The nitrogen stock of the ice-rich yedoma domain

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Abstract

Recent studies on permafrost organic matter (OM) suggest that a portion of previously frozen carbon will enter the active carbon cycle as high latitudes warm. Less is known about the fate of other OM components, including nutrients such as nitrogen (N). The abundance and availability of N following permafrost thaw will regulate the ability of plants to offset carbon losses. Additionally, lateral N losses could alter aquatic food webs. There is growing evidence that some N is lost vertically as N_2O, a greenhouse gas 300 times stronger than CO_2 over 100 years. Despite broad recognition of its role regulating both carbon and non-carbon aspects of the permafrost climate feedback, estimates of permafrost N remain uncertain. To address this knowledge gap, we quantified N content for different stratigraphic units, including yedoma, Holocene cover deposits, refrozen thermokarst deposits, taberal sediments, and active layer soils. The resulting N estimates from this one permafrost region were similar in magnitude to previous estimates for the entire permafrost zone. We conclude that the permafrost N pool is much larger than currently appreciated and a substantial pool of permafrost N could be mobilized after thaw, with continental-scale consequences for biogeochemical budgets and global-scale consequences.

Keywords: Yedoma; permafrost; degradation; nitrogen pool; nitrogen cycle; climate feedback;

Introduction

Organic matter (OM) stored in permafrost constitutes a huge reservoir of carbon (C) and is an important subject in climate research. Multiple studies suggest the high potential for C release and incorporation into the active C cycle following permafrost thaw (Strauss et al., 2017). However, net ecosystem C balance in the permafrost zone depends on more than 'just' C. Many terrestrial ecosystems at high latitudes are nitrogen (N) limited, meaning that the availability of N during and after permafrost degradation could directly control the ability of plants to remove CO_2 from the atmosphere. Because many forms of N are hydrologically mobile, N liberated from permafrost could also be laterally transported to aquatic and estuarine ecosystems (Beermann et al., 2017), where it could alter food webs and productivity. Though some of these N effects could offset a portion of projected soil carbon losses, there are also risks of enhanced greenhouse gas emissions associated with great N availability. When permafrost thaws, changes in the soil profile including increased water content can create heterogeneous soil redox conditions favorable for microbial nitrification and denitrification, producing the potent greenhouse gas nitrous oxide (N_2O), as a side product of nitrification and denitrification (Elberling et al., 2010; Palmer et al., 2011; Repo et al., 2009). Despite its central importance to predicting local and global ecosystem feedbacks to climate change, relatively little is known about N stocks and composition in the permafrost zone (Keuper et al., 2012; Mack et al., 2004; Rustad et al., 2001). To address this knowledge gap, we quantified the abundance and distribution of N in the active layer and permafrost of the yedoma region of Siberia and Alaska.

Materials and methods

The yedoma domain comprises decameter thick ice-rich silts intersected by syngenetic ice wedges, which formed in late Pleistocene tundra-steppe environments, as well as other deposits resulting from permafrost degradation during the Holocene. Together, the deposits in this region constitute 7% of the total permafrost area but contain over 25% of total permafrost organic matter. Based on the most comprehensive data set of permafrost N (>1500 samples of total N content), our study aims to estimate the present pools of N in the different stratigraphic units of the yedoma domain. These are (1) late Pleistocene yedoma deposits; (2) in-situ thawed and diagenetically altered yedoma deposits (taberite); (3) Holocene thermokarst deposits; (4) Holocene cover deposits on top of yedoma and (5) the modern active layer of soils. We implemented statistical bootstrapping techniques, which resample observed values to estimate N stocks. The total mean pool size estimate was derived for each of the 10,000 bootstrapping runs, resulting in an overall estimate of mean and variance derived from 10,000 individual observation-based bootstrapping means. The conceptual formula for our nitrogen stock calculation:

$$m_{\text{TN, tot}} = \sum_{i=1}^{n} m_{\text{TN}, i} = \sum_{i=1}^{n} d_{\text{i}} \left(1 - f_{\text{wedge}, i}\right) \rho_{\text{b},i}\, c_{\text{TN},i}\; A_i$$

$m_{\text{TN, tot}}$: pool of total N in the included units,
$i = 1\ldots$n: index numbers of the single unit considered for the N budgeting,
d_{i}: deposit thickness of unit i,
$f_{\text{wedge}, i}$: volume fraction of ice wedges in unit i,
$\rho_{\text{b},i}$: bulk density of deposits of unit i;
$c_{\text{TN},i}$: content of total nitrogen in deposits of unit i;
A_i: area of unit i

Results and discussion

The deposits of the yedoma domain store a much larger pool of N than previously recognized. Our estimates of permafrost N for the yedoma domain are similar in magnitude to previous estimates of N for the entire permafrost region, which were quantified with 40–60 Pg N (Harden et al., 2012; Weintraub and Schimel, 2003). This suggests that the permafrost N pool may be twice as large as currently estimated. A large portion of this nitrogen is expected to become mobilized after thaw, potentially affecting the recovery trajectory of local ecosystems and the overall magnitude and timing of the permafrost climate feedback. Possible effects of this N release include mitigation of the current nitrogen limitation of Arctic tundra ecosystems, substantial N delivery to freshwater and marine ecosystems, and additional greenhouse gas contributions from permafrost regions in the form of N_2O. In all cases, there is strong evidence that the permafrost-climate feedback will be affected by the amount and availability of this previously unquantified N.

Conclusion

The yedoma domain constitutes a large OM inventory storing several hundred Gt C, but are also known to be nutrient-rich environment due to rapid burial and freezing of plant remains. We found that the deposits of the Yedoma domain store a globally significant pool of N that may partially become activated following permafrost thaw. Future investigation of permafrost deposits should include the analysis of different nitrogen pools to clarify the potential climate feedback mechanisms of bioavailable nitrogen.

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