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Final report

NUTRIENT LIFT UPON PERMAFROST THAW: SOURCES AND CONTROLLING PROCESSES | LIFTHAW

RT/23/LIFTHAW

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ABSTRACT

Context

In the Arctic, permafrost thaw in response to warming air temperatures has a profound impact on tundra ecosystems: hydrological flow paths are altered as well as vegetation cover, and previously frozen organic carbon is exposed to microbial decomposition. The resulting emissions of the greenhouse gases CO2 and CH4 into the atmosphere are the reason why permafrost thaw represents a tipping element in the Earth's climate system. Ground ice melting generates ground subsidence, resulting in locally wetter or drier conditions. Tundra vegetation is actively responding to this changing environment with two major directions of vegetation shift across the Arctic: the expansion of deeply rooted sedges and the widespread increase in shallowly rooted woody shrubs. Changes in vegetation composition, density and distribution have large implications on the Arctic warming and permafrost stability by influencing the albedo, the snow accumulation and the litter decomposition rate. A full grasp of the underlying mechanisms controlling vegetation shift, and the associated effects on Arctic warming, requires assessing the changes in plant nutrient sources upon permafrost thaw, given that nutrient access is a limiting factor for the Arctic tundra vegetation development. Our understanding of how permafrost thaw and vegetation shift influence nutrient cycling is key for the prediction of ecosystem response to environmental changes and their associated feedback on climate change. Specifically, there is a need to identify the processes controlling changes in nutrient sources for Arctic tundra vegetation upon permafrost thaw.

Objectives

The goal of LIFTHAW is to provide a comprehensive assessment of the nutrient mobility response in permafrost regions subject to thawing. Permafrost thaw unlocks previously frozen soil constituents which become available for biogeochemical reactions. There is a lack of constraint on whether this new pool of essential mineral nutrients (such as calcium, magnesium, potassium) is primarily available for the more deeply rooted plant species, or whether the change in water table level associated with permafrost thaw acts as a nutrient lift. It is also poorly understood how changing the water table level affects the mobility of iron and the formation of iron oxyhydroxides acting as a trap for key limiting nutrients such as phosphorous. Crucially, the response of thaw depth to warmer temperature is not uniform at the landscape scale, affecting surface and subsurface water flows, and it is unknown to what extent an increase in connectivity between portion of unfrozen ground located above/within/below permafrost controls the vertical and lateral nutrient mobility.

To tackle these knowledge gaps, the project LIFTHAW is designed to answer the three following research questions (Fig. 1): (Q1) what is the influence of permafrost thaw on the nutrient sources for plant uptake? (Q2) does permafrost thaw lead to nutrient lift upon changes in water table level? (Q3) how does permafrost thaw affect the lateral transfer of nutrients seasonally? To this end, progress in the field of mass spectrometry will be used to unravel sources and processes controlling nutrient mobility in thawing permafrost. Unprecedented insights will be obtained by combining the radiogenic strontium isotope and the silicon isotope tools. Strontium isotopes will be used to trace nutrient sources between organic and mineral soil layers hypothesizing that the foliar radiogenic strontium isotope ratio tracks the rooting depth of nutrient uptake. Silicon isotopes will be used to determine the connectivity of the unfrozen portions of the frozen ground based on the hypothesis that silicon

isotopes are fractionated by freeze-thaw processes. A field monitoring in the Arctic will be led at Eight Mile Lake, a site part of a Long-Term Ecological Research program in Healy, Alaska, US. This monitoring will take place at the early (May-June) and the late (August-October) shoulder seasons, i.e. key transition periods between the frozen and unfrozen status of the active layer; this is the upper section of the ground above the permafrost that thaws every summer and refreezes in the winter, and which largely influences water flow paths, root nutrient uptake, and permafrost carbon emissions. Continuous measurements of thaw depth and water table level will be collected in soils. Soil pore waters along a soil thaw gradient and water tracks draining permafrost catchments will be sampled as a time-series to follow the evolution of their water chemistry (major elements and dissolved organic carbon) and isotope signatures (silicon, strontium). Foliar samples of tundra plant species with contrasted rooting depth will be collected along the soil thaw gradient to determine the evolution of their nutrient sources.

Conclusions

In this project, we demonstrated that permafrost thaw reshapes nutrient mobility in arctic soils, with hydrology being the dominant control mechanism. Experimental warming showed that water-table rise accounts for 56-93% of changes in plant nutrient sources, compared to a relatively low contribution of biocycling (7-34%). The hydrological consequences of permafrost thaw can also be measured with the presence of taliks, zones of perennially thawed soil. These are characterized by enhanced mobility at the soil profile scale, with mixing of surface and deep waters, lateral flushing occurring earlier in the season, likely during snowmelt, and the development of novel biogeochemical pathways altering iron oxide cycling with drastic implications for carbon stabilization. Furthermore, lateral nutrient transfer from soils to rivers shows strong seasonal patterns, with soil-derived contributions to river water reaching up to 67-76% during spring break-up and autumn freeze-up, extending well beyond traditional monitoring periods. Our findings show that the hydrological consequences of permafrost thaw, including water-table rise, talik formation, and altered subsurface flow paths, are the primary drivers reshaping nutrient distribution across degrading permafrost landscapes. These hydrological modifications alter the timing, magnitude, pathways, and therefore fate of nutrients, with critical implications for Arctic ecosystem functioning and carbon cycling under intensified warming.

Keywords

arctic soils – arctic tundra - permafrost thaw – nutrient mobility – nutrient cycling – water table dynamics – talik – soil-river transfer – isotope geochemistry

1. INTRODUCTION

Warming Arctic and permafrost thaw - The Arctic is warming more than twice as fast as the global average and precipitation is projected to increase over high latitude[2]. Permafrost is one of the most sensitive Earth's system component to warming[3]. If global temperatures were to stabilize at 2°C of warming, as aimed with the Paris Agreement, ~25% of the near-surface permafrost (3-4 m depth) is projected to thaw by 2100, whereas beyond 2°C of warming, ~70% of the near-surface permafrost could be lost[2]. Loss of permafrost would radically change high-latitude topography, hydrology, biology and biogeochemical cycling, thereby providing significant feedbacks on climate change[4–8]. One major concern about permafrost thaw is the exposure of immense stores of frozen C to microbial decomposition and the release of greenhouse gases (CO_2 and CH_4) to the atmosphere, which would amplify surface warming[6]. This phenomenon is known as the permafrost carbon feedback[9]. As a consequence, permafrost thaw is considered as a tipping point in the Earth climate system[10].

The mode of permafrost degradation is highly variable, and the topographic and ecological consequences depend on several variables such as soil texture, hydrology, and ice content[11]. A widespread form of permafrost degradation is the thermokarst development[12], that causes ground subsidence upon ground ice melting[13]. The development of a thermokarst landscape locally affects the water table depth, with subsided areas becoming wetter than the nearby elevated areas[14,15]. These local changes in soil moisture conditions strongly affect redox[16] and biogeochemical[17–19] processes in soils, but also rates of microbial decomposition[20–23] and tundra vegetation composition[24–26].

Changes in tundra vegetation - While circumpolar satellite observations highlight a clear trend of Arctic greening since the early 1980s[27–29] (increase in biomass and productivity), recent assessments report some decline in Arctic greenness, referred to as Arctic browning[30–32]. The loss of vegetation biomass and canopy in northern ecosystems may be driven by extreme biological or climatic events, abrupt permafrost thaw or tundra wildfires. These opposing observations bring challenges to predict the future implications of changing vegetation on permafrost ecosystems and climate change. Nevertheless, the browning events currently remain too short-lived and too small-scaled to substantially impact the multi-decadal greening trend[24].

The widespread increase in Arctic tundra vegetation productivity results from warmer temperatures[27,33], longer growing seasons[34] including longer belowground growing season[35,36], increased precipitation[26], deeper and earlier seasonal permafrost thaw[37–39] and increasing atmospheric CO_2 concentrations[40]. Additionally, permafrost thaw can also influence vegetation productivity by stimulating microbial activity and nutrient cycling[41–43] and by releasing newly thawed nutrients from deeper soil horizons[44–46].

Arctic tundra vegetation is mainly composed of vascular plant functional types such as graminoids, forbs, deciduous and evergreen shrubs, and non-vascular species such as mosses and lichens[47]. For the last decades, permafrost degradation has initiated shifts in the tundra vegetation composition[48] towards an overall increasing shrub dominance[15,49,50]. At a local scale, the wetter soil conditions in subsided and poorly drained areas generally favor graminoid expansion[25,26,51]. Conversely, drier soil conditions upon warming drive an expansion in shrubs, called shrubification[15,49,50].

Vegetation-climate feedbacks - Changes in tundra vegetation biomass and distribution induce strong feedbacks on permafrost integrity, northern ecosystem dynamics and climate warming. Firstly, plant canopy directly interferes with the heat transfer to the ground by altering ground albedo (surface reflectance), intercepting the ground solar radiation and shading the ground, or modifying snow distribution in winter (shrub branches and foliage trap the snow and therefore insulate the ground)[52,53]. Secondly, vegetation plays a central role in the net permafrost ecosystem carbon balance through plant respiration, photosynthesis process, and litter decomposition[9,54–57]. A challenge to improve simulations and prediction of vegetation dynamics in the changing northern ecosystems[38,58] is to better constrain the potential evolution of available nutrient sources for Arctic tundra plant species, given that an increase in nutrient availability contributes to the increase in plant biomass production and the shift in plant community composition**.**

2. MOTIVATION AND OBJECTIVES OF THE PROJECT

Gap in knowledge - Given that changing nutrient sources for tundra vegetation has major implications for vegetation changes in the Arctic and thereby on vegetation-climate feedbacks, there is a need to identify the processes controlling changes in nutrient sources for Arctic tundra vegetation upon permafrost thaw. To address this knowledge gap, details are provided for each of the three research objectives (O1, O2, O3).

Unlocking a deep pool of nutrients (O1) - The release of essential nutrients at depth (such as calcium, magnesium, potassium) is expected to increase vegetation production[59–62] and contribute to the shift in vegetation observed across the Arctic[15,26,63]. Indeed, the more deeply rooted graminoids access first the newly thawed soil horizons at depth[44] and thereby benefit first from these newly thawed pools of nutrients. Woody shrubs may benefit latter from the nutrient transfer from deep soil horizons through graminoid surface litterfall deposition. Given the important feedbacks of changing Arctic tundra vegetation on climate change[24], **quantifying the changes in nutrient sources for tundra vegetation is a mandatory step** for future ecosystem models simulating the evolution of vegetation development upon permafrost thaw[26,64–66].

Nutrient lift with water table rise (O2) - We hypothesize that changing water saturation in the active layer upon thawing is a major player in controlling nutrient mobility in tundra soils. The accumulation of iron (Fe) oxides at the redox interface is likely of crucial importance for limiting nutrients such as phosphorous (P). Indeed, some studies have described the importance of ferrihydrite as traps for P in permafrost soils[67,68]. In addition, Fe complexed with organic carbon is also thought to be involved in P binding via organic-Fe-PO_4 ternary complexes[67,69]. Furthermore, poorly crystalline Fe-oxides, such as those accumulated at the redox interface, can better sorb phosphate than well crystalline Fe-oxides[68,70]. Depending on specific plant strategies in nutrient uptake, species may benefit from nutrient lift in surface whereas others will benefit from the release of newly thawed nutrients at depth. **Uncertainties remain regarding the rate at which P would be released in changing soil water saturation conditions**, i.e., lost upon leaching or gradually released allowing time for P assimilation by plant roots[71,72].

Lateral nutrient soil-river transfer through taliks (O3) - In some areas, active layer thickening is so deep that the annual freeze may no longer reach the permafrost table during the winter[73]. As a consequence, a portion of the soil remains unfrozen during the winter forming a talik[74]. Taliks can be open to the atmosphere in surface or closed from the atmosphere below the frozen surface, and they can be laterally connected by water flow or isolated[75]. With increasing soil temperature, taliks can be increasingly connected[74,76], leading to changes in soil biogeochemical connectivity. This increasing connectivity contributes to extends microbial activity and C emissions in the thawed layer well past the point when the surface has refrozen[77]. This contributes to winter C emissions, which may offset the C uptake by vegetation during the summer under future climate conditions[56]. Longer lasting C-emitting areas are expected during the late shoulder season in extensively degraded permafrost areas characterized by more soil subsidence and changes in hydrology than least degraded areas[14]. **Precisely identifying the extent of these areas is required for a clear understanding of the processes modulating permafrost C emissions**, and thereby a reduction of the uncertainty associated with climate model projections[78].

3. METHODOLOGY

To address the three research objectives (O1, O2, O3), the project was organized around **three scientific work packages (WP)**. The *overall methodological approach* of the project was to lead a field effort in the Arctic to monitor the seasonal changes in nutrient sources exposed by permafrost thaw and redistributed within the ecosystem for plant uptake (WP1 for O1), for lifting in soil layers (WP2 for O2) and for export towards the hydrosphere (WP3 for O3) (Fig. 1).

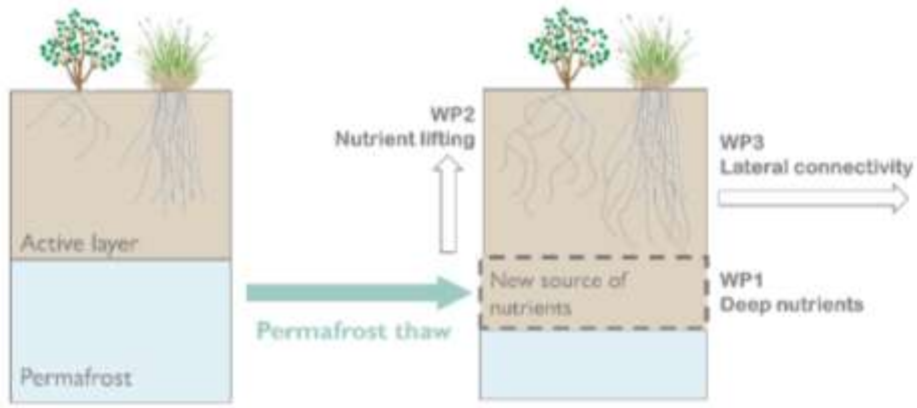

Fig 1. Scheme of the scientific work packages (WP1-2-3) addressing the three objectives of LIFTHAW.

The *novelty* of the project was that progress in the field of mass spectrometry over the last 20 years had considerably advanced our capacity to measure high-precision non-traditional stable isotope ratios such as Si[79,80], and to push further the boundaries (precision, detection limit) to measure the radiogenic isotopes such as Sr[81]. The *original concept* of the project was that these developments in isotope geochemistry would be combined for the first time with *intensive Arctic field monitoring* to quantitatively determine the contribution to element fluxes exported from thawing permafrost to terrestrial and aquatic ecosystems. This *frontier research* crossed disciplinary boundaries between stable isotope geochemistry, cryospheric science and soil science. We used this innovative approach on the different pools from the permafrost ecosystem (vegetation, soil, water) to answer our scientific question about the role of permafrost thaw on the sources of nutrients released. The *challenge* was be to ensure a continuous monitoring at the transition period (early spring and late summer) where the collection of soil pore waters was not be facilitated by weather conditions. **We posit that by combining the Si and Sr isotope tools, unprecedented insights into the sources and processes controlling element fluxes exported from the thawing permafrost to terrestrial and aquatic ecosystems will be obtained.** Pushing the boundaries of the isotope tracers was a major step to generate new knowledge on fragile permafrost regions highly sensitive to climate change.

The *strengths of the project* were that (i) it will directly benefit from recent analytical developments at the host institution to measure Sr and Si isotopic compositions by multi-collector inductively coupled plasma mass spectrometry (MC-ICP-MS) in complex matrix-, organic-rich samples[82–84], (ii) the project was connected to a strong international effort for long-term monitoring in the Arctic and could count on soil temperature and thaw depth measurements at the site for the past 18 years (Bonanza catalog: https://www.lter.uaf.edu/), (iii) the project could rely on a strong background knowledge of the study site at the host institution from the ERC-funded project WeThaw (https://sites.uclouvain.be/wethaw/), and (iv) it benefited from geophysical measurements that were collected at the site by the project LandSense (https://sites.uclouvain.be/landsense/) in 2023-2025 to determine changes in soil moisture as a function of soil microtopography along the thaw gradient as well as in advanced thawed areas (watertrack).

Tracing nutrient sources with Sr isotopes

The *originality* of the approach was that strontium (Sr) isotopes served to trace the contribution from newly exposed nutrient sources upon permafrost thaw. Strontium isotope compositions were determined on foliar samples to track rooting depth of nutrient uptake (WP1), in soil pore waters to track the release of Sr as an analog for the PO_4 trap on Fe-oxides at the water table level (WP2) and in water from water tracks to trace the integrated contributions from organic and mineral layers to nutrient export (WP3).

How to use Sr isotopes to trace the rooting depth of nutrient uptake (WP1)

Strontium has four natural stable isotopes: ^{88}Sr (natural abundance of 82.58%), ^{87}Sr (7.0%), ^{86}Sr (9.86%) and ^{84}Sr (0.56%). Only ^{87}Sr is "radiogenic" and results from the radioactive β–decay of ^{87}Rb (with a half-life of about 49 billion years). The radiogenic Sr isotope ratio ($^{87}Sr/^{86}Sr$) is largely used to trace cation origin at the Earth surface as a function of geological processes involving bedrock lithology and mineral weathering[85–87], and references therein). The ratio is considered more or less radiogenic whether there more or less ^{87}Sr, respectively.

As there is no measurable fractionation of radiogenic Sr isotopes during biological processes, the $^{87}Sr/^{86}Sr$ ratios in plant tissues directly reflects source materials and are particularly useful for nutrient provenance studies[88–94]. Plants take up cations as nutrients from the exchangeable soil fraction, and Sr is well known to be taken up together with Ca[91,95–97]. According to plant physiology and root morphology, foliar $^{87}Sr/^{86}Sr$ composition may vary between plant species[97,98], such as between shallow-rooted Arctic tundra shrubs and deep-rooted Arctic tundra sedges[96,97,99,100].

To answer our first question "How does permafrost thaw influence the nutrient sources for Arctic tundra vegetation?", we used the radiogenic Sr isotopes as tracers of sources for plant nutrient uptake (WP1). More specifically, we compared the $^{87}Sr/^{86}Sr$ ratio of foliar samples for four Arctic tundra species with contrasted rooting depths (*B. nana, V. vitis-idaea*, *V. Uliginosum* and *E. vaginatum*) along a permafrost thaw gradient at Eight Mile Lake, Interior Alaska, USA. The $^{87}Sr/^{86}Sr$ ratio of the exchangeable Sr taken up by the plant is more radiogenic in surface soil horizons than in deeper soil horizons (Fig. 2). Consequently, plants taking up Sr from deeper presented less radiogenic foliar $^{87}Sr/^{86}Sr$ ratio (Fig. 2). The higher foliar $^{87}Sr/^{86}Sr$ ratios measured in shallowly rooted shrubs (*B. nana, V. Uliginosum* and *V. vitis-idaea*) closely reflected the high exchangeable $^{87}Sr/^{86}Sr$ ratios in surface (up to 40 cm depth), whereas the lower $^{87}Sr/^{86}Sr$ ratios measured in the deeply rooted sedge (*E. vaginatum*) reflected a deeper source of Sr (less radiogenic, up to 60 cm depth). According to preliminary data collected on this site, the overall wider range of foliar $^{87}Sr/^{86}Sr$ ratios towards lower values in three plant species (*B. nana, V. vitis-idaea, E. vaginatum*) in more degraded permafrost soils suggested that vegetation accesses deeper sources of Sr (less radiogenic) upon permafrost degradation. However, these data are scarce, and a more systematic approach at the site scale should be the way forward to understand the spatial heterogeneity of nutrient release at depth for the vegetation. This is timely relevant to address this gap given that providing access of Arctic tundra vegetation to deeper reservoirs of available nutrient cations may largely influence the net primary productivity and the Arctic greening.

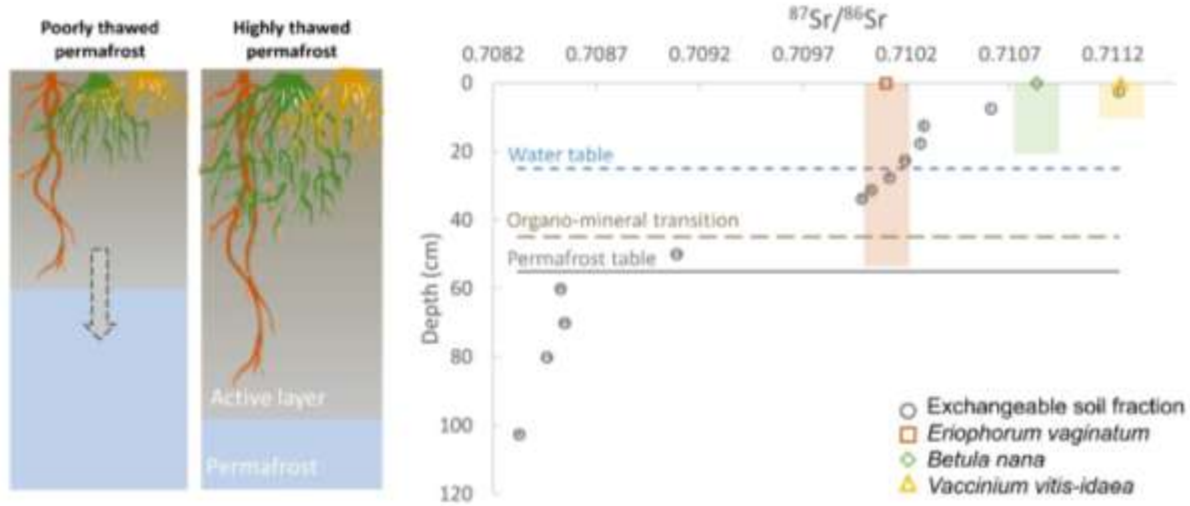

Fig 2. Evolution of the Sr isotope ratio in the exchangeable soil fraction with depth in a soil profile from Alaska, and preliminary data of the foliar Sr isotope ratio of three tundra plant species with different rooting depths (data from[101]).

How to use Sr isotopes to trace nutrient lift (WP2)

According to our hypothesis for WP1, nutrient from deeper layers in the soil profile were characterized by less radiogenic Sr isotope ratios. The aim of WP2 was to test to what extent these deep nutrients could be lifted up by water table rise upon permafrost thaw, and lead to an accumulation in shallower soil layers. This would be particularly key for shallow rooted plants with difficult access to deep nutrient sources, and especially for phosphorous, a key nutrient limiting primary productivity[72,102]. Iron oxides are known to form at the transition between saturated and unsaturated conditions and to play a role of P trap in soils[68,103]. Preliminary data for one tundra soil profile in Alaska confirmed the co-location of Fe-oxides accumulated at the water table level and the accumulation of P (Fig. 3;[104]). Phosphorous is absorbed onto Fe-oxides[68]. Strontium can also be adsorbed onto Fe-oxides and trapped into aggregates[105]. We posited that the Sr isotope ratio of the Sr adsorbed onto Fe-oxides would be less radiogenic if the Sr originated from deeper soil layers, and that this could be used to trace the lifting of deep nutrient towards shallower soil layers.

A major concern was that the role of Fe-oxides as P trap could be highly reversible under changing physico-chemical conditions[106–108] that occur during water table rise upon permafrost thaw. Fluctuating wet-dry cycles drive redox shifts in otherwise well-drained soils resulting in Fe-oxides dissolution and potential P release[68,109–111]. These shifts in redox potential influence redox-sensitive elements such as Fe by modifying the crystallinity of Fe-oxy(hydr)oxides or the distribution of stabilizing surfaces, with subsequent release of the elements adsorbed such as P or C[68,112–115]. Practically, to test the influence of wetting and drying on the nutrient lift from deeper soil layers, we will selected soil sites with contrasted saturation conditions (unsaturated poorly thawed soils, deeply thawed soils persistently waterlogged, and deeply thawed soils partially undersaturated), and monitored the evolution of the Sr isotope ratios in the soil pore waters simultaneously with active layer depth and water table depth.

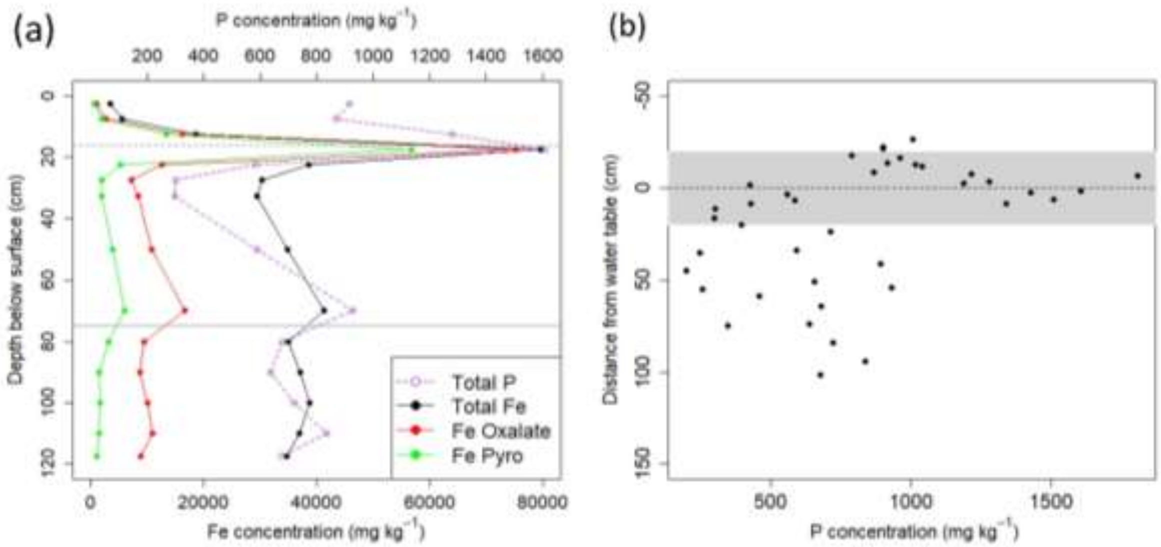

Fig 3. (a) Depth evolution of Fe total (black) and selectively extracted concentrations (oxalate and pyrophosphate; red, green) and total P concentrations (purple) in soil for one profile from Alaska (permafrost table = full horizontal grey line; water table = dashed horizontal grey line); (b) Total P concentration (n = 39) as function of the distance to the water table. The greyish rectangle represents samples from a distance smaller than 20 cm above or below water table (data from [104]).

<u>*How to use Sr isotopes to trace the sources of lateral nutrient export (WP3)*</u>

We hypothesized as in WP1 that nutrient from deeper in the soil profile were characterized by less radiogenic Sr isotope ratios. We posited that the lateral export of deep nutrients exposed by permafrost thaw would lead to less radiogenic Sr isotope ratios in the water, and that this would evolve seasonally as a function of the thaw depth of the active layer, the presence of taliks, and the change in water flow paths (between surface runoff in early spring, and surface and subsurface runoff when soil thawed[116]; Fig. 4). This was why there is a *need for a seasonal monitoring of the lateral export at different seasons* to detect changes in the sources of nutrient export. Water tracks are ideal locations as integrators of the soil contribution.

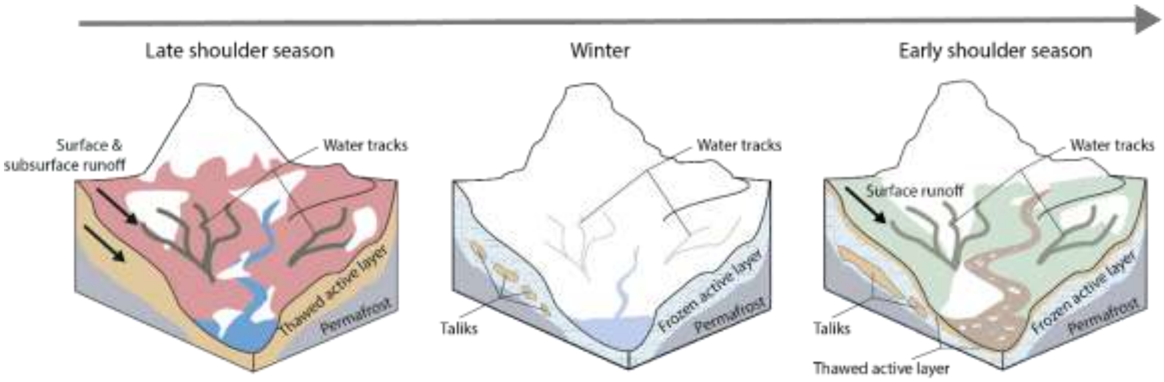

Fig 4. Evolution of the contribution of soil pore water to the watertrack from late shoulder season (Autumn) to Winter to Early shoulder season (Spring). Late shoulder season is characterized by a thawed active layer and a contribution from deep soil layers (less radiogenic) and early shoulder season is characterized by little to no thawed active layer and a contribution dominated by surface soil layers (more radiogenic).

Tracing lateral connectivity induced by permafrost thaw with Si isotopes (WP3)

The *novelty* was that we used silicon (Si) isotopes to trace freeze-thaw processes in soils, and to quantify the lateral connectivity in the active layer soils during the winter. Silicon in soil pore waters (< 0.2 µm) can be a colloidal fraction (~ 0.2 µm to ~ 1 nm) and a truly dissolved fraction of silicic acid (~ < 1 nm) (Fig. 5). We considered that soil pore waters contain different proportions of these Si pools during freezing and thawing and applied this conceptual framework to detect the freezing and thawing conditions in permafrost soils. We used this framework to test to what extent winter hosted soil-water interactions in permafrost soils. We postulated that permafrost degradation generate winter freeze-thaw cycles.

Upon **freezing** of soil pore waters and ice formation under a **closed system**, there iss a decrease in liquid water volume which drives an increase in concentration of silicic acid in the truly dissolved fraction. The decrease in temperature leads to a decrease in amorphous silica solubility[118]. These conditions promote the precipitation of amorphous silica, where up to 90 mol % of the primary dissolved silicic acid is fixed as amorphous silica during freeze-thaw cycles[118]. Amorphous silica precipitation induces silicon isotope (δ^{30}Si) fractionation where the light silicon isotope (^{28}Si) is preferentially incorporated into the amorphous silica and the heavier silicon isotope (^{30}Si) remains in the solution[119]. The formation of amorphous silica drives unidirectional kinetic isotope fractionation forming a solid or colloidal fraction that is 5 ‰ lighter than the surrounding brine[119]. We hypothesised that the resulting soil pore water (< 0.2 µm) in a closed, frozen system was composed of isotopically heavy truly dissolved silicic acid, with a small fraction of isotopically light colloidal amorphous silica[83]. Upon **thawing** of soils, the system is **opened** and waters percolate through the soil matrix. We hypothesise that the residual truly dissolved silicic acid from the closed system soil pore water (< 0.2 µm) mixes with: (i) a fraction of colloidal amorphous silica; and (ii) a pool of truly dissolved silicic acid released via mineral dissolution in the soils. The relative contribution of these different Si pools will determine the soil pore water silicon isotope composition during thawing. A contribution from amorphous silica colloids mobilised into soil pore waters and from truly dissolved silicic acid from mineral dissolution[120] would drive the soil pore waters towards lighter silicon isotope compositions, relative to a closed system.

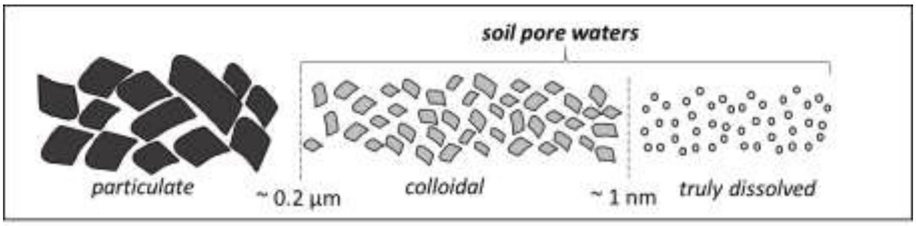

Fig 5. Size distribution of silicon in permafrost soil pore waters.

We tested our hypotheses during periods of closed (frozen) and open (thawed) systems along a gradient of permafrost thaw at Eight Mile Lake, Alaska. At this site, maximum active layer thickness (ALT) exhibits considerable variation over short lateral distances[121] (less than 1 km). Based on this well-documented variation, we compared locations under a 'default' model of minimal permafrost degradation (with ALT < 60 cm) and a 'degraded' model of extensive permafrost degradation (with ALT > 60 cm). To fingerprint the locations of winter freeze and thaw across the landscape, we combined soil temperature measurements with soil pore water geochemical measurements (Si concentration and silicon isotope composition (δ^{30}Si)) during periods of closed (frozen, prior to snowmelt) and open (thawed, late summer) systems. The *research objectives* were: **(i)** determining the influence of permafrost thaw on the **nutrient sources** for plant uptake (in WP1); **(ii)** quantifying the **nutrient lift** driven by changes in water table level upon permafrost thaw (in WP2); **(iii)** detecting when the seasonal thaw of the active layer modified the **lateral transfer** of nutrients upon permafrost degradation (in WP3).

The *methodology of the project* was based on field work and analytical work in the laboratory. The field site location is described in details in the environmental setting. The tools used in the different WPs (Fig. 6) are then described individually to cover field work and analytical work. The *new data that were gathered* from this effort were: (i) continuous field monitoring of thaw depth and water table depth at three key periods: late winter/early spring, late summer/early autumn and deep winter (WP2); (ii) evolution of the geochemical and isotope compositions of soil pore waters and water tracks along these periods (major elements concentration, dissolved organic carbon (DOC) concentration, Sr isotope ratio, Si isotope composition) (WP2 and WP3); (iii) evolution of the foliar Sr isotope ratio for four plant species with contrasted rooting depth with experimental warming and deepening of the active layer (WP1); (iv) foliar Sr isotope ratio of three plant species with contrasted rooting depth across poorly thawed and deeply thawed soils (persistently waterlogged, partially undersaturated) (WP1).

The *expected outcomes* were the identification and quantification of the main drivers for the following processes (by WPs): (WP1) the deep nutrients release by permafrost thaw more readily available for deeply rooted plant species, and progressively available to shallowly rooted plant species; (WP2) the rise in water table level contribution to nutrient lift in shallower soil layers in partially undersaturated soils relative to persistently waterlogged soils; (WP3) the increasing release of deep nutrient across the summer period with the seasonal thaw of the active layer.

Fig 6. Schematic representation of the different tools used by WPs and described here below.

Environmental setting

The work for all WPs was conducted at the Eight Mile Lake (EML) research site in Healy, Interior Alaska, USA[122] (63°52'42N, 149°15'12W; Fig. 7). The site is underlain by degrading permafrost in the discontinuous permafrost zone[121,123]. Climate is characterized by mean monthly temperatures ranging from –16 °C in December to +15 °C in July and average annual precipitation of 381 mm (2007-2017; Healy and McKinley Stations, Western Regional Climate Center, and National Oceanic and Atmospheric 105 Administration National Centers for Environmental Information [NOAA]). Soils are characterized by a 35 to 55 cm thick organic layer (>20% of organic C content) at the surface, lying above a cryoturbated mineral soil (5-20% of organic C) composed of glacial till and loess parent material[121,124,125]. The site is an ideal natural laboratory to reach our goal given that upon projected permafrost degradation at EML[126], the upper permafrost (0-20 cm below the permafrost table) will undoubtedly thaw and expose soil constituents by 2100.

Gradient site: a natural thermokarst gradient

Within the EML watershed, a natural gradient in permafrost thaw and thermokarst formation has developed since the mid to late 1980s[15], and has been defined as the *Gradient site* (Fig. 8). The site is located on a gentle (< 5°) north-facing slope[15,127] and has been monitored since 1990 to follow the impact of permafrost degradation on ground subsidence, thaw depth and water table depth[122]. Field measurements in late August 2019 reported contrasted maximum active layer thicknesses (ALT; from 40 to 90 cm) and water table depths (from 0 to 40 cm) across the site, that were sorted as "poorly" (ALT ≤ 60cm) and "highly" (ALT > 60cm) thawed permafrost sites. The site is located on moist acidic tundra[121,128] (pH_{soil} ~ 3 to 5), with a dominance of tussock-forming sedges, such as *Eriophorum vaginatum* L. and *Carex bigelowii* Torr. ex Schwein, evergreen shrubs (e.g., *Andromeda polifolia* L., *Rhododendron tomentosum* Harmaja, *Vaccinium vitis-idaea* L., and *Empetrum nigrum* L.), deciduous shrubs (e.g., *Vaccinium uliginosum* L. and *Betula nana* L.), and forbs (e.g., *Rubus chamaemorus* L.). Non-vascular plant cover is dominated by mosses (mainly *Sphagnum* spp., *Dicranum* spp., and feather mosses including *Hylocomium splendens* and *Pleurozium schreberi*,) and lichen species (e.g., *Nephroma* spp., *Cladonia* spp., and *Flavocetraria cucullata*)[15,129,130]. The thermokarst development at EML has initiated a shift in the vegetation cover, with evergreen and deciduous shrubs (as *B. nana*), and forbs becoming dominant at the expense of tussock forming sedges (as *E. vaginatum*)[15,131]. **The Gradient site is an ideal situation to test the influence of permafrost thaw on (i) deep nutrient release (WP1), (ii) nutrient lifting with water table rise (WP2), and (iii) lateral connectivity for nutrient export (WP3).**

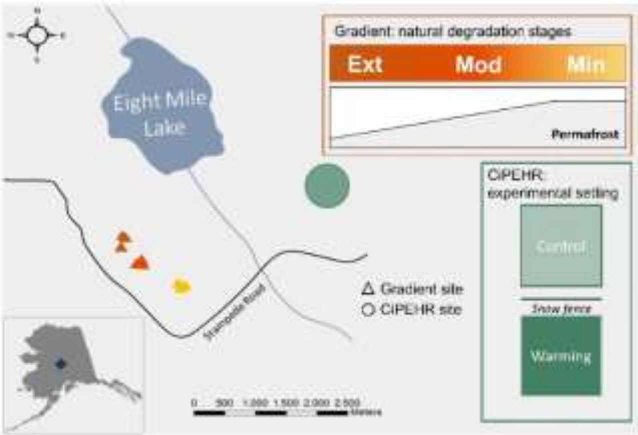

Fig 7. Location of the Eight Mile Lake (EML) research site in Healy, Interior Alaska, USA with the Gradient site (natural thermokarst; left) and the CIPEHR site (experimental warming).

CiPEHR: an experimental warming site

An experimental warming project called CiPEHR (Carbon in Permafrost Experimental Heating Research) was established in 2008 close to EML, on a relatively well-drained gentle (~3°) north-east-facing slope. The experimental setup extends over three replicate areas (~100m apart) and gathers a total of 48 plots distributed equally into control and soil warming treatments (Fig. 7). Soil warming consist of using six snow fence replicates (plots 1.5 m tall × 8 m long) that increase winter snow depth, insulating the soils from extremely cold air temperatures. The extra snow is removed every spring to avoid excess soil moisture due to snowmelt between winter warming and control plots[123]. When the CiPEHR site was installed in 2008, maximum seasonal extent of permafrost thaw depth was ~50 cm and has since increased at a rate of 2 $cm.a^{-1}$ in control areas and 6 $cm.a^{-1}$ in soil warming areas[132]. The

CiPEHR site displayed higher water table upon permafrost degradation and soil subsidence processes between 2009 and 2017, and thereby wetter soil conditions in 2017 than in 2009[14,132]. Furthermore, the vegetation aboveground biomass has been monitored since 2008 and displays a considerable expansion of the sedge species upon warming and wetter soil conditions[133]. In particular, the aboveground biomass of the sedge *E. vaginatum* more than doubled between 2009 and 2017, while the changes in aboveground biomass for other species were much less pronounced, with between 50% decrease and 20% increase. **The CIPEHR site is an ideal situation to test the hypothesis of a deep nutrient release for vegetation upon an accelaterated permafrost thaw (WP1).**

Field work

Field monitoring (WP2 & WP3)

The *LIFTHAW* project provided for the first time a field monitoring of the impact of permafrost thaw on nutrient sources at three key periods: two seasonal transition periods, so called shoulder seasons[134] - late winter/early spring (mid-April until end of June for the early shoulder season) and late summer/early autumn (mid-August until end of October for the late shoulder season) – as well as winter monitoring. We measured the soil active layer thickness (ALT) with a metal probe across the thermokarst gradient to select locations with contrasting ALT, and the water table depth (WTD) was monitored from existing boreholes at the site. We benefited from the measured microtopography at the landscape scale and soil moisture data collected continuously between 09/23-05/25 by the project LandSense (https://sites.uclouvain.be/landsense/), and from soil temperature collected by the LTER Bonanza Creek (https://www.lter.uaf.edu/). The design included poorly thawed soils with active layer below 60 cm (control site) to be compared with deeply thawed soils with contrasted water saturation conditions: persistently waterlogged soil sites (wet), and partially undersaturated soil sites (dry).

Foliar sampling (WP1)

At CiPEHR site, foliar were directly available at the host institution[84] and cover four of the most abundant vascular species from the EML moist acidic tundra: *E. vaginatum, V. uliginosum, B. nana, and V. vitis-idaea* (Fig. 8). The sampling was performed during the peak growing season in July 2009 and in July 2017, thereby covering 8 years of artificially amplified warming, an important deepening of the active layer and a large expansion of the deeply rooted sedge *E. vaginatum*. This sampling involved the collection of fully formed green leaves from the current year's growth over an area of ~1 m^2. Leaves were dried at 60°C and finely ground[130]. These vegetation samples correspond to one bulk foliar sample per species and per plot among the 48 treated plots. The selected species are characterized by contrasted rooting depth, with increasing rooting depth from below 5 cm to 40-65 cm in the following order: *V. vitis-idaea* < *B. nana* < *V. uliginosum* < *E. vaginatum* [44,135] (Fig. 8). It is known that the shallow-rooted shrubs have expanded across northern latitude ecosystems[49,50,53], whereas deeply rooted sedges (as part of the graminoids) have dominated permafrost areas with wetter soil conditions[25,26,51]. These two typical Arctic tundra plant functional types rely on different rooting system strategies. Shrubs (such as *B. nana* and *V. vitis-idaea*) initiate their root growth earlier than sedges, and take advantage of the nutrient pulse after snowmelt, in the early growing season[136]. The deep roots of sedges (such as *E. vaginatum*) access deeper nutrient pools, and benefit first from the release of the newly thawed nutrients upon increasing permafrost thaw[44].
At Gradient, three of the four most abundant vascular species of the site (Fig. 8) were selected[15,123,131]: *E. vaginatum* (sedges), *B. nana* (deciduous shrubs) and *V. vitis-idaea* (evergreen shrubs). We sampled fully formed leaves over an area of ~5 m^2 around three sites along the thaw gradient (in triplicates).

We also collected tissues of the lichen *Flavocetraria cucullata* as a bulk sample at each site. This is a widespread lichen species across the Arctic tundra ecosystems and a great bioindicator of the composition of atmospheric nutrient sources[137,138]. Leaf samples were dried at 60°C and ground.

Fig 8. The four most abundant vascular plant species of the tundra site in Alaska (increasing rooting depth from left to right).

Water sampling (WP2 & WP3)

Field campaigns took place at the Gradient site (EML) between September and November 2023 (late season), in February 2024 and March 2025 (winter) and in June 2024 (early season) to collect time-series of soil pore waters and water from water tracks profiles from soil with contrasts in ALT (measured with a metal probe) and the associated vegetation. In total, nine sites were set up for monitoring to cover contrast in permafrost thaw: poorly thawed soil profiles with ALT ≤ 60cm (n=3), and highly thawed soil profiles with ALT > 60 cm (persistently waterlogged, n=3; partially undersaturated, n=3). *Soil pore waters* were collected using pre-cleaned macro rhizon soil water samplers (length 9 cm, diameter 4.5 mm, porosity 0.2 µm; Eijkelkamp™) (Fig. 9) at three depths (10, 30, 45 cm; including from 30 cm deep boreholes at the monitored plots from Gradient site[122]). The rhizon was inserted using a rhizon insertion tool after preparing the location using an adapted thin soil auger. The rhizon samplers were attached to acid-washed 50 ml syringes, held under vacuum with wooden sticks, and inserted into soils for ~ 24 hours. The collected soil pore waters were stored in acid-washed (5 % HNO_3, commercial) polypropylene bottles at ~ 8 °C. Water from *water tracks* was collected in a similar way to soil pore waters, using pre-cleaned macro rhizon soil water samplers at 3 depths for nine sites.

Fig 9. Type of rhizon sampler to be installed to collect soil pore water.

Analytical work in the lab

Water elemental analysis (WP2 & WP3)

Water elemental analysis was performed on soil pore waters and water tracks at the "Mineral and Organic Chemical Analysis" platform from UCLouvain (MOCA). Major element concentrations (Si, Al, Fe, Ca, Mg, K, Na, P, S, Sr) were measured by inductively-coupled plasma-optical emission spectrometry (ICP-OES; iCAP 6500 Thermo Fisher Scientific). The accuracy was assessed using the water reference material SLRS-5[139]. The DOC concentrations was determined using high-temperature catalytic oxidation (Shimadzu® TOC-VCPH). Anion concentrations (PO_4, SO_4, Cl, NO_3) was determined using an IC20 ion chromatograph (Dionex®). The accuracy was assessed using river water certified reference material LGC6025 (UKAS, 2014). Water pH was measured using a WTW Inlolab 720 pH-meter probe.

Radiogenic Sr isotope analysis (WP1-WP2-WP3)

Strontium isotope compositions was determined on foliar samples, soil pore waters and water from watertracks. Samples were prepared in a clean laboratory (class 100, laminar flow) at the MOCA platform from UCLouvain. The foliar samples were mineralized at 450°C and dissolved in sealed Teflon vials with HF/HNO_3. For the waters, the DOC was removed by reflux with concentrated HNO_3 and H_2O_2 in sealed Teflon vials on a hot plate (180°C). Solutions from digested vegetation and waters were evaporated to dryness and redissolved in 2% HNO_3. The Sr concentration in the resulting solutions was measured by ICP-OES. An aliquot of 500 ng of Sr was dried down and picked up in 100 µl of 3M HNO_3. To purify Sr, the sample was loaded onto Biorad microspin column containing 500 µl of pre-cleaned Strontium specific resin (50-100 µm Triskem), and eluted in several stages with HNO_3[81]. Strontium isotope measurements were carried out by MC-ICP-MS (Neptune Plus™ High Resolution Multicollector ICP-MS, Thermo Fisher Scientific, Earth & Life Institute, UCLouvain, Belgium) in wet plasma mode using a PFA nebulizer of 100 $\mu l.min^{-1}$ uptake rate. The analyses were performed in 2% HNO_3 matrix. Each sample was measured three times and the results were expressed as $^{87}Sr/^{86}Sr$ ratio. External precision was determined on the in-house standard Sr ICP solution and the reference material SRM987.

Silicon isotope analysis (WP3)

Silicon isotope compositions were determined on soil pore waters and water from water tracks. Samples were prepared in a clean laboratory (class 100, laminar flow) at the MOCA platform from UCLouvain. The DOC was removed from the sample matrix by reflux with concentrated HNO_3 and H_2O_2[140]. The Si was separated from the matrix with a one-stage column chemistry procedure using a cation exchange resin (Biorad AG50W-X12)[141]. The silicon isotope composition ($\delta^{30}Si$) was analyzed by MC-ICP-MS (Neptune Plus™ High Resolution Multicollector ICP-MS, Thermo Fisher Scientific, Earth & Life Institute, UCLouvain, Belgium) in wet plasma mode in medium resolution using a PFA nebulizer of 100 $\mu l.min^{-1}$ uptake rate. The instrumental mass bias was corrected using the standard-sample bracketing technique and an external Mg doping[142]. The analyses were performed in 2% HNO_3 matrix. The $\delta^{30}Si$ compositions was expressed in relative deviations of $^{30}Si/^{28}Si$ ratio from the NBS-28 reference standard using the common δ-notation (‰) as follows: $\delta^{30}Si=[(^{30}Si/^{28}Si)_{sample}/(^{30}Si/^{28}Si)_{NBS\text{-}28} -1]\times1000$. Each single δ-value represented one sample run and two bracketing standards, and the $\delta^{30}Si$-values were reported as the mean of isotopic analyses from multiple analytical sessions at least in duplicate. The long-term precision and accuracy of the MC-ICP-MS $\delta^{30}Si$ values was assessed from multiple measurements within each analytical session on reference materials Diatomite and Quartz Merck.

4. SCIENTIFIC RESULTS AND RECOMMENDATIONS

Permafrost thaw at Eight-Mile Lake (Alaska) and along the neighbouring Panguingue Creek provided two complementary windows on how warming reshapes nutrient mobility in Arctic landscapes. Together the findings address the three LIFTHAW work packages (WP): (WP1) influence of permafrost thaw on plant-nutrient sources, (WP2) nutrient lift driven by thaw-induced water-table rise, and (WP3) seasonal lateral transfer of nutrients from soils to surface waters.

- ***Part 1: Modelling the evolution of plant nutrient sources – influence of biocycling and water table rise (WP1 & 2)***

An eight-year soil-warming manipulation (CiPEHR experiment) quantified the relative weight of biocycling versus water-table rise on plant nutrient supply. Foliar $^{87}Sr/^{86}Sr$ ratios from four contrasting tundra species were fitted with a mass-balance isotope model (Fig. 10). Under control conditions the slight isotopic shift was reproduced by biocycling alone, confirming biocycling as the main redistribution pathway in controlled plots. In warmed plots, however, the observed shift could not be matched without introducing water-table rise. Depending on plant rooting depth, this flux accounts for 56 – 93 % of the change, leaving only 7 – 34 % to biocycling even when accelerated by higher temperatures. The dominance of the water table grows with rooting depth, so deeply rooted sedges benefit most from newly mobilised deep cations, whereas shallow-rooted evergreen shrubs respond later as the rising water reaches shallower soil horizons. Field data confirm a progressive upward shift of the water table. This study has been presented at EGU in 2024 (Annexe 1) and is currently under consideration for publication at *Applied Geochemistry* (Annexe 2).

These results fulfil WP1 by identifying and quantifying the impact of biocycling on plant nutrient sources, and WP2 by demonstrating that permafrost-thaw driven water-table rise is the primary mechanism of nutrient-lift at the soil profile scale.

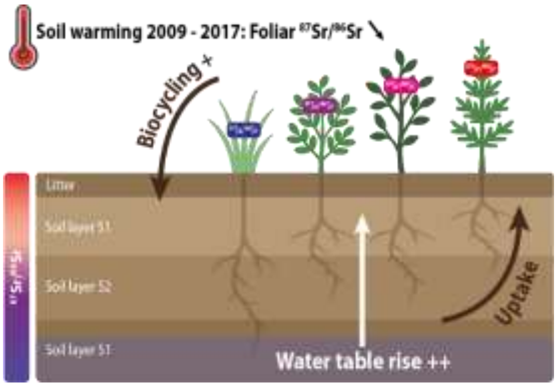

Fig 10: Conceptual model showing the comparative influence of biocycling and water table rise on plant nutrient source under experimentally induced permafrost thaw during 8 years

- ***Part 2: Taliks location, variability and seasonal evolution traced by Sr isotopes (WP2 & 3)***

Five taliks located within the watertrack were selected along an apparent gradient of permafrost degradation characterized by increasing talik thickness, higher observed soil moisture, deeper permafrost tables, and shallower talik occurrence. The most degraded taliks, located at the bottom of the watertrack, exhibited distinct degradation features, including the formation of iron oxides at the soil surface, a phenomenon not observed at any other site, suggesting sustained waterlogged conditions and active redox processes unique to this location. To evaluate talik seasonal evolution, each was sampled twice: in winter (February 2024, March 2025) and during talik breakthrough in early summer (June 2024), when vertical thaw reconnected them with the surface. Surface flowing water was also sampled during summer breakthrough to evaluate vertical nutrient mobility during soil early thaw.

Our results demonstrate that nutrient mobility intensifies with permafrost degradation, occurring both vertically within soil profiles and laterally downslope. In more degraded taliks, chemical signatures reveal enhanced vertical mixing between surface water and talik pore water. This increased mixing is evidenced by greater variability in dissolved organic carbon (DOC), pH, strontium (Sr), and $^{87}Sr/^{86}Sr$ ratios as degradation stage advances. The data reveal that degraded taliks experience pronounced nutrient flushing, characterized by substantial shifts in DOC content, pH, and $^{87}Sr/^{86}Sr$ ratios between winter and summer periods. This flushing effect intensifies with degradation stage. Importantly, the lack of significant chemical changes during summer talik breakthrough suggests that this flushing occurred earlier in the season, most likely during snowmelt through shallow subsurface flow. The most degraded talik at the watertrack bottom exhibits a unique nutrient mobility pattern dominated by iron oxide movement within the soil profile. This behavior appears linked to the rerouting of mineral-rich groundwater, likely resulting from deep water recirculation associated with advanced permafrost degradation. Consequently, iron undergoes active dissolution-precipitation cycles that strongly influence both vertical and lateral nutrient dynamics. This highly dynamic system has significant consequences for organic carbon stabilization and plant phosphorus availability. This work has been the subject of two master thesis, one conference communication (section 5), and will be utilized for an upcoming paper (Annexe 3 & 4).

The result of this study is linked to WP2 by showing that heavily degraded talik amplify the nutrient lift driven by thaw-induced water-table rise. Furthermore, this study is linked to WP3 by tying the degradation stage to the timing and magnitude of the lateral transfer of nutrients from soils during early-season talik flushing.

- ***Part 3: From Soils to Rivers: Radiogenic Sr isotopes Reveal Extended Seasonal Windows of Soil-River Dissolved Organic Carbon Transfer in an Arctic Permafrost Catchment (WP3)***

A multi-isotope survey tracked the seasonal dynamics of dissolved organic carbon (DOC), iron and strontium exported laterally from thawing soils to Panguingue Creek river. 42 filtered river samples were collected across spring break-up, summer base-flow, autumn freeze-up and winter under-ice flow. $^{87}Sr/^{86}Sr$ mixing diagrams show that river chemistry is controlled by binary mixing between groundwater and a single soil-derived endmember, with occasional snowmelt/rain contributions confined to brief transition events. Soil-derived fractions peak at about 67 % during spring ice break-up and 76 % at the onset of autumn freeze-up, and remain detectable (> 20 %, Fig. 11) more than thirty days beyond the traditional end-of-season monitoring in late September. The apparently uniform soil signal, despite deepening thaw, points to mobilisation of Sr-rich Fe-oxide colloids that migrate vertically into surface organic layers before being flushed laterally. Absence of talik signatures under winter ice suggests that continuous year-round pathways have not yet established, but elevated winter $^{87}Sr/^{86}Sr$ hints at incipient rerouting of groundwater flow. This study is to be submitted for publication in *Chemical Geology* (Annexe 5).

These results further fulfil WP3 by resolving seasonal controls on lateral nutrient and carbon transfer and by quantifying that the shoulder-season window is likely underestimated in current Arctic carbon budgets.

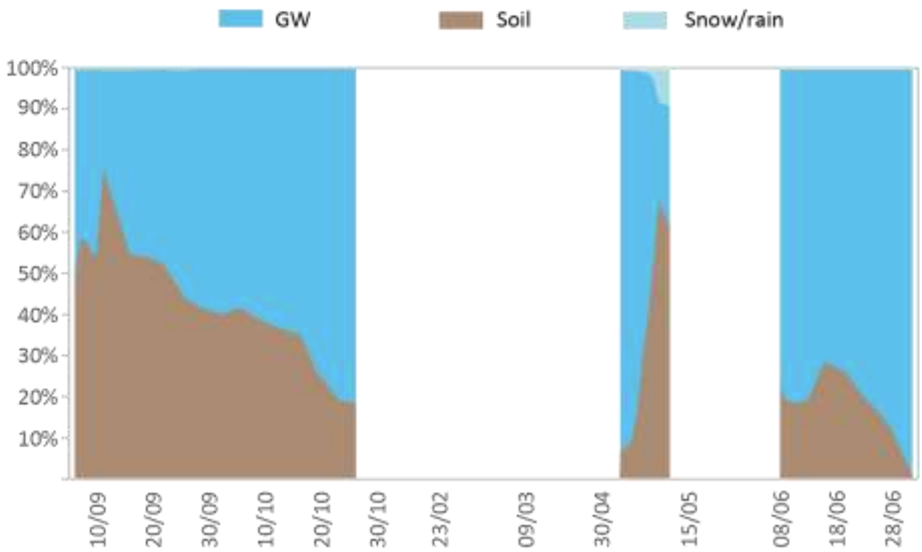

Fig 11: Seasonal contributions of groundwater, soil-derived, and snow/rain inputs to Panguingue Creek river Sr, calculated using a mixing model based on $^{87}Sr/^{86}Sr$ isotope ratios.

- ***Part 4: Collaborative outputs***

LIFTHAW also contributed to and benefited from the expertise acquired from other projects.

Through LandSense, two complementary outputs were generated. First, lidar, multispectral and thermal imagery were combined with in-situ active-layer measurements and vegetation indices to predict active layer depth across the Eight-Mile Lake site. The resulting model is currently being presented at the EGU 2025 conference and is the focus of a paper now under review in *Applied Geochemistry*. Second, the same drone layers helped identify probable talik hotspots, which led to a targeted winter-2024 Ground-Penetrating Radar campaign that imaged suprapermafrost taliks within water-track depressions. That study, completed as a master's thesis during the 2024-2025 school year (Annexe 6), is being developed into a journal manuscript.

Through THAWNECT, LIFTHAW benefited from the study of biogeochemical connectivity in degrading permafrost soils. The resulting paper (Villani et al., 2025 *Geochemical Perspectives Letters*) shows that early-winter snowmelt infiltration lowers redox potential, dissolves Fe oxides, and liberates DOC, Fe and associated nutrients for lateral export—even while soils remain partly frozen. The observed formation of taliks at Eight-Mile Lake motivated this Si-isotope approach, because these unfrozen zones act as key conduits linking freeze-thaw cycles to subsurface nutrient and carbon transport.

Finally, two additional master's theses (Annexe 7 & 8) at Eight-Mile Lake investigated how permafrost-induced redox shifts govern the mobility of iron oxide and their co-transport of phosphorus and organic carbon from profile to landscape scale. Together, their findings helped us understand the pathways by which altered redox conditions impact nutrient lift and downslope transfer.

Part 4: Recommendations

In order to improve our understanding of how permafrost thaw impacts nutrient mobility and carbon dynamics, we are suggesting three targeted research priorities:

First, river and soil monitoring must run seamlessly from the onset of freeze-up in late autumn through break-up in early spring: shoulder-season flows already convey roughly one-third of the annual dissolved-organic-carbon (DOC) load, yet most observatories still leave a 6- to 8-month blind spot during this period of sustained biogeochemical activity

Second, provided the discharge of the studied first order stream Panguingue Creek can be continuously measured, the consistent inverse relationship between strontium and DOC concentrations can be exploited as a proxy for providing accurate soil DOC export via rivers and its evolution with permafrost thaw.

Third, emerging techniques that constrain the key soil-hydrological parameters controlling talik flushing are essential for determining when and how newly forming taliks deliver soil-derived DOC to rivers, a process with outsized implications for the timing and magnitude of carbon export under amplified global warming. Together, these measures provide the observational backbone needed to integrate winter processes, small-catchment dynamics and subsurface flow paths into next-generation Earth-system models.

5. DISSEMINATION AND VALORISATION

Participation to scientific conferences

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Media and outreach

- Fev 2025 - Danse, roches & permafrost – Les Temps Vécus, conférence avec l'artiste en résidence Louise Vanneste au Centre culturel du Brabant wallon (15/02/25)
- Dec 2024 - Quel Temps pour la planète, RTBF, interview en direct sur le pergélisol et ses émissions de carbone (17/12/24)
- Dec 2024 - Gérer et protéger les sols passe par la recherche, Journée mondiale des sols
- Nov 2024 - "Arctique, quand le sol dégèle sous tes pieds", conférence grand public au café citoyen Le Six Heures
- Nov 2024 - La rencontre de la géologie et de la danse, bord de scène avec l'artiste en résidence Louise Vanneste au théâtre Le Vilar (28/11/24)
- Nov 2024 - Lauréate du prix du Public des Trophées de Vulgarisation Scientifique de Matière Grise (bande annonce; interview; article Paris Match 28 novembre 2024)
- Nov 2024 - NoTélé – Zone franche, interview of M. Villani on permafrost
- Nov 2024 - Les Visages de la Recherche, émission sur LN24, interview par Pascal Vrebos
- Sept 2024 - Podcast WiseNight, Femmes et Sciences en Belgique, projet visant à encourager les femmes à s'engager dans des études STEM (science, technology, engineering, and mathematics)
- Sept 2024 - Exposition photos WiseNight, photographe Michiel Devijver: portraits de scientifiques
- June 2024 - Article dans La Libre et dans la DHnet sur la mission de terrain menée en février-mars 2024 en Alaska en collaboration avec IMAQA
- May 2024 - Exposition photo au MuséeL "Arctique en transition", Journée européenne des musées, en dialogue avec des gravures de G. Marchoul
- April 2024 - LIMIT (YouTube) - Le géant endormi - Interview of S. Opfergelt by V. Kanté
- March 2024 - Printemps des Sciences, conference, "Arctique : quand le sol dégèle sous tes pieds "
- March 2024 - Soirée inaugurale du Printemps des Sciences, table-ronde, 20 000 lieues sous les terres
- Feb 2024 - Exposition photo à la maison culturelle Jonniaux "Arctique en transition", Pommeroeul, Belgium (reportage)
- Jan 2024 - Interview in the letter from the "Plateforme wallone pour le GIEC" about permafrost
- Oct 2023 - Reportage about fieldwork in Alaska (Daily science article ; Le Soir web article ; La Libre Belgique web article ; L'Avenir article print ; La Dernière Heure web article ; Sud Info ; RTL Info web article ; interview RTBF Matin Première)

6. PUBLICATIONS

Publications directly related to the Work Packages of LIFTHAW

- Roux P., Lemarchand D., Schuur E., Opfergelt S., *submitted to Applied Geochemistry,* Tracing nutrient uplift from permafrost thaw using radiogenic Sr isotopes in plants: a field-based soil warming experiment. ***(Paper 1 related to Work Package 1 and 2)***

- Roux P., Hirst C., Villani M., du Bois d'Aische E., Osy C., Schuur E., & Opfergelt S., *to be submitted to Chemical Geology,* From Soils to Rivers: Radiogenic Sr isotopes Reveal Extended Seasonal Windows of Soil-River Dissolved Organic Carbon Transfer in an Arctic Permafrost Catchment. ***(Paper 2 related to Work Package 3)***

- Roux et al., *in prep,* Publication on the seasonal evolution of taliks. ***(Paper 3 related to Work Package 2 and 3)***

- Villani et al. *in prep,* Publication in preparation on the biogeochemical connectivity of taliks in winter. ***(Paper 4 related to Work Package 3)***

Publications in collaboration related to the topic of LIFTHAW

- Strauss J., Fuchs M., Hugelius G., Miesner F., Nitze I., Opfergelt S., Schuur E., Treat C., Turetsky M., Yang Y., and Grosse G. Organic matter storage and vulnerability in the permafrost domain. *Encyclopedia of Quaternary Science,* 2025, 3rd Edition, p. 399-410, doi: 10.1016/b978-0-323-99931-1.00164-1. ***(related to Work Package 1)***

- Opfergelt, Sophie, Gaspard, François, Hirst, Catherine, Monin, Laurence, Juhls, Bennet, Morgenstern, Anne, Angelopoulos, Michael & Overduin, Pier Paul (2024). Frazil ice changes winter biogeochemical processes in the Lena River. *Communications Earth & Environment*, *5*, doi :10.1038/ s43247-024-01884-9. ***(related to Work Package 3)***

- Villani M., Hirst C., du Bois d'Aische E., Thomas M., Lundin E., Giesler R., Mörth C.-M ., Opfergelt S. Lengthening of biogeochemical processes during winter in degraded permafrost soils. Geochemical Perspectives Letters, 2025, 34:36-42. doi.org/10.7185/geochemlet.2511 ***(related to Work Package 2)***

- Burn, Christopher R., Bartsch, Annett, Chakraborty, Elora, Das, Soumik, Frauenfelder, Regula, Gärtner-Roer, Isabelle, Gisnås, Kjersti G., Herring, Teddi, Jones, Benjamin M., Kokelj, Steven V., Langer, Moritz, Lathrop, Emma, Murton, Julian B., Nielsen, David M., Niu, Fujun, Olson, Christine, O'Neill, H. Brendan, Opfergelt, Sophie, Overduin, Pier Paul, Schaefer, Kevin, Schuur, Edward A. G., Skierszkan, Elliott, Smith, Sharon L., Stuenzi, Simone M., Tank, Suzanne E., van der Sluijs, Jurjen, Vieira, Gonçalo, Westermann, Sebastian, Wolfe, Stephen A. & Yarmak, Ed (2024). Developments in Permafrost Science and Engineering in Response to Climate Warming in Circumpolar and High Mountain Regions, 2019–2024. *Permafrost and Periglacial Processes*, doi :10.1002/ppp.2261 ***(related to Work Package 1 and 2)***

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- du Bois d'Aische E., Jonard F., Hirst C., Villani M., Thomas M., Giesler R., Morth C.M., Lundin E., Van Oost K., Vanacker V., Lambot S., Opfergelt S. Permafrost thaw drives iron and organic carbon release into soil pore water during palsa to degraded palsa transition. Permafr. Periglac. Process., in review ***(related to Work Package 1 and 2)***

<u>Master thesis related to LIFTHAW</u>

- Léa Godefroid - Variabilité spatiale des taliks et leur influence sur la mobilité des nutriments : Approche de traçage avec les isotopes du strontium ***(related to Work Package 1 & 2)***

- Adèle Vandestrate - The impact of thawing permafrost on iron mobility in arctic soils: a strontium isotopic approach ***(related to Work Package 2 & 3)***

- Nicolas Sandron - Influence des dégradations thermokarstiques de plaine sur les interactions fer-carbone organique ***(related to Work Package 2 & 3)***

- Djim Verleene - Identification et facteurs de formation des taliks dans le pergélisol : combinaison de méthodes géophysiques et de télédétection à très haute résolution ***(related to Work Package 2 & 3)***

- Mélinda Afram - Tracing changes in redox conditions in thawing permafrost with Ce anomalies: implications for iron-organic carbon interactions ***(related to Work Package 2 & 3)***

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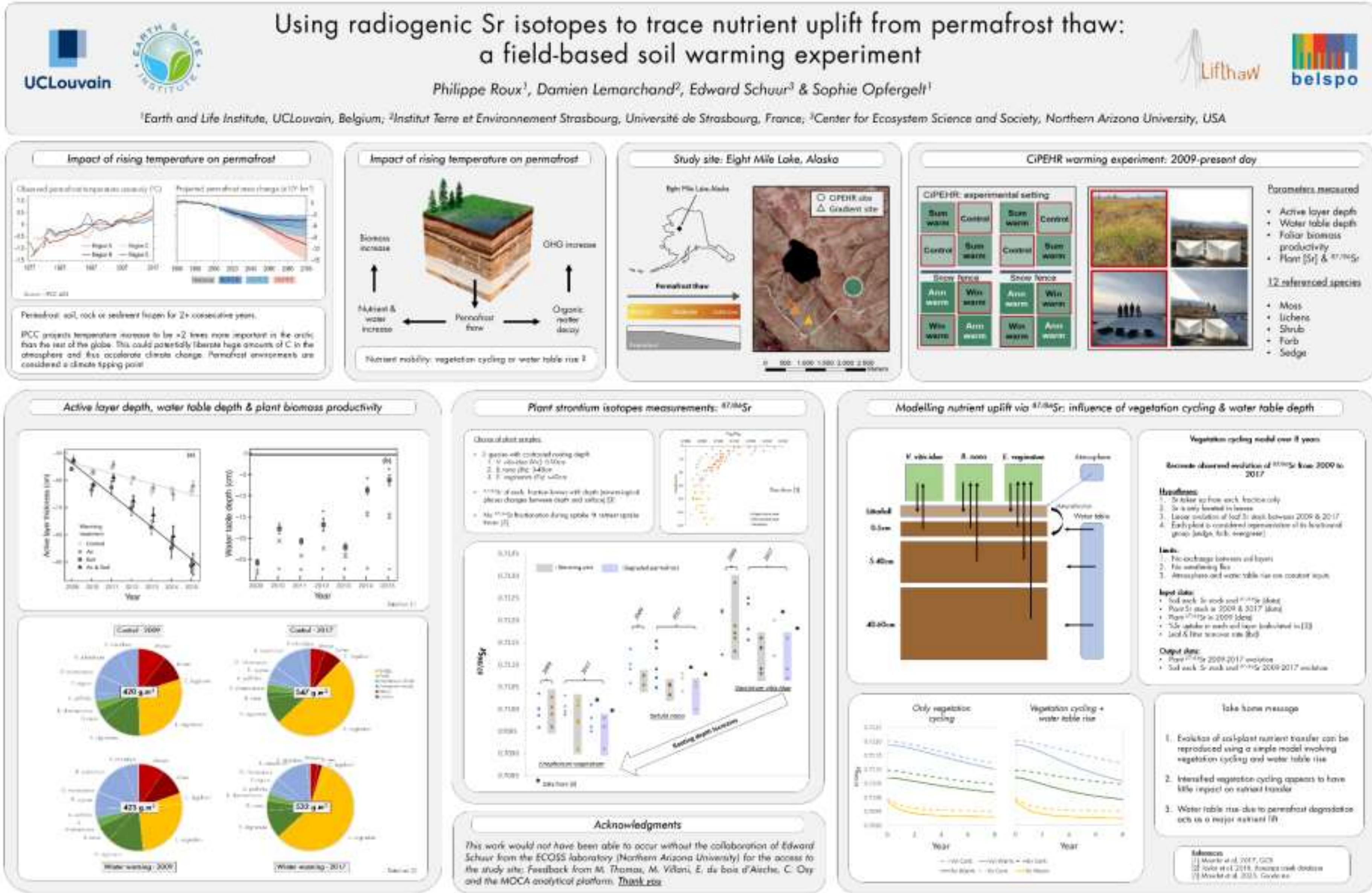
Annexe 1
EGU 2024 poster (next page)



UCLouvain
Using radiogenic Sr isotopes to trace nutrient uplift from permafrost thaw: a field-based soil warming experiment
Lifthaw
belspo
Philippe Roux[1], Damien Lemarchand[2], Edward Schuur[3] & Sophie Opfergelt[1]
[1]Earth and Life Institute, UCLouvain, Belgium; [2]Institut Terre et Environnement Strasbourg, Université de Strasbourg, France; [3]Center for Ecosystem Science and Society, Northern Arizona University, USA
Impact of rising temperature on permafrost
Permafrost: soil, rock or sediment frozen for 2+ consecutive years.
IPCC projects temperature increase to be ×2 times more important in the arctic than the rest of the globe. This could potentially liberate huge amounts of C in the atmosphere and thus accelerate climate change. Permafrost environments are considered a climate tipping point
Impact of rising temperature on permafrost
Biomass increase
GHG increase
Nutrient & water increase
Permafrost thaw
Organic matter decay
Nutrient mobility: vegetation cycling or water table rise ?
Study site: Eight Mile Lake, Alaska
CiPEHR site
Gradient site
Permafrost thaw
CiPEHR warming experiment: 2009-present day
CiPEHR: experimental setting
Sum warm
Control
Snow fence
Win warm
Ann warm
Parameters measured
Active layer depth
Water table depth
Foliar biomass productivity
12 referenced species
Moss
Lichens
Shrub
Forb
Sedge
Active layer depth, water table depth & plant biomass productivity
Year
Control - 2009
Control - 2017
420 g.m²
547 g.m²
425 g.m²
532 g.m²
Winter warming - 2009
Winter warming - 2017
Plant strontium isotopes measurements: ⁸⁷/⁸⁶Sr
Rooting depth horizons
Acknowledgments
This work would not have been able to occur without the collaboration of Edward Schuur from the ECOSS laboratory (Northern Arizona University) for the access to the study site; Feedback from M. Thomas, M. Villani, E. du bois d'Aische, C. Ory and the MOCA analytical platform. Thank you
Modelling nutrient uplift via ⁸⁷/⁸⁶Sr: influence of vegetation cycling & water table depth
Atmosphere
Water table
Vegetation cycling model over 8 years
Only vegetation cycling
Vegetation cycling + water table rise
Year
Take home message
1. Evolution of soil-plant nutrient transfer can be reproduced using a simple model involving vegetation cycling and water table rise
2. Intensified vegetation cycling appears to have little impact on nutrient transfer
3. Water table rise due to permafrost degradation acts as a major nutrient lift

Annexe 2 - Publication 1

Abstract

Permafrost thaw in Arctic ecosystems is altering soil structure and hydrology, deepening the active layer and increasing the availability of nutrients previously locked in frozen ground. These changes contribute to the current trend of increased plant productivity and shifts in species composition. Because arctic plant functional types have specific nutrient acquisition strategies due to differing rooting depths, it is therefore essential to identify the mechanisms responsible for changes in nutrient sources during permafrost degradation. The aim of this study is to quantify the contribution of biocycling, through litter turnover rate and water table rise on nutrient sources available to four major plant functional types upon permafrost thaw. To do so, we developed a model based on an eight-year soil warming experiment on the Eight Mile Lake study site in Interior Alaska. This model combines vegetation composition survey, water table depth data with foliar strontium (Sr) concentrations and isotopic composition ($^{87}Sr/^{86}Sr$) to simulate Sr transfer in the soil-plant system. Our results show that biocycling alone is sufficient to explain the isotopic shift under control conditions for all four plants. However, despite a faster litter turnover rate, the isotopic shift under soil warming conditions requires a 56-90% contribution from water table rise, thus highlighting the dominant role of hydrological changes in nutrient redistribution. While permafrost thaw is a key source of newly available nutrients, the faster uplift of deeper nutrient pools by water table may have a stronger influence on plant nutrient access than gradual biocycling processes.

Annexe 3 - Master Thesis Léa Godefroid

Variabilité spatiale des taliks et leur influence sur la mobilité des nutriments

Approche de traçage avec les isotopes du strontium

Léa Godefroid

Le pergélisol constitue l'un des plus vastes réservoirs de carbone organique de la planète. Sous l'effet du réchauffement climatique, il subit une dégradation progressive qui entraine la formation croissante de taliks — zones du sol qui restent dégelées toute l'année. Ces taliks modifient la dynamique thermique, hydrologique et chimique du sol. Leur fréquence, en forte augmentation, représente une évolution majeure des environnements périglaciaires, avec des conséquences encore peu étudiées sur le cycle du carbone, la chimie de l'eau et la végétation.

Ce mémoire s'intéresse à la compréhension du fonctionnement interne des taliks, en lien avec leur niveau de dégradation, et à l'impact qu'ils peuvent avoir sur la circulation des éléments contenus dans l'eau, la disponibilité des nutriments, et la redistribution du carbone dans les sols. Pour cela, des prélèvements ont été réalisés sur quatre profils de taliks situés en Alaska, avec un gradient de dégradation du moins au plus avancé. Des échantillons d'eau ont été collectés en surface, dans les taliks, et à différentes profondeurs, à deux saisons (hiver et été). Les paramètres mesurés incluent le pH, la concentration en carbone organique dissous (COD), en strontium (Sr), le ratio isotopique radiogénique $^{87}Sr/^{86}Sr$ ainsi que des concentrations en éléments nutritifs pour la végétation (N, Ca, Mg, K, P, B).

Les résultats montrent que la présence de taliks favorise la mobilité verticale des éléments, en particulier dans les taliks les plus dégradés. Le strontium radiogénique a permis d'identifier un transfert d'éléments des eaux issues d'horizons supérieurs vers les couches profondes. Les comparaisons entre les données d'hiver et d'été ont mis en avant l'accumulation de nutriments en hiver et leur libération en été, encore plus marquée au sein des taliks fortement dégradés. L'ensemble de ces observations montre que les taliks, loin d'être des zones passives, jouent un rôle actif dans la redistribution des éléments nutritifs et du carbone dans les sols en cours de dégel.

Dans un contexte de réchauffement global, les taliks devraient devenir de plus en plus fréquents, en particulier dans les zones de pergélisol discontinu. Comprendre leur fonctionnement est essentiel pour anticiper les conséquences à long terme de la dégradation du pergélisol sur le climat, l'hydrologie et les écosystèmes arctiques.

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Annexe 4 - Master Thesis Adèle Vandestrate

Impact of thawing permafrost on iron mobility in arctic soils: a strontium isotopic approach

Adèle Vandestrate

Permafrost degradation in arctic regions fundamentally impacts climate change by exposing vast stocks of organic carbon (OC) to microbial decomposition, thereby amplifying greenhouse gas emissions. Iron (Fe) dynamics play a significant role in stabilising OC through the formation of Fe-OC interactions. However, the mechanisms governing Fe mobility during permafrost thaw still need to be better understood in order to predict arctic carbon feedback under warming climate.

In this study, we demonstrate that strontium isotope ratios ($^{87}Sr/^{86}Sr$) effectively trace Fe mobilisation in thawing permafrost soils at Eight Mile Lake in Alaska. Under waterlogged conditions resulting from permafrost thaw, we observed increased Fe mobilization from deeper layers via reductive dissolution. This mobilised Fe migrates upwards with the rising water table and eventually reaches oxic zones, where it co-precipitates with dissolved OC to form a 'rusty carbon sink'. We observed these sinks at the surface and at a depth of 30 cm, the latter corresponds to an oxic zone created by an oxic groundwater influx. Although Fe-OC associations accumulate in this oxic zone, they progressively dissolve as redox conditions shift towards more reducing states.

Our findings challenge the assumption that Fe-OC interactions provide long-term carbon stabilisation in thawing permafrost. Instead, we present evidence that these “rusty sinks” may act as transient reservoirs that dissolve periodically under reducing conditions, releasing previously sequestered OC for microbial mineralisation into CO_2 or CH_4.

These insights highlight the importance of studying seasonal variations in Fe mobility in order to accurately incorporate Fe dynamics into arctic carbon models and improve projections of climate feedback.

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Annexe 5 - Publication 2

Abstract

Arctic permafrost contains ~50% of global soil carbon stocks, yet seasonal dynamics of soil-to-river carbon transfer remain poorly understood. We used strontium isotopes ($^{87}Sr/^{86}Sr$), water isotopes ($\delta^{18}O$ & δD), dissolved organic carbon (DOC), and iron (Fe) concentrations to investigate soil-river connectivity across four hydrological periods in Panguingue Creek, Alaska: spring ice break-up, summer thaw, autumn freeze-up, and winter under-ice flow.

DOC varied from 0.5-28 mg L^{-1}, peaking during break-up. Unexpectedly, $^{87}Sr/^{86}Sr$ revealed a consistent soil signature (0.7122 ± 0.0001) across all seasons, leading us to hypothesize that DOC mobilization occurs via iron oxide colloids from surface organic horizons rather than progressively deeper thaw layers. Soil contributions reached 67% during spring break-up and 76% during autumn freeze-up.

Critically, soil-river connectivity extended well beyond traditional monitoring periods: contributions persisted 30+ days past typical late-season cutoffs (20% in late October) and appeared before complete ice break-up (30%). This extended mobilization indicates current Arctic carbon flux estimates significantly underestimate annual DOC export.

As climate warming lengthens shoulder seasons, these previously unaccounted export windows will expand, accelerating permafrost carbon release. We observed complete soil-river disconnection in winter, but with increasing permafrost degradation, talik formation could enable continuous carbon mobilization throughout the year. First-order Arctic rivers require year-round monitoring as their direct connection to permafrost soils enables early detection of changes in soil-to-river transfer dynamics under rapid climate change.

Annexe 6 - Master Thesis Djim Verleene

Identification et facteurs de formation des taliks dans le pergélisol : combinaison de méthodes géophysiques et de télédétection à très haute résolution

Cas d'étude à Eight Mile Lake (Alaska, États-Unis)

Djim Verleene

Dans l'hémisphère Nord, les environnements reposant sur du pergélisol couvrent environ 25 % des terres émergées. Le pergélisol constitue un puits de carbone majeur en raison de la quantité significative de matière organique gelée qu'il renferme, estimée à environ 1 700 milliards de tonnes de carbone – soit près du double de la quantité actuellement présente dans l'atmosphère. Pourtant, depuis la fin du XX^{e} siècle, l'Arctique s'est réchauffé près de quatre fois plus vite que la moyenne mondiale sous l'effet du changement climatique. Ce réchauffement rapide entraine le dégel du pergélisol, provoquant la libération de carbone anciennement stocké dans les sols gelés. Cette libération alimente une boucle de rétroaction positive du cycle du carbone, qui accentue le dégel du pergélisol et accroit les émissions associées.

L'un des principaux mécanismes induits par le dégel du pergélisol est l'épaississement de la couche active, accompagné de l'apparition de taliks – des zones de sol non gelées qui persistent durant l'hiver. Ces taliks représentent un enjeu majeur principalement en raison de leurs émissions de carbone hivernales – non prises en compte dans les modèles climatiques actuels – ainsi que de leur influence sur la mobilisation et le transport du carbone par l'eau non gelée.

Ce mémoire s'est intéressé à l'identification et à l'étude de taliks sur un site situé en Alaska, en s'appuyant sur une approche combinée intégrant des méthodes géophysiques, de télédétection à très haute résolution et de mesures *in situ*. Les résultats mettent en évidence (i) la présence de taliks sur le site, et leur potentielle connectivité hydraulique, (ii) une forte corrélation entre la présence de taliks et de structures hydrologiques de type *watertrack*, et (iii) le rôle dominant du manteau neigeux dans les transferts de chaleur dans le sol, susceptible de favoriser l'apparition et la persistance des taliks.

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Annexe 7 - Master Thesis Nicolas Sandron

Influence des dégradations thermokarstiques de plaine sur les interactions fer-carbone organique

Expérience de réchauffement (CiPEHR), Alaska

Nicolas Sandron

Le réchauffement climatique accélère le dégel du pergélisol arctique, qui couvre environ 21 millions de km² dans l'hémisphère nord et contient entre 1460 et 1600 milliards de tonnes de carbone organique (OC), libérant potentiellement d'importantes quantités de ce carbone dans l'atmosphère. Les interactions entre le OC et les minéraux du sol, notamment les oxydes de fer (Fe), jouent un rôle déterminant dans la stabilisation du OC. Pourtant, la manière dont ces interactions évoluent en contexte de dégradations thermokarstiques reste mal connue. Ce travail évalue l'influence de ces dégradations sur les interactions Fe–OC dans une tourbière arctique soumise à un réchauffement expérimental (projet CiPEHR, Alaska). Les résultats montrent que : (i) la complexation constitue le principal mécanisme d'interactions organo-minérales, avec 17 ± 8 % du OC total sous forme complexée, suivi marginalement par les associations des oxydes de Fe peu cristallins (0,8 ± 2,9 % du OC total) ; (ii) le Fe complexé représente la proportion majoritaire (69 ± 18 %) du fer total ; (iii) le Fe s'accumule préférentiellement à l'interface redox, contrôlée par la nappe phréatique, reflétant une dynamique de redistribution du Fe liée au régime hydrique ; (iv) sur 13 années, le réchauffement expérimental a provoqué un approfondissement de la couche active de 126 cm, anticipant d'environ cinq années l'effet du réchauffement naturel ; (v) ce réchauffement expérimental ne semble pas pour autant altérer les stocks totaux de Fe du sol. Ces résultats appellent à un suivi temporel renforcé sur le site de CiPEHR et soulignent la nécessité d'intégrer ces mécanismes d'interactions organo-minérales dans les modèles globaux de rétroaction climat–carbone.

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Annexe 8 - Master Thesis Mélinda Afram

Tracing changes in redox conditions in thawing permafrost with Ce anomalies: implications for iron-organic carbon interactions

Afram Mélinda

The periglacial environment is severely affected by climate change, particularly in terms of soil conditions. Permafrost is soil that stays frozen for at least two consecutive years and acts as a massive carbon reservoir. It is gradually thawing and releasing elements such as carbon and iron into the active layer, which is the soil layer between permafrost and the surface. This released carbon can be emitted into the atmosphere as greenhouse gases, which in turn amplify climate change through a positive feedback loop. For this reason, it is crucial to study the behavior of carbon in permafrost soils, especially the associations between carbon and iron, as iron has the ability to stabilize carbon in both solid and aqueous soil phases. It is also important to investigate soil redox conditions, which notably influence the formation of these carbon-iron associations. Measuring redox potential in soil solutions can be challenging due to the extreme climatic conditions of subarctic and polar regions. Therefore, a potential redox proxy is being explored: cerium anomalies. Cerium is one of the Rare Earth Elements (REE) and cerium anomales are sensitive to redox conditions. A field campaign was conducted during the late shoulder season near Eightmile Lake, Alaska, USA, to collect soil pore water along a Gradient Site representing a permafrost degradation gradient. Measurements included soil temperature, soil water content, redox potential, along with soil solution conductivity, pH, and concentrations of dissolved organic carbon (DOC), Fe, and REE, which were measured in soil pore waters. Results showed that (i) Redox conditions vary significantly throughout the season and with depth, enabling the identification of redox interfaces; (ii) Associations between iron and DOC appears mainly as organo-metallic complexes, with a large portion of dissolved free Fe in soil pore waters; (iii) Cerium anomalies were very weak or absent, and were not influenced by redox conditions, indicating that redox changes observed during the season did not reflect any anomalies in cerium.

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Annexe 9
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