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The Forgotten Nutrient—The Role of Nitrogen in Permafrost Soils of Northern China

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1.   Introduction: permafrost carbon and nitrogen feedback to climate change

Permafrost refers to any ground, including soils, sediments and rocks, with a temperature at or below the freezing point of water (0°C) for two or more consecutive years (Biskaborn et al., 2019). Permafrost soils of the Northern Hemisphere store vast amounts of both organic carbon (C) and nitrogen (N) (Tarnocai et al., 2009; Harden et al., 2012; Mueller et al., 2015). Only in the uppermost 3 m, soils in the northern permafrost zone contain 1035 ± 150 Pg C, corresponding to around one third of the C stocks in the uppermost 3 m of soils worldwide (Hugelius et al., 2013, 2014; Schuur et al., 2015). Due to global warming and permafrost degradation, large amounts of C previously stored in frozen organic matter have been released to the atmosphere in the forms of carbon dioxide (CO_2) and methane (CH_4) (Zimov et al., 2006; Schuur et al., 2009). The total C release resulting from permafrost degradation might be as high as 92 ± 17 Pg C from now to 2100, with an estimated contribution by CO_2 and CH_4 of 97.7% and 2.3%, respectively (Schuur et al., 2015). The feedbacks between climate change and permafrost C release are accelerated by the extraordinarily fast warming in arctic regions, occurring at a more than doubled pace compared to the global average (IPCC, 2014). Permafrost degradation with associated C release is thus assumed to be a key driver of global temperature increase in the 21st century (Schuur et al., 2013).

In contrast to the intensive levels of research having been carried out to address the permafrost C climate feedback (e.g., the Permafrost Carbon Network; http://www.permafrostcarbon.org/), research on permafrost soil N biogeochemistry and the associated release of the potent greenhouse gas (GHG) nitrous oxide (N_2O) under a changing climate is strongly lagging behind. Thus far, little is known about the fate of formerly protected organic N during thawing of permafrost soils that

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store as much as 67 Pg N (Harden et al., 2012). Until recently, the soil N cycle in cold and pristine ecosystems was thought to be largely confined to organic N cycling due to the scarcity of N inputs, slow decomposition at low temperatures and high competition for bioavailable N between biota (van Cleve and Alexander, 1981; Schimel and Bennett, 2004). Thus, it has been postulated for a long time that N_2O emissions from permafrost soils are low as a result of limited amounts of inorganic N (Rodionow et al., 2006; Chapin et al., 2011). However, over the last decade, a growing number of studies have reported very high N_2O emissions from permafrost soils, which are in a comparable range as observed for tropical forests or agricultural ecosystems (e.g., Repo et al., 2009; Elberling et al., 2010; Marushchak et al., 2011; Palmer et al., 2012; Abbott and Jones, 2015; Voigt et al., 2017a; Liu et al., 2018; Wilkerson et al., 2019). In addition, the few available studies on experimental warming of permafrost soils hint at a stimulation of N_2O emissions by temperature (Chen et al., 2017; Voigt et al., 2017a, b; Cui et al., 2018). The potential significance of inorganic N cycling and N_2O release in permafrost soils can be illustrated by a simple calculation. If 10% of the organic N stored in permafrost soils (i.e., 6.7 Pg N) is released between the present day and the year 2100, as it has been estimated for C release (Schuur et al., 2015), and only 1% is emitted as N_2O (67 Tg N_2O-N), just like the IPCC's default N_2O emission factor for N mineralized from mineral soils (IPCC, 2006), this would be equivalent to 10 times the global annual rate of N_2O emissions from soils under natural vegetation [6.6 Tg N_2O-N yr^{-1} (Ciais et al., 2013)]. Consequently, there is an urgent need to better understand N biogeochemistry and associated gaseous N emissions in permafrost soils under the auspices of a warming climate.

2.   The Sino-German NIFROCLIM project

The NIFROCLIM project (Soil nitrogen turnover and nitrous oxide emissions in permafrost landscapes of northern China in a changing climate; www.nifroclim.de) tackles the lack of research concerning soil N turnover and N_2O emissions in permafrost landscapes. NIFROCLIM is a Sino-German project funded by the German Science Foundation (DFG) and the National Science Foundation of China (NSFC). The central goal of NIFROCLIM is to gain a process-based and functional understanding of (1) gross N turnover as well as associated N_2O formation and consumption (i.e., reduction to dinitrogen gas) in the vertical soil profile; (2) differences in soil gross N turnover and N_2O emissions across ecosystem transects in typical permafrost landscapes; and (3) the effects of warming and permafrost degradation on (1) and (2). Thus, NIFROCLIM aims at a strong contribution towards closing knowledge gaps on permafrost N biogeochemistry.

Therefore, NIFROCLIM combines (1) research on the quality and quantity of N in soil organic matter; (2) molecular measurements of the abundance and activity of soil microbes involved in the N cycle; (3) isotope-based quantitative biogeochemical process studies; and (4) measurements of N gas (NO, N_2O, N_2) production in soil and the exchange at the soil–atmosphere interface in an interdisciplinary approach.

NIFROCLIM was launched with a kickoff meeting and a first campaign in the target region of Mohe County, Northeast China, in July 2019. The sampling concept in the research area encompasses (1) high-resolution soil and gas sampling in vertical soil profiles from the soil surface to the active layer and into the upper layers of the permafrost; (2) soil and vegetation sampling as well as GHG flux measurements across topographic landscape transects covering different upland forests and lowland bogs; and (3) investigations of climate change effects by using open top chambers (OTCs) to simulate warming.

3.   Study area and key scientific infrastructures

Besides high-altitude and alpine permafrost on the Tibetan Plateau and in Northwest China (1.35×10^6 km²), there is a subarctic discontinuous permafrost region with an area of 0.24×10^6 km² at the very northern end of China (Cheng and Jin, 2013). The latter permafrost region in Northeast China is part of the Eurasian permafrost complex—the world's largest permafrost area (Fig. 1a). Being located at the southern edge of the Eurasian permafrost complex, this region is sensitive to ongoing climate change, making it an ideal study area for research targeted at constraining predictions of GHG release from permafrost soils under global warming. The study sites of the NIFROCLIM project are located in the Fukuqi River catchment on the northern slope of the Great Hing'an Mountains (~105 km²; Fig. 1b). The annual mean temperature and precipitation in this catchment are −4.2°C and 425 mm, respectively [1959−2013 (Guo et al., 2018)]. Bogs are distributed along the river valley and surrounded by birch (*Betula platyphylla* Suk.) or alder (*Alnus sibirica* Fisch. ex Turcz) groves. Dominant plant species in the ombrotrophic bogs include dwarf shrubs [*B. fruticosa* Pall., *Ledum palustre* L., *Vaccinium uliginosum* Linn., and *Rhododendron lapponicum* (L.) Wahl.), sedges (*Eriophorum vaginatum* L., and *Carex globularis* L.] and mosses (*Sphagnum* spp.). Most of the upland coniferous forests were destroyed during a forest fire in 1987 and hence replaced in the course of natural succession by secondary broad-leaved forests (*B. platyphylla* Suk.; 64% of the upland forest area) and via planting of coniferous forests [*Larix gmelinii* (Rupr.) Kuzen. and *Pinus sylvestris* Linn. var. *mongolica* Litv.]. The flat (bogs and lowland groves) and hilly (upland forests) lands account for 29% and 71% of the catchment area, respectively. The growing season typically starts in mid-April to early May and ends in late September. The soils are classified as Cryic Histosols with a peat layer of 30 to 50 cm in bogs, and as Gelic Umbrisols with a thin soil layer of 10 to 30 cm in upland forests (IUSS Working Group WRB, 2015). Maximum active layer depths appear at the end of August to the beginning of
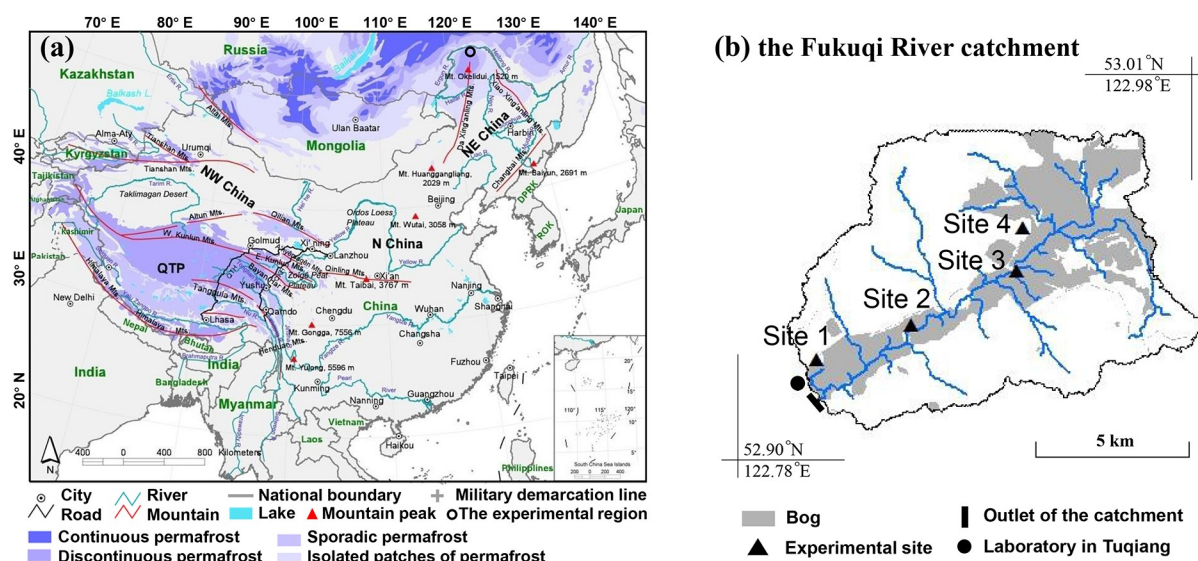
Fig. 1. (a) Map of permafrost-affected areas in China (Cheng and Jin, 2013) showing the Eurasian permafrost in the northeast. (b) Geographical location of the experimental region.

September, and range from 50 to 100 cm in bogs and from 80 to 150 cm in upland forests.

Scientific infrastructure has been established at four sites in the upper, middle and lower reaches of Fukuqi River to investigate permafrost N biogeochemistry and soil–atmosphere gas exchange (Fig. 1b). At the most extensively equipped Site 2, the effects of long-term warming are studied in situ, using OTC warming platforms in different habitats (*B. fruticosa* and *L. palustre* communities of ombrotrophic bogs) against controls outside the OTCs. The OTCs increase the soil temperature (5 cm depth) and active layer depth on average by 2°C and 7 cm, respectively, during the growing seasons (Cui et al., 2018). At the same site, fully automated static chamber measuring systems with 12 chambers and an eddy covariance system allow for online quantification of CO_2, CH_4 and N_2O fluxes at hourly temporal resolution [Figs. 2a and b (Liu and Zheng, 2019)] from March to November. To further address landscape-scale flux variations, manual static and dynamic chamber measuring systems are used to detect the soil–atmosphere CO_2, CH_4, N_2O and NO_x fluxes at daily to sub-weekly temporal resolution at all sites in the catchment (overall > 100 flux chambers) (Figs. 2c and d) (Valente et al., 1995; Zhang et al., 2014).

Air samples from manual chamber measurements are analyzed by gas chromatography and a chemoluminescence NO-NO_2-NO_x analyzer in the field laboratories at Tuqiang—a town at the outlet of the catchment (Fig. 1b). The laboratories at Tuqiang also offer basic equipment for extraction and stabilization of DNA from soils, which is needed to analyze the soil microbiome and to track soil microbial N transformations via molecular microbiological approaches. Moreover, at Tuqiang, soil samples including intact frozen soil cores are processed and labeled for stable isotope studies (Fig. 3) in order to quantify soil gross N turnover rates [protein depolymerization, ammonification, nitrification, microbial immobilization, biological N fixation (BNF)].

Topography, climate, land use, soil (e.g., soil texture, bulk density, pH, total N and organic C contents), vegetation and management information are collected at the site or catchment scale to run the process-oriented hydrobiogeochemical model CNMM-DNDC [Fig. 4 (Zhang et al., 2018)]. Soil variables (e.g., temperature, moisture, dissolved organic C and inorganic N concentrations), soil–atmosphere gas fluxes, stream discharge and related dissolved C and N losses during runoff processes are measured to validate the model at the grid (150 m × 150 m) or catchment scale. The hydrobiogeochemical model CNMM-DNDC will finally be used to upscale gaseous and dissolved C and N losses at the catchment scale, as well as to conduct scenario analyses of climate change to evaluate the influences of permafrost thawing on vegetation succession, permafrost N cycling and N_2O emissions under the Representative Concentration Pathways.

4. Supportive studies by other co-operation partners

The presence of *Alnus sibirica* at the study sites urges the question of the role of BNF by symbiosis between the roots of this tree species and the N_2-fixing bacteria *Frankia* spp. This is of particular significance for N cycling in permafrost soils, because *Alnus* is relatively deep-rooting and BNF requires large amounts of energy (Anand et al., 2012), which may enhance temperatures in the rhizosphere. These features might constitute an important N input into the ecosystem and could contribute significantly to below-ground CO_2 fixation by the phosphoenolpyruvate carboxylase of alder roots (Fotelli et al., 2011). However, the relevance of BNF by the *Alnus–Frankia* complex for N cycling in permafrost soils, its temperature
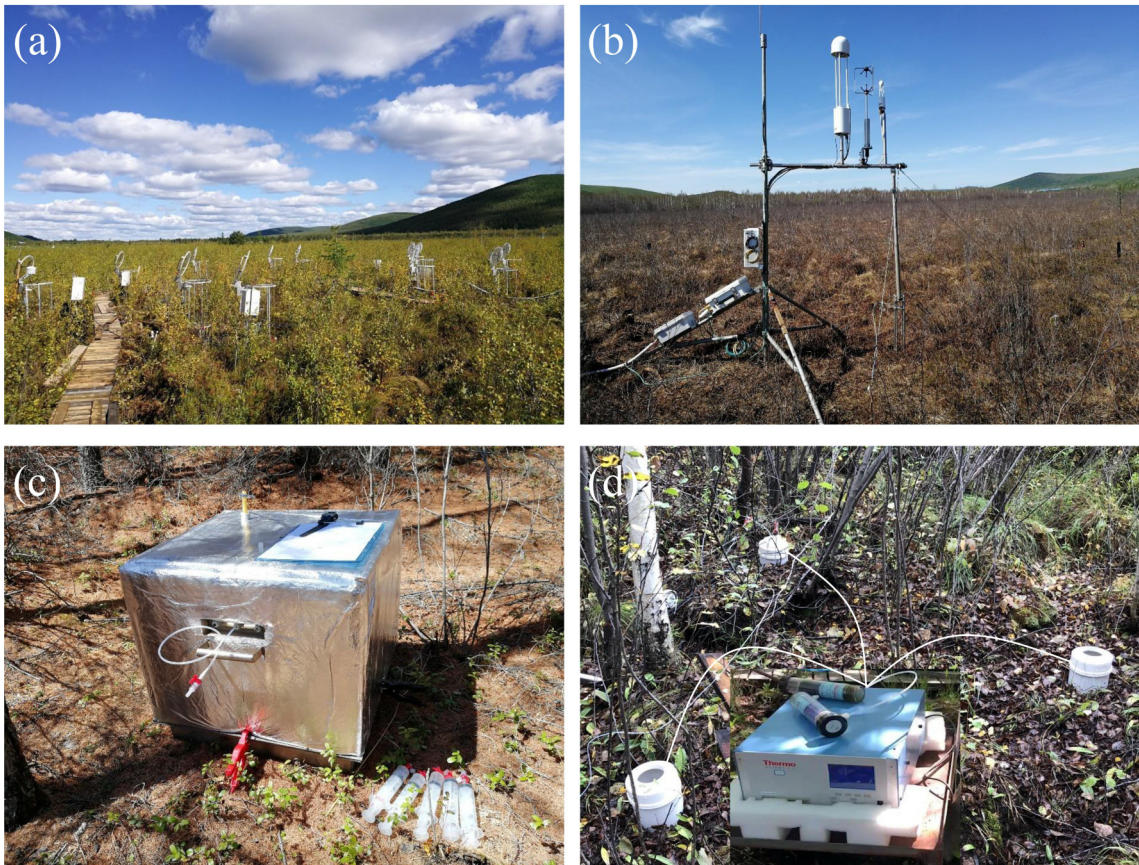
Fig. 2. The measuring systems used to quantify biosphere–atmosphere gas fluxes. (a) Automated static translucent chambers for measuring CO_2, CH_4 and N_2O fluxes. (b) Eddy covariance system for measuring CH_4, CO_2 and water vapor exchanges. (c) Manual static opaque chambers for measuring soil respiration, CH_4 and N_2O fluxes. (d) Manual dynamic opaque chambers for measuring NO_x fluxes.

Fig. 3. Permafrost soil sampling. (a) Frozen ground at ~20 cm depth in July 2019 at a wetland site with soil temperature measurement showing 4.7°C at 6.5 cm depth and 2.0°C at 14 cm depth. (b) Intact frozen soil core. (c) Labeling of frozen soil for stable isotope studies.

dependency, as well as the phosphoenolpyruvate carboxylase activity of *Alnus* roots, are largely unknown and require both basic research in the laboratory and extensive field studies. It is envisaged that such investigations will be performed in a cooperation with the Center of Molecular Ecophysiology (CMEP) of Southwest University, Chongqing, China.
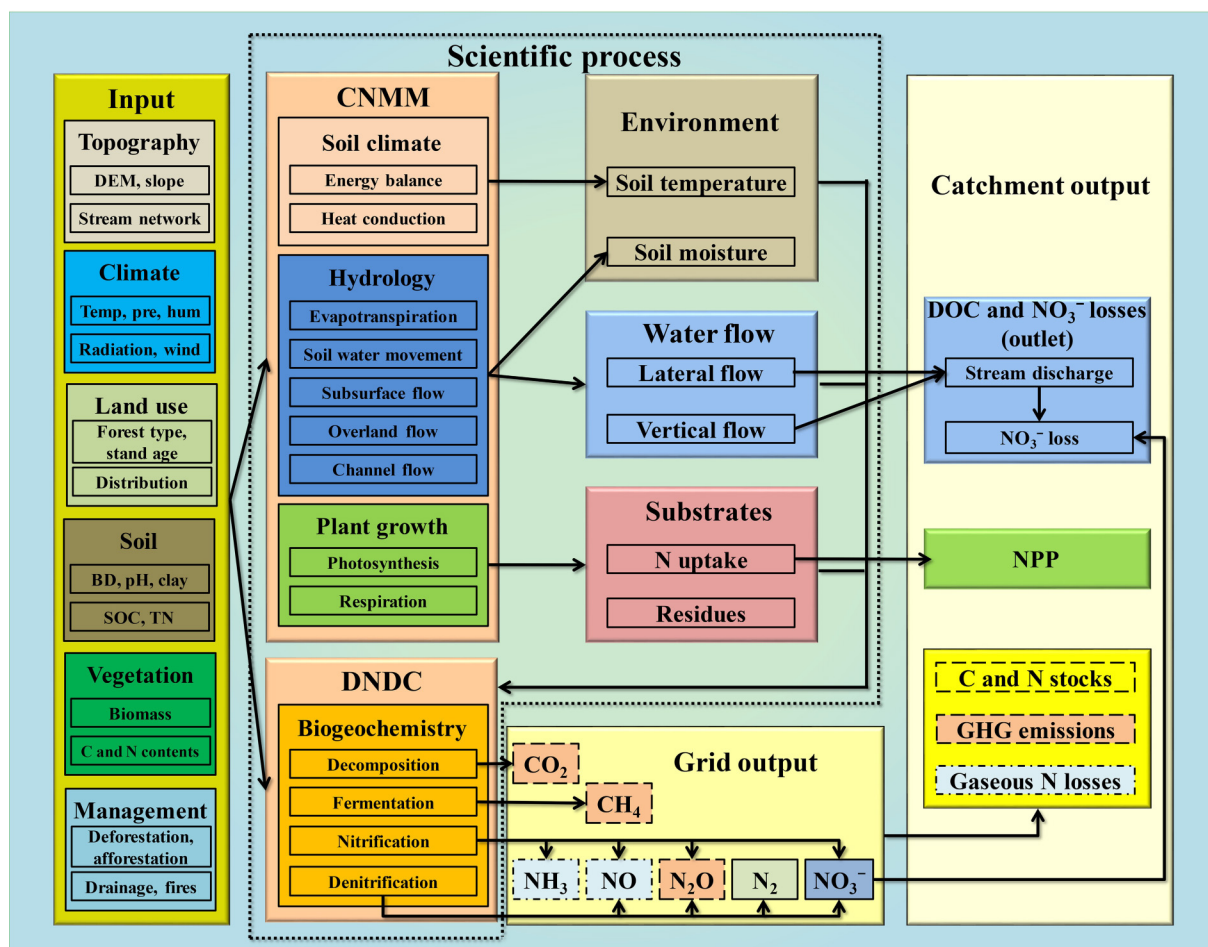
Fig. 4. The CNMM-DNDC model structure [Reprinted from Zhang et al. (2018)].

5.   Outlook

In the near future, the NIFROCLIM consortium will focus on quantification of N inputs to permafrost ecosystems, i.e., (1) BNF by alder trees as well as *Sphagnum* mosses in ombrotrophic bogs, and (2) dry and wet atmospheric deposition of N at a catchment scale (Pan et al., 2012). Further foci will be (3) on disentangling the importance of soil organic versus mineral N as plant N sources, (4) the contribution of tree-mediated to ecosystem-level GHG emissions from the lowland birch and alder groves, and (5) to better understand the links between soil organic matter composition and the N cycle on permafrost-affected soils. In addition, laboratory studies are planned (6) to quantify soil N_2 emissions and identify controls of N_2:N_2O emission ratios.

By combining the expertise of the researchers involved, the project is targeted at providing a comprehensive picture of the N cycle and N balances for the main ecosystems present in the permafrost region of Northeast China. Through the interdisciplinary cooperation between atmospheric physicists, soil biogeochemists, microbiologists, plant physiologists and soil scientists, NIFROCLIM aims at a holistic understanding of the permafrost soil N cycle and associated N_2O emissions at a catchment scale under the auspices of climate change, and thus at providing a significant contribution towards a better prediction of potential N to climate feedbacks of permafrost ecosystems. In this context, NIFROCLIM is also seen as a platform for international cooperation on permafrost research in China and beyond.

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