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Incorporation of NPP into forest CH_4 efflux models

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Forest soils are the largest atmospheric methane (CH_4) sinks in terrestrial ecosystems, but models simulating this uptake have considerable uncertainties. Soil organic matter derived from aboveground vegetation net primary productivity (NPP) significantly influences CH_4 uptake; therefore, we propose that the incorporation of NPP into global CH_4 uptake models will greatly improve model predictions.

Significance and uncertainty of forest methane sinks

CH_4 is the second most influential greenhouse gas, accounting for up to 25% of the global greenhouse effect. The single-molecule warming potential of CH_4 is 25–30 times that of carbon dioxide (CO_2) [1]. Consequently, small changes in the concentration of CH_4 in the atmosphere can have a disproportionally large impact on global warming [2]. Given that atmospheric CH_4 concentrations have increased by a factor of ~2.5 since the Industrial Revolution (722 parts per billion to 1866 parts per billion in 2019), there is considerable interest in tracking atmospheric CH_4 fluxes (e.g., FLUXNET-CH_4) [1]. There are many CH_4 sources (e.g., wetlands, biomass burning, landfills, etc. [3]), but only two sinks: (i) hydroxyl radicals in the troposphere reacting with CH_4 to produce carbon monoxide and CO_2, thereby absorbing ~90% of atmospheric CH_4; and (ii) upland terrestrial soils, which provide a niche for microorganisms that oxidize ~9–10% of atmospheric CH_4 [2]. Forests are the largest atmospheric CH_4 sinks among the terrestrial ecosystems, comprising 52% of the total terrestrial CH_4 sink [2,4].

Models predicting the extent of CH_4 oxidation in forested areas currently produce estimates that can differ substantially when compared with both each other and the observed data [5]. This inconsistency both between models and with observed data is potentially driven by the impact of localized or transitory extreme climate events (e.g., forest fires and drought) that cannot be reliably simulated [2,6], and by the spatial variability of various environmental factors that influence the relative oxidative capacity of a forest soil, confounding extrapolation of local studies to wider scales [4,6]. More importantly, our understanding of the microbial processes that underpin forest CH_4 sink capacity remains incomplete, and the impact of potentially important factors, such as the availability of organic matter to support methanogenesis, is not accounted for [7,8]. Consequently, models simulating the rates and extent of forest CH_4 sinks have limited accuracy, and this uncertainty has substantial flow-on effects for efforts to understand global atmospheric CH_4 balances [5,6].

Microbial processes driving the soil methane balance

The extent of the potential CH_4 sink of a given soil is determined by the balance between two processes: CH_4 production by soil methanogens, which use materials produced during plant decomposition under anaerobic conditions [8], and CH_4 oxidation under aerobic conditions by methanotrophs [7,8] (Figure 1). Substrates for methanogenesis are derived from the decomposition of plant-derived organic matter. Under anaerobic conditions, complex organic matter is converted to monosaccharides and then fermented into fatty acids, CO_2, and hydrogen gas (H_2); the fatty acids are then oxidized by syntrophs to produce acetic acid, CO_2, and H_2. The CO_2 and H_2 produced throughout this process are used by hydrogenotrophic methanogens to generate CH_4, whereas acetic acid is used as a substrate by acetoclastic methanogens [9]. Although anaerobic conditions are essential for this pathway to occur, the availability of suitable substrates is also a critical determinant. The oxidation of CH_4 is mediated by methanotrophs, which are Gram-negative bacteria within the *Verrucomicrobia, Proteobacteria*, and novel *NC10* phylum [7]. The key step in soil CH_4 oxidation is catalyzed by CH_4 monooxygenase, which converts CH_4 into methanol, which is then further broken down by the bacteria to produce energy [7,8]. Aerobic conditions facilitate gas exchange between the aboveground and soil atmospheres, allowing methanotrophs access to CH_4.

The balance between CH_4 production and oxidation is dictated by soil moisture because of its impact on gas diffusion through the soil; however, it is also affected by soil temperature and texture [7,8]. In general, forest soils are dry and well aerated, creating an aerobic environment that favors methanotrophs; nevertheless, *in situ* observations have demonstrated that transient increases in soil moisture content caused by heavy rain can create anaerobic conditions that cause the soil to become a source of CH_4 [6,10]. Other events, such as compaction, can also reduce aeration, creating anaerobic sites. Direct interactions may also be possible, because soil methanotrophs can use the CH_4 produced by methanogens before it leaves the soil atmosphere (Figure 1).

Factors predicting methane sink capacity in forest soils

To estimate the balance between aerobic and anaerobic conditions, models such as the Methanotrophy Model (MeMo v1.0), focus on climate, soil physical and chemical

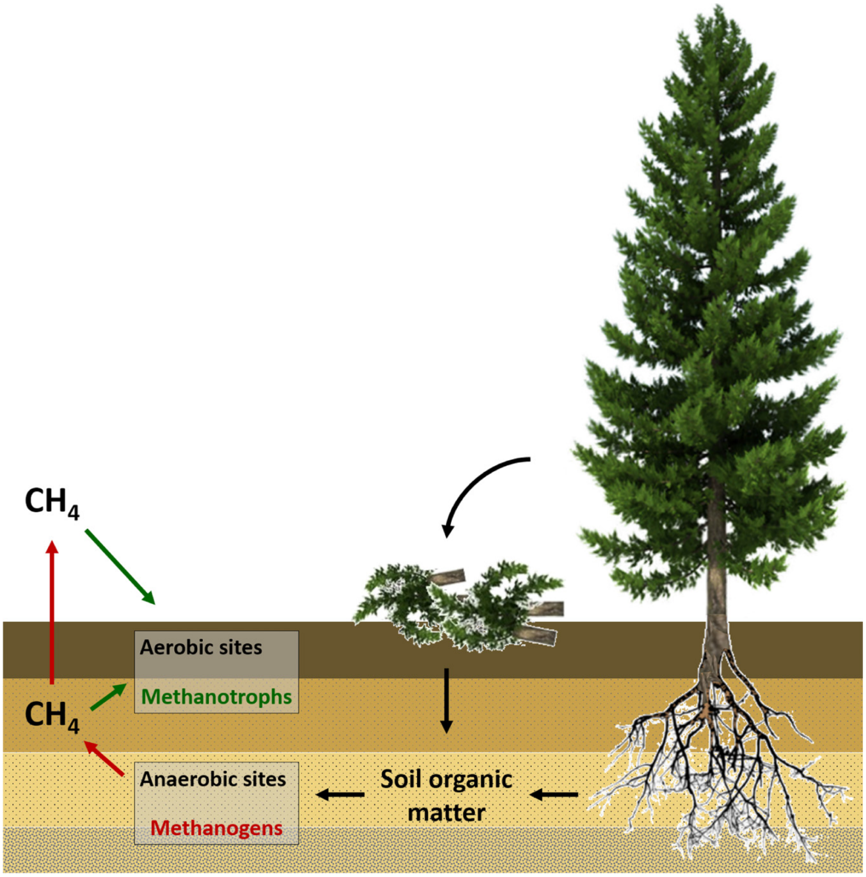

Figure 1. Schematic showing the pathway by which plant productivity can affect soil methane (CH_4) efflux via organic matter production in forest ecosystems. The CH_4 efflux across the soil–atmosphere interface is determined by production and oxidation processes in the anaerobic and aerobic soil sites, with soil organic matter providing the resources required for methanogenic activity.

properties, the diffusion of CH_4 in the soil, and the kinetics of CH_4 monooxygenase as the key drivers of CH_4 dynamics [5]. However, the impact of available organic matter on CH_4 production is not as thoroughly considered. Given the fundamental importance of soil organic matter as the raw material for methanogenic activity [9], we suggest that the NPP of the aboveground vegetation should also be integrated in models, such as MeMo, to improve estimates of forest CH_4 sink size [4–6].

This viewpoint is supported by consideration of the fate of carbon captured through plant growth. It has been established that 30–60% of photosynthetically fixed carbon is allocated to plant roots, more than half of which is eventually transferred to the soil in various forms [11]; the aboveground plant litter adds further to this pool. Under anaerobic conditions, a large proportion of this carbon is rapidly transformed and emitted as CH_4 [9,12]. In a recent wetland CH_4 emission model, the researchers explored NPP as a predictor and found that it explained variations in CH_4 flux better than did established climatic factors, improving the overall accuracy of model predictions [13]. On the basis of this outcome, it is reasonable to consider that, with greater NPP from a given soil, the pool of organic matter available to support methanogenesis is also proportionally greater. Therefore, when conditions are suitable for methanogens to become active, the rate of methanogenesis will be greater than for soils in which organic matter is less available. If the availability of organic matter becomes a rate-limiting step in methanogenesis, this could lead to variations in the CH_4 balance that can be predicted by NPP.

Concluding remarks and perspective

Direct measurement of NPP at the level of precision required to support improvements to broad-scale models of the forest soil CH_4 balance are unlikely, but the advent of remote-sensing capabilities provides a new opportunity to develop and apply useful proxies. For example, calculations of vegetation index values from remotely captured spectral characteristics have been used to support the normalized difference vegetation index (NDVI), which has become an established tool for modeling NPP effectively [14]. This offers the potential to generate NPP estimates rapidly and accurately at scalable levels of spatial resolution for forest ecosystems and, thus, explore the relationships among forest NPP, NDVI, and CH_4 balance at the ecosystem level (Figure 2). Examination of these relationships will confirm the potential value of integrating NPP values into forest CH_4 sink models and verify whether they can provide additional parameters to improve the accuracy and, therefore, the utility of these models.

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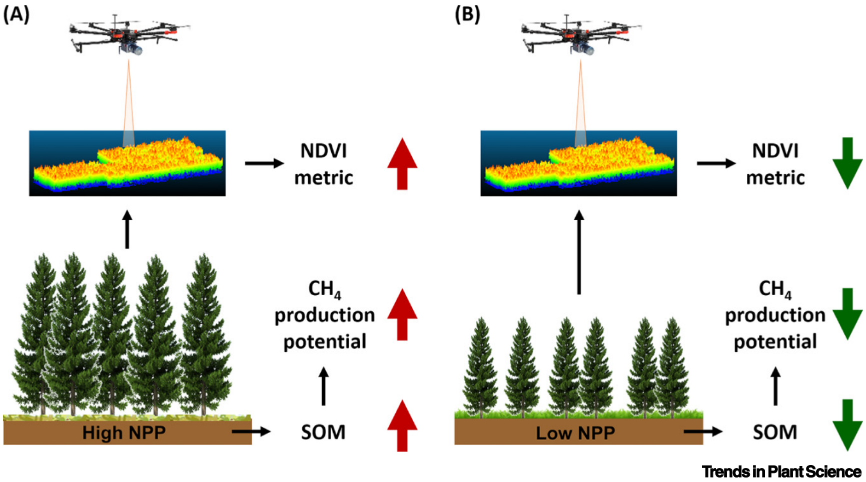

Figure 2. Schematic showing the relationships between forest net primary productivity (NPP), normalized difference vegetation index (NDVI), and methane (CH$_4$) production potential at the ecosystem scale. We can use NDVI based on remote sensing to estimate the NPP of forest ecosystems: when forest NPP is high, the soil CH$_4$ production potential is higher and vice versa. Abbreviation: SOM, soil organic matter.

Declaration of interests

No interests are declared.

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