facilitates a deeper understanding of the relationship between vegetation dynamics and CH_4 flux variations. Traditional process models often face limitations in effectively integrating the combined impacts of multidimensional

Table 1. Advantages and disadvantages of CH_4 efflux measurement technique

Method	Spatial scale	Frequency	Advantages	Disadvantages
Static chamber methods	~1 m^2	Several times a day or a week	(i) Low operational and observation costs; (ii) high sensitivity, capable of detecting low efflux; (iii) minimal field requirements with no need for power	(i) Labor-intensive; (ii) lack of spatial and temporal representativeness; (iii) slow measurement times can lead to excessive accumulation of gas flux concentrations, resulting in significant underestimation of gas flux; (iv) small coverage area, neglecting gas diffusion gradients in the chamber; (v) prone to deviations due to soil disturbances and insufficient gas mixing
Flux towers	~1 km^2	10–20 Hz	(i) Long-term dynamic observation of temporal patterns; (ii) large-area networked observations of spatial patterns; (iii) integrated observation of efflux, processes, and environmental transformations	(i) Gas leakage can occur on sloped terrain, leading to underestimation of efflux; (ii) insufficient sensitivity to accurately monitor low efflux; (iii) relatively complex data processing and expensive detectors; (iv) not applicable in situations of insufficient turbulence or calm conditions
Remote Sensing	~625 m^2	1 day	(i) Covering a wide geographical area, suitable for regional or global monitoring of atmospheric methane; (ii) capable of obtaining large amounts of data quickly, improving monitoring efficiency and reducing labor and resource consumption; (iii) integrating data from various remote sensing platforms and sensors (such as satellites, aircraft, and ground sensors) to enhance monitoring accuracy	(i) Remote sensing technology often has limited spatial resolution, making it challenging to capture small-scale CH_4 emission sources and sinks; (ii) atmospheric factors such as cloud cover and water vapor can affect signal transmission and ultimately impact measurement results; (iii) remote sensing data require complex post-processing and analysis, involving numerous algorithms and models, which increases the difficulty of data interpretation; (iv) while remote sensing can reduce long-term monitoring costs, initial investments (such as satellite launches and equipment procurement) can be quite high
CH_4 process models	~55 km (0.5°latitude)	1 h	(i) Models can simulate CH_4 efflux over larger spatial and temporal scales; (ii) providing predictions on the impacts of various management measures on CH_4 efflux, which assists policymakers in assessing and selecting effective reduction strategies	(i) The uncertainty of predictions from CH_4 process models is influenced by multiple factors, including model assumptions and parameters; (ii) models often require extensive input data, including information on weather, soil, vegetation, and human activities, making data collection and organization cumbersome; (iii) the effectiveness of the model relies on a thorough understanding of each emission source; limited knowledge of specific sources or processes may lead to unreliable model outputs

variables – including vegetation, soil, and climate – on the CH_4 processes. By contrast, machine learning models offer significant advantages in capturing the nonlinear relationships among these factors, as well as the effects of complex interactions and time-lag effects on CH_4 dynamics. Models trained on extensive datasets can be used to estimate key parameters in CH_4 process models for various vegetation environments, such as the maximum reaction rates (K_{max}) of methanogenesis and methanotrophy. These estimated parameters can then serve as dynamic inputs in CH_4 models, substantially enhancing the accuracy of future CH_4 flux predictions. By combining process models with machine learning, researchers can more precisely simulate variations in soil CH_4 sources or sinks across different vegetation types and predict the potential impacts of vegetation changes on soil CH_4 sources or sinks under future climate conditions. Additionally, these models can assess the effectiveness of various management strategies for reducing CH_4 emissions. It is widely recognized that land use practices and vegetation restoration strategies are fundamentally linked to vegetation dynamics. Incorporating these dynamics into methane process models can lead to more accurate simulations of changes in CH_4 sources and sinks [11–13]. Such models can thus aid decision-makers in identifying optimal approaches to maximize emission reductions while minimizing costs. With the accumulation of more high-quality data and advancements in technology, such integrated models are expected to play a critical role in addressing climate change in the future.

Summary and perspective

In conclusion, understanding vegetation dynamics and their interactions with CH_4 sources and sinks in the pan-Arctic region is of paramount importance due to their significant impact on global climate change. As ecosystems in this region undergo rapid warming, particularly in unique soil types like Yedoma, it is crucial to develop adaptable models that incorporate vegetation and leverage technological advancements such as machine learning for better anticipation of ecological responses to climate change. A holistic approach is therefore needed to study and manage CH_4 efflux in this vulnerable region.

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Declaration of interests

No interests are declared.

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