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INTEGRATING PERSPECTIVES OF PERMAFROST THAW, CHANGE, AND ADAPTATION

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Cover Photo: Lake in ice-rich terrain in tundra uplands northwest of Inuvik, Northwest Territories. Ice wedge polygons are visible adjacent to the lake (Photo: Rachelle Landriau).

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2024

XII

WHITEHORSE YUKON

INTEGRATING PERSPECTIVES OF PERMAFROST THAW, CHANGE, AND ADAPTATION

The eastern Siberian tundra, a highly variable and uncertain greenhouse gas source

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Following decades of warming at almost four times the average global rate (Rantanen et al. 2022), the Arctic is changing rapidly. The vast amounts of carbon stored in Arctic soils (Hugelius et al. 2014) present a potentially strong positive feedback loop. Siberia, home to a significant proportion of the global tundra, remains understudied and long-term greenhouse gas (GHG) monitoring using eddy covariance (EC) is scarce (Chu et al. 2017). With more than 15 years of data between 2003 and 2021, we present one of the longer EC monitoring series in eastern Siberia. We show that the eastern Siberian tundra is currently a highly variable and uncertain GHG source. Net CO_2 uptake in the growing season is offset by methane emissions, roughly half of which are emitted outside of the carbon uptake season. The cumulative CO_2 uptake has increased over the last decades. However, cumulative methane emissions are strongly coupled to carbon uptake, with roughly 1.97 g CO_{2eq}-C emitted as methane per 1 g CO_2-C taken up during the carbon uptake period. As a result, any future increase in tundra productivity is offset by enhanced methane release, strengthening the GHG source of the Siberian tundra.

Arctic tundra in a changing world

Current warming is changing the Arctic at an unprecedented rate, leading to 'greening' of the tundra and growing season lengthening (Piao et al. 2007). This affects primary production more than soil respiration (Forkel et al. 2016), increasing the carbon sink. However, not considered is the coupling with methane emissions, long-term measurements of which are rare, especially in Siberia. In this study we combine EC measurements with machine learning to analyse CO_2 and methane dynamics in an extremely remote site in northeastern Siberia.

Summer CO_2 uptake is offset by 'shoulder season' methane emissions

The average CO_2 uptake during the carbon uptake period was 120 ± 16 g·C·m^{-2}. Methane emissions were on average 104 ± 44 CO_{2eq} g·C·m^{-2}, rarely completely offsetting the CO_2 uptake, Figure 1. However, outside of the carbon uptake period both CO_2 and methane emissions were mostly positive. Previous research has established the importance of emissions within the so-called 'zero-curtain', the period in which soils remain unfrozen despite freezing surface temperatures, leading to emissions that offset the GHG balance (Oechel et al. 2014; Zona et al. 2016).

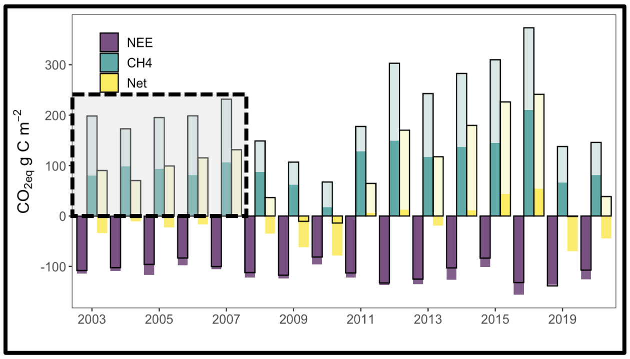

Figure 1. Cumulative greenhouse gas emissions of CO_2 (NEE, purple), CH_4 (green) and combined (Net, yellow) in CO_{2eq} g·C·m^{-2}. Methane and net fluxes in the grey box are modelled estimates. Dark shades show growing season and light tints 'shoulder season' cumulative fluxes.

However, keeping a constant power supply – a prerequisite to EC monitoring in winter – can be near impossible in remote areas with extreme winter conditions. This, together with other logistic considerations, led to the absence of winter flux measurements within this study. Instead, we have opted for careful and conservative estimation of 'shoulder season' fluxes, consisting of gap-filled or modelled data up to 45 days before snowmelt and 30 days after the first average sub-zero temperature day. These limits avoid gap-filling outside of environments in which measurements are available, while providing estimates for years without 'shoulder season' data. Taking these fluxes and estimates into account show highly variable net GHG emissions of 97 $\pm$ 79 CO_{2eq} $g{\cdot}C{\cdot}m^{-2}$ annually, reiterating the importance of non-growing season activity on annual fluxes (Zona et al. 2016), Figure 1.

The lack of winter measurements makes true annual GHG emissions uncertain, though likely to be higher. Years with data outside of the growing season (6 out of 11) unequivocally showed positive cumulative emission of methane. We found positive methane fluxes even outside of the 'zero curtain' and no indication of diminished strength with lower surface temperatures. Similarly, in Arctic tundra sites in Alaska methane is emitted year-round (Zona et al. 2016), and in other Russian Arctic tundra sites positive CO_2 measurements have been recorded throughout winter.

Trends GHG exchange

Since the 1990s, strong gradual surface temperature increases have advanced the start of the snow free period, resulting in an earlier onset of net carbon uptake, Figure 2A-B. Following an initial lag-phase of roughly 40 days after snowmelt, a strong positive trend can be seen in CO_2 uptake and incoming solar radiation (not shown). On average the start of the growing season occurs after the incoming solar radiation maximum, and thus an earlier carbon uptake period translates in a longer growing season. During the carbon uptake period CO_2 uptake is limited by sunlight and the end of the period coincides with diminishing sunlight, not temperature (not shown). As such, potential lengthening of positive temperatures at the end of the season will almost certainly not lead to increased annual CO_2 uptake.

Over the last decades a positive trend can be seen in the cumulative growing season carbon uptake, Figure 2C. However, cumulative growing season methane emissions are significantly related to cumulative growing season carbon uptake, Figure 2D. For every additional gram of carbon taken up as CO_2 during the carbon uptake period, almost 2 grams of CO_{2eq}-CH_4 is released. This strong coupling shows that greater carbon uptake in the growing season results in increased net GHG emissions.

Future Arctic tundra GHG exchange

Temperature increase is projected to continue, resulting in the earlier onset of snowmelt and a lengthening of the carbon uptake period. Our results show that while this lengthening of the growing season can lead to additional CO_2 uptake, the net GHG flux will increase through methane emission coupling. Local data shows that winter temperatures rise faster than annual averages (not shown), potentially creating favourable conditions for winter GHG release. Since no trend with temperature and 'shoulder season' emissions can be seen, it is not certain whether this will increase winter emissions. However, with minimum temperatures lower than -40 °C it does not seem unreasonable that emissions are indeed lower at these extreme conditions than what we measured in the 'shoulder season'. Other studies suggest that the lengthening of the 'zero-curtain' may increase emissions (Zona et al. 2016), a shortening of the 'extreme cold curtain' might do the same.

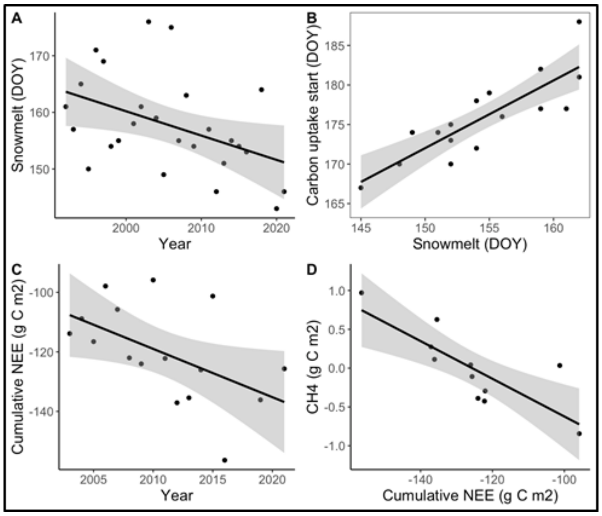

Figure 2. A) snowmelt (day of year), B) start of carbon uptake vs snowmelt (day of year), C) cumulative CO2 uptake (NEE) $g{\cdot}C{\cdot}m^{-2}$, D) methane emissions (g C-CO_{2eq} m^{-2}) vs CO_2 flux (NEE).

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