Stockholm, 31-10-2019

Re.: Revised version of manuscript BG-2019-89

Dear Associate Editor,

I have uploaded the revised version of the manuscript as a word file of the main text, with all changes highlighted in track changes (including tables and figures), as well as a pdf of the revised supplement.

I believe we have addressed all concerns made in the reviews and the one interactive comment that we suggested in our Author's response.

There were some technical/formatting changes requested by the reviewers, most significantly:

1) To remove Figure 2, because these regressions were also included in Figure 3, etc
2) To prepare a Table S2 for Supplementary Materials that summarizes landscape representation in each experiment/study area
3) To move paragraphs in results to methods, particularly the ones explaining the division of the datasets into landscape classes (and their subdivisions in the PAGE21 experiment)
4) To add number of samples (and, in some cases, legends) in the Figures

As for the text, following the main concerns raised in the reviews, the most important changes are:

5) Expanded method description for the CryoCarb experiment
6) Expanded discussion

Detailed summary of most important changes:

Line 3:	Added co-author
L54-58	Added statements
L182-183	Added statement
L195-234	Additional details for CryoCarb experiment
L285-287	Added Table S2
L288-299	From results to methods
L317-327	From results to methods
L352 + L362	Added number of samples for each regression
L385	Removed Figure 2
L540	Small error in slope value for PAGE21 Pt, corrected 0.20 to 0.24, 0.14 to 0.17
L691-698 + L708-749	Added discussion paragraphs
L840+	Added references
Figures 2, S3-S5	Added number of samples
Figures 3 and 4	Added legends and number of samples, Change in symbol and color regression line in Fig. 3d

We hope you find these revisions adequate.

Kind regards, Peter Kuhry

Lability classification of soil organic matter in the northern permafrost region

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Abstract

The large stocks of soil organic carbon (SOC) in soils and deposits of the northern permafrost region are sensitive to global warming and permafrost thawing. The potential release of this carbon (C) as greenhouse gases to the atmosphere does not only depend on the total quantity of soil organic matter (SOM) affected by warming and thawing, but also on its lability (i.e. the rate at which it will decay). In this study we develop a simple and robust classification scheme of SOM lability for the main types of soils and deposits ~~of~~ in the northern permafrost region. The classification is based on widely available soil geochemical parameters and landscape unit classes, which makes it useful for upscaling to the entire northern permafrost region. We have analyzed the relationship between C content and C-CO_2 production rates of soil samples in two different types of laboratory incubation experiment. In one experiment, c. 240 soil samples from four study areas were incubated using the same protocol (at 5 °C, aerobically) over a period of one year. Here we present C release rates measured on day 343 of incubation. These long-term results are compared to those obtained from short-term incubations of c. 1000 samples (at 12 °C, aerobically) from an additional three study areas. In these experiments, C-CO_2 production rates were measured over the first four days of incubation. We have focused our analyses on the relationship between C-CO_2 production per gram dry weight per day (µgC-CO_2 gdw^{-1} d^{-1}) and C content (%C of dry weight) in the samples, but show that relationships are consistent when using C/N ratios or different production units such as µgC per gram soil C per day (µgC-CO_2 gC^{-1} d^{-1}) or per $cm^3$of soil per day (µgC-CO_2 cm^{-3}~~$^{-1}$~~ d^{-1}). C content of the samples is positively correlated to C-CO_2 production rates but explains less than 50 % of the observed variability when the full datasets are considered. A partitioning of the data into landscape units greatly reduces variance and provides consistent results between incubation experiments. These results indicate that relative SOM lability decreases in the order: Late Holocene eolian deposits > alluvial deposits and mineral ~~upland~~ soils (including peaty wetlands) > Pleistocene Yedoma deposits > C-enriched pockets in cryoturbated soils > peat deposits. Thus, three of the most important SOC storage classes in the northern permafrost region (Yedoma, cryoturbated soils and peatlands) show low relative SOM lability. Previous research has suggested that SOM in these pools is relatively undecomposed and the reasons for the observed ~~resistance to~~low rates of decomposition in our

experiments need~~s~~ urgent attention if we want to better constrain the magnitude of the thawing permafrost carbon feedback on global warming.

1. Introduction

Permafrost has been recognized as one of the vulnerable carbon (C) pools in the Earth System (Gruber et al., 2004). A recent report of the International Panel on Climate Change (IPCC, 2018) identifies the thawing permafrost carbon-climate feedback as one of the key uncertainties when assessing global emission targets to keep global warming under 1.5 (2) °C. Furthermore, the urgency of additional research is highlighted by the fact that most permafrost in the northern circumpolar region has already experienced warming in recent decades (Biskaborn et al., 2019).

In the ~~most recent~~last decade there has been a surge in papers dealing with the permafrost carbon feedback on climate change (e.g. Schuur et al., 2008; Kuhry et al., 2010). This increased interest was fueled by a new and high estimate of the total soil organic carbon (SOC) storage in the northern permafrost region (Tarnocai et al., 2009), which was received with great interest by the Earth System Science community (e.g., Ciais, 2009). Since this first new estimate was published, a multitude of new SOC inventories at the landscape level have been conducted across the Circumpolar North (e.g. Hugelius and Kuhry, 2009; Hugelius et al., 2010; Horwath Burnham and Sletten, 2010; Palmtag et al., 2015; Gentsch et al., 2015a; Siewert et al., 2016). Recent studies have also focused on re-evaluating the spatial extent and SOC storage of the Yedoma ‘Ice Complex’ and Alas deposits (Strauss et al., 2013; Walter-Anthony et al., 2014; Hugelius et al., 2016; Shmelev et al., 2017).

This new data has prompted an update of the total SOC storage in the northern permafrost region, its vertical partitioning and its broad (continental scale) distribution (Hugelius et al., 2014). The new estimate amounts to c. 1400 PgC for the top 3 m of soils and deeper deposits, including permafrost and non-permafrost organic soils (Histels/Histosols, 302 PgC), cryoturbated permafrost mineral soils (Turbels, 476 PgC), non-cryoturbated permafrost mineral soils (Orthels) and non-permafrost mineral soils (256 PgC), and deeper Yedoma (301 PgC, >300 cm) and Delta (91 PgC, >300 cm) deposits. The spatial distribution of SOC stocks according to the major permafrost soil (Gelisol) suborders, non-permafrost mineral soils and Histosols (Soil Survey Staff, 2010) is graphically represented in the updated version of the Northern Circumpolar Soil Carbon Database (NCSCDv2, 2014).

The importance of an accurate estimate of total SOC storage in the northern permafrost region is illustrated by a recent review of the permafrost carbon feedback (Schuur et al., 2015), which included a comparison of future C release in a total of eight Earth System models~~ (ESMs)~~. The magnitude of the projected cumulative C loss from ~~thawing ~~the permafrost region by 2100, largely based on the RCP 8.5 scenario (IPCC, 2013), varied greatly between models from 37 to 174 PgC. However, by normalizing for the initial ~~permafrost ~~C pool size in the different models~~ESMs~~, the proportional C loss from the permafrost zone was constrained to a much narrower range of 15 ± 3 % of the initial pool. This indicates that the quantity of SOC is a primary control when assessing C losses from the northern permafrost region.

The magnitude of the permafrost carbon feedback, however, will not only depend on the rate of future global warming (and its polar amplification), its effect on gradual and abrupt permafrost thawing (Grosse et al., 2011), or the total size (and vertical distribution) of the permafrost SOC pool. As shown by Burke et al. (2012), based on simulations with the Hadley Centre climate model, quality (decomposability) parameters need also to be considered. Thus, in terms of C pool parameters, the potential C release from the northern permafrost region will depend not only on SOC quantity but also on soil organic matter lability (i.e. the rate at which SOM will decay following warming and thawing). An important tool to assess potential C release from permafrost soils and deposits are laboratory incubation experiments that consider both different types of substrate (e.g., Schädel et al., 20132014) and time of incubation (e.g. Elberling et al., 2013).

The aim of this study is to add a measure of SOM lability to the current estimates of SOC quantity, in order to define vulnerable C pools across the northern circumpolar region. We focus on the relationship between solid phase geochemical parameters (particularly C content) and C release rates in laboratory incubations of active layer and thawed permafrost samples from the main types of soils and deposits found in the northern permafrost region. Our objective is to develop a SOM lability classification scheme based on widely reported soil geochemical parameters in field SOC inventories and general landscape classes, that can be linked to existing spatial SOC databases such as the NCSCD (Tarnocai et al., 2009; Harden et al., 2012; Hugelius et al., 2014). We test the robustness of our SOM lability classification by comparing two very different types of incubation experiment, both in setup as well as timing of C release measurements.

2. Materials and methods

2.1. Study areas

The samples used in the incubation experiments were collected as part of landscape-level inventories carried out in the context of the EU PAGE21 and ESF CryoCarb projects to assess total storage, landscape partitioning and vertical distribution of SOC stocks in study areas across the northern permafrost region. SOC storage data from these areas are presented in Weiss et al. (2017) for Svalbard, Siewert et al. (2016) for Lena Delta, Palmtag et al. (2016) for Taymyr Peninsula, Palmtag et al. (2015) for Lower Kolyma, Hugelius et al. (2011) for Seida, and Siewert (2018) for Stordalen Mire. The location of all study areas is shown in Figure 1. The Lower Kolyma experiment includes samples from two nearby located study areas (Shalaurovo and Cherskiy); the Taymyr Peninsula experiment also includes samples from two nearby located study areas (Ary-Mas and Logata). Metadata for each of these areas, including geographic coordinates, permafrost and vegetation zones, climate parameters, number of soil profiles and incubated samples, type of incubation experiment, and time of field collection, are presented in Table S1 (Supplementary Materials).

Figure 1. Location of study areas in northern Eurasia. PAGE21 experiment (Ny Ålesund, Adventdalen, Stordalen Mire, Lena Delta); CryoCarb 1-Kolyma experiment (Shalaurovo, Cherskiy); CryoCarb 2-Taymyr experiment (Ary-Mas, Logata); CryoCarb 3-Seida experiment. Permafrost zones according to Brown et al. (1997).

2.2. Field methods

The sampling strategy applied for SOC field inventories was aimed at capturing all major landscape units in each of the study areas, while at the same time ensuring an unbiased selection of soil profile location. This semi-random sampling approach consisted of deciding on the positioning of generally 1 or 2 km long transects that crossed all major landscape units, with a strictly equidistant sampling interval at normally 100 or 200 m that eliminated any subjective criteria for the exact location of each soil profile. For SOC storage calculations, the mean storage in each landscape unit class was weighed by its proportional representation in the study area based on remote sensing land cover classifications.

At each soil profile site, the topsoil organic layer was collected by cutting out blocks of known volume in three random replicates to account for spatial variability. These samples do not always strictly adhere to the definition of an 'O' soil genetic horizon, because in areas with thin topsoil organics (like in floodplains and mountain terrain) there can be a large admixture of minerogenic material resulting in C contents of less than 12 %. Active layer samples were collected from excavated pits by horizontally inserting fixed-volume cylinders. The permafrost layer was sampled by hammering a steel pipe of known diameter incrementally into the ground, retrieving intact samples for each depth interval. Depths intervals are normally 5 to 10 cm or less (e.g., when the topsoil organic layer was very thin). The standard sampling depth was to 1 m below the soil surface; at some sites it was not possible to reach this depth due to large stones in the soil matrix or thin soil overlying bedrock (often in mountainous settings).

2.3. Incubation experiments

2.3.1. The PAGE21 incubation experiment

The PAGE21 incubation experiment was carried out at the University of Copenhagen (Denmark). This experiment included one sample from the topsoil organics, one sample from the middle of the active layer and one sample from the upper permafrost layer (normally 10-15 cm below the upper permafrost table) from all mineral soil profiles collected in three of the PAGE21 study areas (Ny Ålesund, Adventdalen and Lena Delta). Samples were selected based on depth criteria and not any specific soil characteristic (e.g., presence of C-enriched cryoturbated material or absence of excess ground ice). In some cases, upper permafrost samples could not be collected due to very deep active layers and/or thin soils (particularly in mountain settings). Peat samples are available from a fourth PAGE21 study area (Stordalen Mire). In total c. 240 soil samples from four study areas across the northern permafrost region (Ny Ålesund and Adventdalen, Svalbard; Stordalen Mire, N Sweden; Lena Delta, N Siberia) were incubated in one and the same experiment (Faucherre et al., 2018).

The Dry Bulk Density (DBD) of samples used for incubation was measured at Stockholm University (Sweden). The %C and %N of dry weight of the incubated samples were measured in an elemental analyzer (EA Flash 2000, Thermo Scientific, Bremen, Germany) at the University of Copenhagen (Denmark).

Samples were kept in frozen condition from collection until the start of the laboratory incubation experiment. Samples were incubated at 5 °C and field water content levels (aerobic conditions) over a one-year time period. Mean volumetric water content varied between 30 % (topsoil organics), 45-50 % (active layer and permafrost layer mineral soil) and 69 % (peat). In the original PAGE21 experiment (Faucherre et al., 2018), C-CO_2 production rates were measured at five different occasions between 7 to 343 days after the start of the experiment, using a nondispersive infrared LI-840A CO_2/H_2O Gas analyzer (LICOR® Biosciences). Since all samples from all study areas were processed and incubated using the same protocol, results are directly comparable. ~~Here~~In this study, we use the C release rates ~~after nearly one year~~on day 343 of incubation ~~as a measure of SOM lability~~. These results, therefore, mostly address the 'slow' (Schädel et al., 2014) and 'stable' (Knoblauch et al., 2013) SOM pools, with C cycling typically within a timespan of a (few) decade(s).

2.3.2. The CryoCarb incubation experiments

The CryoCarb incubations were carried out at the University of South Bohemia (Ceske Budovice, Czech Republic). These experiments included all samples from all profiles collected in each of three study areas (CryoCarb 1-Kolyma in NE Siberia; CryoCarb 2-Taymyr in N Siberia; and CryoCarb 3-Seida in NE European Russia). In total c. 1000 samples were incubated.

The Dry Bulk Density (DBD) of samples used for incubation was measured at Stockholm University (Sweden). The %C and %N of dry weight were measured in an EA 1110 Elemental Analyzer (CE Instruments, Milan, Italy) at Stockholm University (Seida samples) and the University of Vienna (Kolyma and Taymyr samples).

The CryoCarb 1-Kolyma and CryoCarb-2 Taymyr samples were stored in a ground pit dug into the active layer for up to two weeks, before further processing. Active layer samples would be little impacted by this storage under ‘natural’ conditions, but (some of) the gradually thawing permafrost layer samples might have experienced initial decay. CryoCarb 3-Seida samples collected in 2009 were kept in frozen storage for c. 10 years (see Table S1), before further processing.

In the laboratory, ~~Collected~~ soil samples were dried at 40-50 °C within two weeks after field sampling (or retrieval from cold storage) and kept in a cold room (at 4 °C) until analyzed. For each sample, 0.2g of dry soil was inoculated with 0.003-0.008g of soil inoculum in 1.6 ml of water (soil:H_2O, 1:100, weight/volume) in 10 ml vacutainers, after which the vacutainers were hermetically closed and the soil slurry was incubated in an orbital shaker at 12 °C for 96 hours. At the end of incubation, CO_2 concentration in the headspace was analyzed using an HP 5890 gas chromatograph (Hewlett-Packard, USA), equipped with a TC detector.

The study area and layer specific composite soil inoculi were prepared from fresh soil taken separately from topsoil organic layer, mineral active layer, peat active layer, mineral permafrost layer and peat permafrost layer, from multiple soil profiles collected in each study area. ~~The~~ F~~f~~resh soil was kept in a cold room (at 4 °C) and then conditioned at 15 °C for one week before inoculum preparation. We consider that the small dry weight of our soil inoculi (which, in turn, have ≤2% microbial biomass) has no significant impact on our C release measurements. The viability of inoculi was checked by incubation in water and measuring its respiration.

The short term C-CO_2 production rates measured i~~I~~n the CryoCarb experiments most likely address the ‘fast’ (Schädel et al., 2014) and ‘labile’ (Knoblauch et al., 2013) SOM pools, which represent a small fraction of the total pool and decompose within a (few) year(s).~~, short term C-CO_2 production rates after rewetting of dried soil samples was used as an indicator of SOM lability.~~ The CryoCarb approach is based on the so-called ‘Birch effect’ (Birch, 1958), showing that after a dry/wet cycle CO_2 mineralization increases. The extra C originates from mineralization of available C released from organo-mineral complexes and dead biomass. In our sample pretreatment with rapid drying at ≤ 50 °C we expect that a larger part of biomass died and decomposed already during this process, which should therefore not severely affect our later measurements. Fierer and Schimel (2003) showed that a substantial part of the released C can also come from microbial biomass which died due to the osmotic shock after rewetting of soil. However, in their case, samples were dried at room temperature resulting in less of a shock in the drying process to the microbial community. Our measurements could have been affected by limitation of C mineralization due to the small size of surviving biomass, which we overcame by inoculation with living cells. The principle of the ‘Birch Effect’ is still used in ecological studies ranging from large scale carbon cycling in ecosystems to detailed studies of SOC availability (e.g. Jarvis et al., 2007). It is well documented that the amount of extra C released after rewetting of dry soil is site and soil type specific and represents an easily available fraction of soil C (e.g. Franzluebbers et al., 2000; Šantrůčková et al., 2006). Due to different sample pretreatment, including duration until ~~drying and~~ incubation experiment, as well as the different ‘local’ soil inoculi used, we consider the CryoCarb incubations of the three different study areas as separate experiments.

2.4. Geochemical parameters and C-CO_2 production rates

As potential explanatory geochemical parameters we have considered dry bulk density (DBD), carbon content (%C of dry weight) and carbon to nitrogen weight ratios (C/N). In this study, we focus on the relationship between %C in samples and the corresponding C-CO_2 production in aerobic incubation experiments. An important practical reason is that %C is most widely available since it can be derived with a high degree of confidence from Elemental Analysis, but also from indirect methods such as loss-on-ignition at 550 °C. However, there are also theoretical considerations for the choice of %C. DBD is expected to be related to quantity and degree of compaction (decomposition) of SOM. However, in the permafrost layer of soils it will also co-vary with the volume of excess ground ice. C/N is a good indicator of degree of SOM decomposition in peat deposits (Kuhry and Vitt, 1996) and tundra upland soils (Ping et al., 2008). Recent soil carbon inventories in permafrost terrain have shown a clear decrease in soil C/N as a function of age/depth (e.g., Hugelius et al., 2010; Palmtag et al., 2015). However, C/N is also sensitive to original botanical composition of the peat/soil litter. In contrast, the %C of plant material is much more narrowly constrained to around 50 % of dry plant matter. For instance, based on data in Vardy et al. (2000), we can calculate a C/N range of 48.5 ± 27.9 (mean and standard deviation) in modern phytomass samples from permafrost peatlands in the Canadian Arctic (n=27) that included vascular plants, mosses and lichens. The corresponding %C range was much narrower at 47.3 ± 5.1. An additional benefit of using %C is that it has a clear 'zero' intercept in regressions against C-CO_2 production per gram dry weight per day (i.e., at zero %C in soil samples we can expect zero C release). This is also the reason why expressing C release as a function of gram dry weight (gdw) is more straightforward than against gram C (gC). The latter would have the benefit of expressing C release directly as a function of C stock, but the relationship is complex with recent studies showing high initial C release rates per gC at low %C values (Weiss et al., 2016; Faucherre et al., 2018). In this study DBD is available for all samples, and we can also express C release as a function of soil volume (cm^3). In the results we primarily show µgC-CO_2 production per gdw per day (µgC-CO_2 gdw^{-1} d^{-1}) as a function of %C in the sample. However, in the Supplementary Materials we also refer to regressions against C/N and C-CO_2 production rates per gC per day (µgC-CO_2 gC^{-1} d^{-1}) or per cm^3 of soil per day (µgC-CO_2 $cm^{3-1\ 3}$ d^{-1}) against %C, to test the robustness of our results.

2.5. Landscape partitioning

We have investigated C-CO_2 production rates for the full datasets as well as for samples grouped into landscape unit classes that can be used for an assessment of vulnerable C pools at northern circumpolar levels. For this purpose, we have subdivided our datasets to reflect the main Gelisol suborders, non-permafrost mineral soils and Histosols recognized in the spatial layers of the NCSCD, as well as deeper Quaternary deposits for which there are separate estimates of spatial extent, depth and SOC stocks (Tarnocai et al., 2009; Strauss et al., 2013; Hugelius et al., 2014). We identify the following landscape classes: peat deposits (Histels, and some Histosols), peaty wetland deposits (mostly Histic Gelisols, peat layer <40 cm deep), mineral soils (Turbels and Orthels, and some non-permafrost mineral soils) in mountain and lowland settings, fluvial/deltaic (alluvial) deposits, and eolian/Pleistocene Yedoma deposits. Special attention is paid to the lability of SOM in Holocene peat deposits, in deeper C-enriched buried layers and cryoturbated pockets, and in Pleistocene Yedoma deposits. All main classes are represented in the PAGE21 and CryoCarb 1-Kolyma incubation experiments. The CryoCarb 2-Taymyr dataset lacks sites with eolian parent materials, whereas the CryoCarb 3-Seida dataset does not include soils formed into either alluvial or eolian deposits. Pleistocene Yedoma deposits are only represented in the CryoCarb 1-Kolyma experiment. We~~, therefore,~~ focus on results from the PAGE21 and CryoCarb 1-Kolyma experiments but present the main results from the two other experiments in the Supplementary Materials. For a full overview of landscape unit class representation in each of the incubation experiments and study areas, see Table S2.

In addition, we have applied a further subdivision of landscape unit classes in the PAGE21 experiment to allow a more detailed statistical analysis of the dataset and assess the role of minerogenic inputs, cryoturbation and peat accumulation in SOM lability. For this purpose, the eolian class is separated into actively accumulating deposits (Adventdalen) and Holocene soils formed into Pleistocene Yedoma parent materials (Lena Delta); Alluvial deposits are subdivided into profiles from active and pre-recent floodplains (multiple study areas); Mineral soils are separated into active colluviation sheets (mountain slopes on Svalbard) and other mineral soils (multiple study areas); Finally, for wetland deposits we discriminate between peat deposits (fens and bogs in Stordalen Mire; >40cm peat) and peaty wetland profiles (multiple study areas, <40 cm peat). It should be stressed that these subclasses are not specifically recognized in any circumpolar SOC database and therefore of limited use for further upscaling. In all cases, SOM lability in samples of deeper C-enriched buried layers and cryoturbated pockets is shown for comparative purposes.

2.6. Statistics

Relationships between C-CO_2 production rates and geochemical parameters for all samples, as well as for groupings of samples into landscape unit classes, for each incubation experiment separately, are statistically analyzed using linear, polynomial and other non-linear regressions in the Microsoft Excel 2010 and Past3 (Hammer et al., 2001) software packages. Regressions are considered significant if $p<0.05$. These analyses visualize SOM lability for full profiles including samples from topsoil organic to mineral layers that have a wide range of DBD, %C and C/N values. In some cases, replicates are not normally distributed (or even unimodal) and statistics should be interpreted with caution. This is particularly the case in peatland profiles, with clusters of samples with low DBD and high %C and C/N in the peat and opposite trends in samples of the underlying mineral subsoil.

To alleviate the issue on non-normal distributions, C-CO_2 production rates in samples as a function of %C are also tested grouped into soil horizons (PAGE21 and CryoCarb 1-Kolyma experiments). This approach yields classes that are much better constrained in terms of %C values. Because data were still not fully normally distributed, non-parametrical Mann-Whitney tests were used (Hammer et al., 2001). The data were log-transformed to reduce skewness in data distributions and to reduce the influence of fractional data. For the mineral soils in the PAGE21 incubation experiment, we differentiated between the topsoil organic layer, the active layer mineral soil, the permafrost layer mineral soil, and C-enriched pockets in both active layer and permafrost layer. Samples from topsoil organic layer, the active layer mineral soil and the permafrost layer mineral soil from profiles formed in Late Holocene loess deposits in Adventdalen (Svalbard) are considered separately, as are the active layer peat samples from Stordalen Mire (N Sweden). A similar grouping has been made for mineral soils in the CryoCarb 1-Kolyma experiment. In this case, Pleistocene Yedoma loess samples (both frozen and thawed) are considered separately. Peat samples are much better represented in the CryoCarb 1-Kolyma than PAGE21 experiment, and are subdivided into samples from thin peat layers in the active layer of peaty wetlands (Histic Gelisols), as well as samples from the active layer and permafrost layer of deep peat deposits (Histels). For this approach, we express C-CO_2 production rates per gC to take into account the large differences in %C among the different soil horizon classes. The tests are run to evaluate null hypotheses regarding differences in SOM lability between soil horizon classes, with a focus on those that are considered typical for specific landscape ~~unit~~ classes (C-enriched pockets for Turbels, peat samples for Histels and loess samples for Pleistocene Yedoma).

3. Results

3.1. Simple geochemical indicators of SOM lability

We first assessed the relationship between C release rates in incubation experiments and widely available physico-chemical parameters in samples from soil carbon inventories carried out throughout the northern permafrost region. The latter include dry bulk density (DBD), C content as a percentage of dry sample weight (%C), and carbon to nitrogen weight ratios (C/N). In recent studies dealing with incubation of soil samples from the northern permafrost region, %C and C/N of soil samples were highlighted as best parameters to predict C release (Elberling et al., 2013; Schädel et al., 20132014). DBD was highlighted as a useful proxy in the recent synthesis of PAGE21 incubation studies presented in Faucherre et al. (2018). All three parameters are significantly (anti-)correlated with each other in the four different incubation experiments (Table 1 and Fig. S1). This can be expected, since organically enriched topsoil samples have low DBD, high %C and high C/N values compared to mineral layer soil samples. Also deeper soil samples, C-enriched through the process of cryoturbation (Bockheim, 2007), have generally relatively low DBD, high %C and high C/N values compared to adjacent mineral soil samples (e.g. Hugelius et al., 2010; Palmtag et al., 2015).

Table 1. R^2 values of cross correlations and number of samples (in brackets) between three geochemical parameters for all samples in the PAGE21 and three CryoCarb incubation experiments (all significant, $p<0.05$). For regression models see Figure. S1.

All three considered geochemical parameters are significantly (anti-)correlated with measured C release rates in the four different incubation experiments. Lower DBD, higher %C and higher C/N values are associated with higher C-CO_2 production per gdw of the samples (Table 2 and Fig. S2). Of the three parameters, DBD explains most of the observed variability in C release in two experiments, whereas C/N shows highest R^2 values in the other two experiments.

Table 2. R^2 values of regressions and number of samples (in brackets) between three geochemical parameters and µgC-CO_2 production per gram dry weight for all samples in the PAGE21 and the three CryoCarb incubation experiments (all significant, $p<0.05$). For regression models see Figure. S2.

3.2. Partitioning of the datasets based on landscape unit classes

Our results show a significant relationship between µgC-CO_2 production per gdw as a function of %C of the soil sample for the full datasets in each of the four incubation experiments (Table 2 and Fig.. S2). However, less than 50 % of the variability is explained by this relationship, which implies that it has limited usefulness to predict C release based on %C of the samples only (Table 2). BothThe experiments show a large range in µgC-CO_2 production per gdwC release, particularly at medium to high %C values. In this section we analyze whether a grouping of samples according to landscape unit classes can disentangle some of the observed variability.

Figure 2 shows the significant relationships between C release rates and %C in the samples for the full datasets grouped according to major landscape unit classes in the PAGE21 (measured on day 343 of incubation) and CryoCarb 1-Kolyma (measured over the first four days of incubation) experiments. For the sake of simplicity, we apply linear regressions with intercept zero to all classes. These are identified by different colors and symbols that have been consistently used in Figs. 2-3 and

S3-S5. The regression for the full data set is provided as reference (dotted lines), but it should be noted that its slope is partly determined by the number of samples in each of the recognized landscape units.

Figure 2. µgC-CO_2 production per gram dry weight as a function of %C of the sample for the full datasets in the (a) PAGE21 (top panel) and (b) CryoCarb 1-Kolyma (lower panel) incubation experiments (both regressions significant, $p<0.05$).

Figure 32. µgC-CO_2 production per gram dry weight as a function of %C of the sample for the full datasets and different landscape classes in the longer-term PAGE21 (a, top panel) and short-term CryoCarb 1-Kolyma (b, lower panel) incubation experiments: All samples (dotted grey lines; Alluvial class (red line and diamonds); Eolian class (blue line and triangles); Mineral class (brown line and squares); Peaty wetland class (dark green line and circles); Peatland class (light green line and circles). All regressions significant, $p<0.05$, except for the PAGE21 peatland class (n.s.).

A first observation is that C release rates per gdw are c. 15 times lower in the longer-term PAGE21 experiment compared to the short-term CryoCarb 1-Kolyma experiment. In the PAGE21 dataset (Fig. 3a2a), the soils developed into alluvial and eolian deposits and in peaty wetlands all show similar and relatively high SOM lability. Mineral soils show intermediate values, whereas the peat deposits display low SOM lability (when considering %C values). All regressions are significant, except for 'peat deposits' due to very high variability in three surface peat samples (but see Fig. 4d3d). In the CryoCarb 1-Kolyma data set (Fig. 3b2b), alluvial and eolian soils/deposits show the highest SOM lability, followed by mineral soils. In this case, peaty wetlands show a slightly lower lability than mineral soils/deposits but still considerably higher than peatlands. This clear dichotomy in the SOM lability of mineral soils (including peaty wetlands) and peat deposits is also apparent from the CryoCarb 2-Taymyr and CryoCarb 3-Seida results even though not all landscape classes are represented in those experiments (Fig. S3). The explanatory power of the regressions (R^2 values) in the peatland class is generally lower than that in the mineral soil/deposit classes. These statistics are, however, greatly improved when removing the surface peat samples from the analyses (not shown), which display very high variability.

Linear regression analyses between C-CO_2 production per gdw and C/N ratios for all four experiments (Fig. S4) show small deviations from the above patterns but generally maintain the clear difference between 'peat deposits' and the remaining landscape units. However, C-CO_2 production was similar in peat deposits and mineral soils/deposits at low peat deposits with low C/N values (≤ 20) seem to decompose at similar rates as SOM in mineral soils and deposits with similar C/N ratios. R^2 values for the landscape classes are generally lower than in regressions against %C and regression lines at low C release tend to converge to C/N values of 8-12, which are typical for microbial decomposer biomass suggesting only slow internal cycling of remaining SOM (Zechmeister-Boltenstern et al., 2015).

The PAGE21 dataset with C-CO_2 production rates expressed per gC as a function of %C of the soil sample also shows similar results, however, with generally lower R^2 and sometimes non-significant regressions (Fig. S5a). The same patterns are also noted when expressing C release as a function of soil volume (cm^3), however, R^2 values are generally even lower and more often non-significant (Fig. S5b).

3.3. Further subdivision of landscape unit classes in the PAGE21 dataset

~~In~~ Figure~~.~~ ~~4~~3a-~~d~~c, presents SOM lability in a further subdivision of the mineral soil/deposit landscape ~~unit~~ classes in the PAGE21 dataset. We have compared profiles with active accumulation/movement in eolian, alluvial and colluvial settings, with Holocene soils developed into older eolian, alluvial or other mineral parent materials, respectively. In each of these comparisons, we specifically identify samples from deeper C-enriched buried layers and cryoturbated pockets. ~~have been further subdivided and different functions (second order polynomial or exponential) providing better fits have been applied. The eolian class is subdivided into actively accumulating deposits (Adventdalen) and Holocene soils formed into Pleistocene Yedoma parent materials (Lena Delta), and specifically identifies buried C-enriched samples (Fig. 4a3a). Alluvial deposits are separated into profiles from active and pre-recent floodplains (multiple study areas), again separating samples from deeper C-enriched buried layers and cryoturbated pockets (Fig.4b3b). Mineral soils are separated into active colluviation sheets (mountain slopes on Svalbard) and other mineral soils (multiple study areas), highlighting the one buried C-enriched sample found in this class (Fig. 4c3c).~~ Generally speaking, a second order polynomial (intercept zero) provides the best fit and has been applied for the sake of uniformity to all described subclasses. All these ~~three~~ datasets have in common that the subclasses with active surface accumulation/movement have topsoil samples that show relatively low C content due to the continuous admixture of minerogenic materials. At the same time, these all show the highest C-CO_2 production per gdw (when considering %C). Furthermore, the second order polynomial regressions of all subclasses (except for buried C-enriched samples) suggest that the topsoil samples are particularly labile suggesting the presence of a ~~'fast'~~more degradable SOM pool in the recently deposited plant litter. Deeper C-enriched material shows relatively low lability and does not show rapidly increasing lability at higher %C values.

Figure ~~4d~~ 3d compares the SOM lability in ~~peat~~ fen and bog deposits (~~fens and bogs in~~ Stordalen Mire) and peaty wetland profiles (multiple study areas), adding for comparison the results from the previously described deeper C-enriched buried layers and cryoturbated pockets in mineral soils (see Figs. ~~4a~~3a-c). In this case, exponential functions best describe observed trends and~~,~~ ~~pointing to~~indicate very high lability of surface peat(y) samples. The thin peat layers in peaty wetlands have relatively low %C values pointing to admixture of minerogenic materials. The SOM in these profiles show relatively high C-CO_2 production per gdw compared to 'true' peat samples (when considering %C). Compared to the non-significant linear regression for all peat samples shown in Fig. ~~3a~~2a, exponential regressions for the peatland class as a whole as well as for fens and bogs separately are statistically significant. Particularly in fen peat, this regression is able to capture some very high C release values of two surface peat samples (corresponding to graminoid-derived plant litter). Deeper C-enriched material in mineral soils displays only slightly higher SOM lability compared to the mineral subsoil underlying peat deposits. It is important to bear in mind that the total number of peat samples from Stordalen Mire is limited (n=13) and that results cannot be compared directly to adjacent mineral soil profiles because field sampling in that particular study area focused solely on the peatland area.

Figure ~~4~~3. µgC-CO_2 production per gram dry weight as a function of %C of the sample for different landscape classes and their subdivisions in the PAGE21 incubation experiment. (a) Eolian class separated into actively accumulating deposit (light blue), Holocene soil formation into Pleistocene Yedoma parent materials (dark blue) and buried C-enriched samples (pink); (b) Alluvial class separated into active floodplain (rose), Holocene soil formation into pre-recent floodplain deposits (red) and buried C-enriched samples (pink); (c) Mineral class separated into active colluviation sheet (light brown), other mineral soils (dark brown) and ~~the~~one buried C-enriched sample~~s~~ (pink); (d) W~~w~~etland class separated into wetlands with thin peat layers (green), fens (light green) and bogs (dark green) with deep peat deposits and, for comparison, buried C-enriched samples in mineral soils (pink). The hatched line represents the regression for all ~~true~~ peatland samples (fens and bogs) together. C-release from one surface peat sample (green-orange) in the margin of a peatland is also indicated, but not included in the regressions. All regressions are significant ($p<0.05$).

3.4. C-enriched cryoturbated and Pleistocene Yedoma samples in the CryoCarb 1-Kolyma dataset

In the PAGE21 incubation each collected profile included only one sample from the mineral soil in the middle of the active layer and one sample from the upper permafrost layer. Thus, the selection of samples was based on depth-specific criteria. As a result, the number of samples from deeper C-enriched buried layers and cryoturbated pockets is limited (n=13). In the CryoCarb 1-Kolyma experiment samples from entire profiles were incubated and the number of deeper C-enriched samples in the mineral soil horizons is much larger. Figure ~~5a~~ 4a compares the C-CO_2 production per gdw from organically-enriched topsoil and mineral soil samples not affected by C-enrichment with that in deeper C-enriched cryoturbated samples in tundra ~~upland~~ profiles. For the sake of clarity, only those cryoturbated samples which are C-enriched by at least twice the adjacent mineral soil %C background values are included (n=22). It should be emphasized that the actual absolute %C values for the C-enriched samples and mineral soil samples not affected by C-enrichment can vary between study areas and profiles, among others due to differences in soil texture (Palmtag and Kuhry, 2018). The results from this much more narrowly defined dataset are similar to those presented for the PAGE21 experiment, i.e. SOM in deeper C-enriched cryoturbated samples is less labile than in organically-enriched topsoil samples with similar %C.

The PAGE21 experiment does not include any samples from Pleistocene Yedoma deposits. In contrast, the CryoCarb 1-Kolyma dataset ~~includes~~ has samples from two Yedoma exposures along river and thermokarst lake margins. The material was collected from perennially frozen Yedoma deposit as well as from thawed out sections of the exposures. C-release from these samples are presented in Figure 4b, which for comparison also shows samples from Holocene lowland soils, mineral subsoil samples beneath peat deposits and deeper C-enriched cryoturbated samples. The C-CO_2 production per gdw of Pleistocene Yedoma is lower than that of Holocene lowland soils, but somewhat higher than that of mineral subsoil beneath peat and deeper C-enriched material (when considering %C). Furthermore, the SOM lability of thawed out deposits is somewhat lower than that of the intact permafrost Yedoma material.

Figure 4. µgC-CO_2 production per gram dry weight as a function of %C of the sample in the CryoCarb 1-Kolyma incubation experiment for (a) Deeper C-enriched samples (pink line and triangles), compared to samples of organically enriched topsoil and mineral soil not affected by C-enrichment in all tundra profiles (blue line and triangles, showing lower part of regression line), and for (b) Perennially frozen Pleistocene Yedoma samples (black line and triangles) and thawed out Pleistocene Yedoma samples (red line and triangles), compared to samples of organically enriched topsoil and mineral soil not affected by C-enrichment in Holocene lowland profiles (blue line and triangles, showing start of regression line), mineral subsoil samples beneath peat deposits (green line and circles, showing start of regression line) and buried C-enriched samples (pink line and triangles, showing start of regression line). All regressions (power fit) are significant ($p<0.05$).

3.5. Relative lability ranking of SOM landscape unit classes

Table 3a shows the slopes of the linear regressions (intercept zero) between C-CO_2 production per gdw and %C of samples for the different landscape unit classes in all four incubation experiments. From these results it is clear that results from the four experiments cannot be compared directly in quantitative terms. To facilitate comparison across experiments ~~the~~ results were ~~therefore~~ normalized to the lowland mineral soil class, which consistently showed intermediate SOM labilities. Table 3b shows the normalized regression slopes (with the slope for mineral soils set to 1), and their mean and standard deviation (when the landscape class is represented in more than one incubation experiment). This approach confirms the previous results that peat deposits and deeper C-enriched samples in mineral soils consistently show very low relative lability, whereas areas with recent mineral sediment accumulation (e.g. in ~~active floodplains and~~ recent eolian deposits) display generally somewhat higher SOM lability (when considering %C). Pleistocene Yedoma deposits, only represented in one incubation experiment, also display relative low SOM lability.

Table 3. (a) Slopes of linear regressions (intercept zero) between %C and C-CO_2 production per gdw in samples of the different landscape classes in the four experiments; (b) Normalized slopes of linear regressions between %C and C-CO_2 production per gdw for samples in the different landscape classes in the four experiments (slope of mineral soils in lowland settings set to 1). Abbreviations: 'Pt' = peat deposits (Histels/Histosols), excluding two surface graminoid litter samples (PAGE21, Stordalen Mire); 'Min/CE' = C-enriched pockets in cryoturbated soils (Turbels); 'Min Mtn' = mineral soils in mountain settings; 'Min Pty' = peaty wetlands (mineral soils with histic horizon); 'Min Lowl' = mineral soils in lowland settings; 'Alluv' = recent alluvial deposits and Holocene soils formed in alluvial deposits; 'Eol' = recent eolian deposits; 'Pl Yed' = Pleistocene Yedoma deposits.

3.6. SOM lability based on soil horizon criteria

We also tested SOM lability in samples grouped according to soil horizon criteria (PAGE21 and CryoCarb 1-Kolyma experiments), with special attention to those horizon classes that can be linked to the specific landscape units ~~that~~ showing low relative SOM lability (C-enriched pockets for Turbels, peat samples for Histels and loess samples for Pleistocene Yedoma). This approach yielded classes with data distributions that are much better constrained in terms of %C values.

~~For the mineral soils in the PAGE21 incubation experiment, we differentiated between the topsoil organic layer, the active layer mineral soil, the permafrost layer mineral soil, and C-enriched pockets in both active layer and permafrost layer. Samples from topsoil organic layer, the active layer mineral soil and the permafrost layer mineral soil from profiles formed in Late Holocene loess deposits in Adventdalen (Svalbard) are considered separately, as are the active layer peat samples from Stordalen Mire (N Sweden). A similar grouping has been made for mineral soils in the CryoCarb 1-Kolyma experiment. In this case, Pleistocene Yedoma loess samples (both frozen and thawed) are considered separately. Peat samples are much better represented in the CryoCarb 1-Kolyma than PAGE21 experiment, and are subdivided into samples from thin peat layers in the active layer of peaty wetlands (Histic Gelisols), as well as samples from the active layer and permafrost layer of deep peat deposits (Histels).~~

In this analysis we focus on C-CO_2 production per gC to take into account large differences in %C between soil horizon classes (see Fig. S6). The main difference between the two experiments is the much lower %C values of the topsoil organic class in the PAGE21 incubation, which can be explained by a greater surface admixture of minerogenic material in alluvial (Lena Delta), eolian and mountainous areas (Svalbard). In contrast, the predominant lowland setting of the CryoCarb 1-Kolyma study area is characterized by soils with thicker, more C-rich, topsoil organic layers.

Figure ~~6~~ 5 shows C-CO_2 production per gC in the soil horizon groups of the longer term PAGE21 and short-term CryoCarb 1-Kolyma experiments. Results of the Mann-Whitney paired tests for both these experiments are shown in Table 4. PAGE21 classes show fewer statistically significant differences than in the CryoCarb 1-Kolyma experiment, which can at least partly be ascribed to smaller sample sizes. The number of samples in the PAGE21 incubation for C-enriched pockets in the active layer (n=3) and for peat (n=6) are particularly low.

Figure ~~6~~5. µgC-CO_2 production per gram carbon in samples of (a) the PAGE21 and (b) the CryoCarb 1-Kolyma incubation experiments, grouped according to soil horizon criteria. Abbreviations: AL-OL = Active layer topsoil organics; AL-Min = Active layer mineral; AL-Ce = Active layer C-enriched; P-Min = Permafrost layer mineral; P-Ce = Permafrost layer C-enriched; AL-Pty = Active layer thin peat (CryoCarb 1-Kolyma experiment only); AL-Pt = Active layer peat; P-Pt = Permafrost layer peat (CryoCarb 1-Kolyma experiment only); AL-Lss OL = Active layer topsoil organics in Late Holocene loess deposits (PAGE21 experiment only); AL-Lss Min = Active layer mineral in Late Holocene loess deposits (PAGE21 experiment only); P-Lss Min = Permafrost layer mineral in Late Holocene loess deposits (PAGE21 experiment only); ~~P~~Fr-Yed = Permafrost Pleistocene Yedoma deposits (CryoCarb 1-Kolyma experiment only); Th-Yed = Thawed out Pleistocene Yedoma deposits (CryoCarb 1-Kolyma experiment only). Box-whisker plots show mean and standard deviation (in red) and median, first and third quartiles and min/max values (in black), for the different soil horizon groups.

Table 4. p Values of Mann-Whitney paired tests of µgC-CO_2 production per gram carbon for soil horizon groups in (a) the PAGE21 and (b) the CryoCarb 1-Kolyma incubation experiments. Abbreviations as in Figure~~.~~ ~~6~~5. Differences are considered significant when $p<0.05$.~~Yellow denotes significant differences (p<0.05).~~

~~The~~ C release rates in topsoil organic samples from ~~the~~ actively accumulating Holocene loess soils are significantly higher than those in topsoil organic samples from the remaining PAGE21 mineral soils (Fig. ~~6a~~ 5a and Table 4a). Both topsoil organic classes show significantly higher rates than all mineral soil and peat classes. Peat samples have the lowest mean and median C release rates from all these classes but only the rates from permafrost layer mineral soil and C-enriched pocket samples are significantly higher. Both mean and median C release rates from active layer and permafrost layer C-enriched pockets are somewhat lower (but not significantly different) than those from adjacent, non C-enriched, mineral soil samples.

C release rates in the soil horizon classes from the CryoCarb 1-Kolyma experiment show similarities, but also some differences to those observed in the PAGE21 experiment. Absolute C release rates per gC are more than an order of magnitude higher in the CryoCarb 1-Kolyma experiment (measured as a mean release over the first four days of incubation) compared to those in the PAGE21 experiment (measured ~~at~~ on day 343 of incubation). Another important difference is that C release rates per gC in the short-term CryoCarb 1-Kolyma incubation do not differ significantly between the topsoil organic class and the active layer and permafrost layer mineral soil classes, which we ascribe to the presence of a highly labile C pool (e.g. DOC, plant roots) in the mineral soil layers that is quickly decomposed (see Weiss et al., 2016; Faucherre et al., 2018). However, rates from active layer and permafrost layer C-enriched pockets are significantly lower than those from adjacent, non C-enriched, mineral soil samples. Both active layer and permafrost layer peat samples show significantly lower C release rates than all other classes, with active layer peat samples having significantly higher rates than permafrost layer peat samples. Samples from the Pleistocene Yedoma loess ‘frozen’ and ‘thawed’ classes display significantly lower C release rates per gC than those in the topsoil organic layer, active layer and permafrost layer mineral soil classes, but significantly higher rates than those in the peat classes. The two Yedoma classes do not differ significanty from each other, the active layer and permafrost layer C-enriched pocket classes, nor the peaty wetland class.

4. Discussion

The analysis and comparison of results in the PAGE21 and CryoCarb 1-Kolyma incubations show consistent trends in C-CO_2 production rates as a function of simple soil geochemical parameters in both the full datasets as well as in the grouping of samples according to landscape classes. However, it is not possible to directly compare these two very different laboratory experiments quantitatively. The varying field collection techniques, field storage, transport and laboratory storage, pretreatment, experimental setup and time of measurement after start of incubations have a clear effect on the magnitude of the observed C-CO_2 production rates. The same methods were applied to all samples from all study areas in the PAGE21 experiment, but these differed markedly from those applied in the CryoCarb setup and even between the three individual CryoCarb experiments (e.g., addition of different 'local' microbial decomposer inoculi to rewetted samples).

In quantitative terms, C-CO_2 production rates per gdw measured over the first 4 days in the CryoCarb 1-Kolyma samples incubated at 12 ºC are about 15 times higher than those measured after about one year in the PAGE21 samples incubated at 5 ºC (see Fig. 2). Similarly, C-CO_2 production rates per gC are also more than an order of magnitude higher in the short-term CryoCarb-Kolyma 1 than the longer term PAGE21 incubation (see Fig. ~~6~~5). Upper permafrost mineral soil samples (<3 %C) from Kylatyk in NE Siberia, incubated at 2 ºC directly after field collection and thawing (measurement after 20-30 hr, following 3 days of pre-incubation), show median C release rates of c. 750 µgC-CO_2 gC^{-1} d^{-1} (Weiss et al., 2016), compared to c. 1750 µgC-CO_2 gC^{-1} d^{-1} in the same class of CryoCarb 1-Kolyma samples. Median C release rates in upper permafrost mineral soil samples of the PAGE21 experiment (Faucherre et al., 2018) decrease from c. 170 on day 8 to c. 35 µgC-CO_2 gC^{-1} d^{-1} on day 343 since start of incubation. It is obvious from these results that there is a rapid decline in C release rates over time of incubation. Longer incubation experiments (up to 12 years) have shown that the overall rate of C loss decreases almost exponentially over time (Elberling et al., 2013). However, even when laboratory incubation setups and time of measurement are similar, large differences can occur in C release rates. For instance, peat samples in the CryoCarb 1-Kolyma incubation display about twice the C-CO_2 production rates per gdw than those observed in the CryoCarb 3-Seida incubation (Figs. ~~3b~~ 2b and S3b).

Nonetheless, a comparison of C-CO_2 production rates per gdw for landscape unit classes in terms of relative SOM lability provided useful and robust results. These classes were implemented to allow upscaling of results to the northern permafrost region. They reflect main Gelisol (and non-Gelisol) soil suborders and deeper Quaternary deposits to permit direct comparison with the size and geographic distribution of these different SOC pools (Tarnocai et al., 2009; Hugelius et al., 2014). Samples from mineral soil profiles, including wetland deposits with a thin peat(y) surface layer, display high relative SOM lability compared to peat deposits, deep C-enriched buried or cryoturbated samples and Pleistocene Yedoma deposits (when considering %C of the incubated sample). These results are confirmed by the more stringent statistical analysis of samples grouped into soil horizon classes. Peat deposit, C-enriched pocket and Yedoma deposit samples show significantly lower C-CO_2 production rates per gC than topsoil organics and mineral layer samples (Cryo-Carb-1-Kolyma experiment). The same trends are observed in the incubation experiment of upper permafrost samples from Kytalyk, reported by Weiss et al. (2016). C-enriched pockets (3-10 %C) showed lower C-CO_2 production rates per gC than mineral soil samples (<3 %C), while a buried peat sample (c. 40 %C) displayed a very low C-CO_2 production rate per gC. The PAGE21 experiment also revealed that peat samples mineralized a smaller fraction of C over the one year of incubation compared to mineral soil samples (Faucherre et al., 2018).

A further subdivision of landscape classes and more careful analysis of incubation results in the PAGE21 experiment provide additional useful insights. For example, separation of eolian deposits into actively accumulating deposits during the Late Holocene (Adventdalen) and Holocene soils formed into Pleistocene Yedoma parent materials (Lena Delta) showed clear differences in C release rates per gdw (when considering %C), with the former displaying a higher SOM lability in topsoil organic samples (see Fig. ~~4a~~3a). The topsoil organic samples from the actively accumulating eolian deposits in Adventdalen also displayed significantly higher C release rates per gC than all other topsoil organic, mineral layer and peat(y) horizon classes (see Table 4a). Separation of alluvial deposits into active floodplain deposits and Holocene soils formed in pre-recent river terraces and of mineral soils into active colluviation sheets (mountain slopes on Svalbard) and other mineral soils ~~(multiple study areas)~~ showed similar trends in SOM lability (see Fig. ~~4b~~3b-c). These results suggest that admixture of minerogenic material in topsoil organics of actively accumulating eolian, alluvial and colluvial deposits promotes SOM decomposition. Peaty wetland deposits display much higher C release rates per gdw (when considering %C) than peatland deposits (see Fig. ~~4d~~3d). These two landscape classes are poorly represented in the PAGE21 experiment, but a statistical test of C release rates per gC in these peat(y) soil horizon classes of the CryoCarb 1-Kolyma incubation confirms this difference (see Table 4b). This is interesting because even though wetlands with a thin peat layer do not have particularly high C stocks, they can be important sources of methane (CH_4) to the atmosphere (Olefeldt et al., 2013). ~~-~~These further subdivisions into landscape subclasses are of limited use for upscaling purposes because they are not considered explicitly in any available geographic database for the northern permafrost region.

The implementation of landscape classes (and their subdivisions) in the PAGE21 and CryoCarb incubation experiments have greatly constrained variation in C release rates compared to the full datasets. However, much within-class variability remains and there is a need to further investigate the sources of this variability. Important additional soil and environmental factors such as microbial community, moisture, texture, pH, redox potential, etc. were not available for the (full) PAGE21 and CryoCarb datasets and could, therefore, not be tested. We conclude that additional research is needed to further constrain observed SOM lability across the northern permafrost region and within the classes proposed here.

The relatively low lability in the peatland class is surprising. The low DBD, high %C and high C/N of peat are normally associated with a relatively low degree of decomposition. This, in turn, is the result of environmental factors such as anaerobic and/or permafrost conditions that largely inhibit SOM decay (Davidson and Janssens, 2006). One could expect that this less decomposed material would show high lability following thawing and warming, but our results point to the opposite. This is particularly surprising when considering the setup of the CryoCarb experiments, in which a slush of rewetted material inoculated with microbial decomposers was incubated at 12 °C. ~~The~~ Although the CryoCarb experiments are very short assays (4 days), ~~but~~ the longer term PAGE21 incubation data ~~experiment~~ (measured after roughly one year) provides similar results.

In the case of peat deposits, it should be considered if this low decomposability is an evolved ‘biochemical trait’ in peat-forming species that maintains their favored habitat, similar to the role of *Sphagnum* anatomy (hyaline cells), physiology (acidification) and cell wall chemistry (phenolic compounds) in sustaining moist and acid surface conditions, and inhibiting peat decomposition (Clymo and Hayward, 1982). Furthermore, the generally high C/N ratios of peat provide a poor substrate quality to the decomposer community (Bader et al., 2018). Diáková et al. (2016) reported low microbial biomass in subarctic peat deposits of the Seida study area (Northeast European Russia).

Permafrost degradation in peatlands can result in two opposite pathways, one resulting in surface collapse and an increase in soil moisture (particularly mimicked in the CryoCarb incubation setup) and another one resulting in drainage, drying and accelerated C losses, not the least due to a higher incidence of peat fires (Kuhry, 1994).

Our results on the low lability of peat deposits can be compared to the findings of Schädel et al. (2014) in their assessment of SOM decomposability in the northern permafrost region. That study recognized a group of organic soil samples (>20% initial C), ranging in depth between 0 and 120 cm. We consider that this group will include both topsoil organic samples as well as deeper peat deposits. In the Schädel et al. (2014) study, this group showed the largest range in decomposability, with some samples showing high potential C losses, whereas deeper organic samples were less likely to respire large amounts of C. We suggest, therefore, that both studies might show the same trends.

In our incubation experiments, SOM from deeper C-enriched buried layers and cryoturbated pockets show relatively low lability when compared to organic-rich topsoil samples. These results are corroborated by Čapek ~~Capek~~ et al. (2015) and Gentsch et al. (2015b), who report low bioavailability of SOM in subducted horizons of Lower Kolyma soils (NE Siberia). The reason why this relatively undecomposed material displays low lability remains unclear. One reason could be that the decomposer community needs time to adapt to the new environmental conditions following thawing/warming, another one that there is a simple mismatch between the microbial community adapted to decompose relatively undecomposed organic material and the physico-chemical environment (e.g., higher bulk density) prevailing in (thawed out) deeper soil horizons (Gittel et al., 2013; Schnecker et al., 2014). Kaiser et al. (2007) and Čapek ~~Capek~~ et al. (2015) reported low microbial biomass in deeper C-enriched soil samples.

These results pose interesting questions regarding the role of organic aggregates and organo-mineral associations for SOM lability (e.g. ~~Kaiser et al., 2007;~~ Gentsch et al., 2018). On the one hand, our samples from topsoil organic horizons with active minerogenic inputs in eolian, alluvial and colluvial settings display (very) high C release rates, whereas deeper C-enriched soil materials show low decomposability. The underlying soil physico-chemical and microbial processes require urgent attention in order to better constrain C release rates from soils and deposits in the northern permafrost region.

~~To these two categories of samples can be added~~ Pleistocene Yedoma deposits, represented in the CryoCarb 1-Kolyma incubation experiment, also display low relative SOM lability, ~~which~~ despite incorporation of relative fresh plant root material caused by syngenetic permafrost aggradation~~, also display low relative SOM lability~~. These results are corroborated by results from Schädel et al. (2014) for their group of deep mineral samples (with Yedoma provenance).

An important consideration is if the consistent differences in relative SOM lability of landscape and soil horizon classes observed in our incubation experiments will be maintained over periods of decades to centuries of projected warming and thawing. Very short-term incubations, such as in the CryoCarb setup (four days), might register the initial decomposition of highly labile SOM components, such as microbial necromass, simple molecules (e.g., sugars or amino acids), low molecular-weight DOC, etc., or might not provide enough time for an adaptation of the microbial decomposer community to new environmental settings (Weiss et al., 2016; Weiss and Kaal, 2018). On the other hand, in longer incubation experiments such as in the PAGE21 experiment (one year), the conditions in the incubated samples become gradually more artificial compared to field conditions. Specifically, microbes in long-term incubations become increasingly C limited, as no new C input by plants occur, whereas inorganic nutrients, such as nitrate or ammonium accumulate to unphysiological levels. Care, therefore, should be taken when extrapolating our results over longer time frames if no corroborating field evidence for longer term decay rates can be obtained (e.g. Kuhry and Vitt, 1996; Schuur et al., 2009).

5. Conclusions

The PAGE21 and CryoCarb incubation experiments confirm results from previous studies that simple geochemical parameters such as DBD, %C and C/N can provide a good indication of SOM lability in soils and deposits of the northern permafrost region (Elberling et al., 2013; Schädel et al., ~~2013~~2014; Faucherre et al., 2018.). In our analyses we have focused on %C of the sample since it is the most widely available of the three investigated geochemical parameters. Furthermore, %C is less sensitive than C/N to botanical origin of the plant litter and, in contrast to DBD, not dependent on ground compaction or volume of excess ground ice.

When considering the full datasets of the four experiments, our regressions of C release as a function of %C were statistically significant but explained less than 50 % of the observed variability. Subsequently, we investigated whether a further division of samples into predefined landscape unit classes would better constrain the observed relationships. In defining these classes, we applied a scheme that could easily be used for spatial upscaling to northern circumpolar levels. We adopted the main Gelisol suborders (Histels, Turbels and Orthels), non-permafrost Histosols and mineral soils, and types of deeper Quaternary (deltaic/floodplain and eolian/Yedoma) deposits used in the NCSCD and related products to estimate the total SOC pool in the northern permafrost region (Tarnocai et al., 2009; Strauss et al., 2013; Hugelius et al., 2014). We conclude that these landscape classes better constrain observed variability in the relationships and that the relative SOM lability rankings of these classes were consistent among all four incubation experiments, for both regressions against %C and C/N (all four experiments), and for regressions of %C against different units of C-CO_2 production *'per gram dry weight'*, *'per gram C'* and *'per cm^3'* (PAGE21 dataset). Our results based on full profiles indicate that C-CO_2 production rates per gdw decrease in the order Late Holocene eolian > alluvial and mineral ~~upland~~ (including peaty wetlands) > Pleistocene Yedoma > C-enriched pockets > peat, with lowest C release rates observed in peat deposits (when considering %C). These results are corroborated by statistical analysis of C release rates per gC for samples grouped according to soil horizon criteria (PAGE21 and CryoCarb 1-Kolyma datasets).

An important conclusion from these results is that purportedly more undecomposed SOM, such as in peat deposits (Histels and Histosols), C-enriched cryoturbated samples (Turbels), and Pleistocene Yedoma deposits, does not seem to imply higher SOM lability. These three SOC pools, which together represent ≥50 % of the reported SOC storage in the northern permafrost region (Hugelius et al., 2014; Palmtag and Kuhry, 2018), display relatively low rates of C release. Consequently, there is an urgent need for further research to understand these results in order to better constrain the thawing permafrost carbon feedback on global warming.

6. Data availability

The soil geochemical data and incubation results presented in this paper are available upon request from PK (peter.kuhry@natgeo.su.se). For full PAGE21 incubation data, please contact BE (be@ign.ku.dk). For full CryoCarb incubation data, please contact JB (jiri.barta@prf.jcu.cz).

7. Author contribution

PK developed the initial concept for the study. All authors contributed with the collection of soil profiles at various sites. The PAGE21 incubation experiment was planned and conducted at CENPERM (University of Copenhagen) by SF, CJJ and BE, whereas the CryoCARB incubation experiments were carried out at the University of South Bohemia (Ceske Budejovice) under guidance of HS and JB. PK performed all statistical analyses, in cooperation with GH. All co-authors contributed to the writing of the manuscript, including its discussion section.

8. Competing interests

The authors declare that they have no conflict of interest.

9. Acknowledgments

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Tables

Pages ….

Figures

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Table 1

	%C vs C/N	%C vs DBD	C/N vs DBD
Correlation	positive	negative	negative
PAGE21, All sites	0.53 (228)	0.67 (232)	0.57 (228)
CryoCarb 1-Kolyma	0.79 (418)	0.78 (413)	0.63 (413)
CryoCarb 2-Taymyr	0.64 (484)	0.69 (480)	0.47 (480)
CryoCarb 3-Seida	0.47 (71)	0.84 (79)	0.47 (71)

Table 2

	DBD vs C release/gdw	%C vs C release/gdw	C/N vs C release/gdw
Correlation	negative	positive	positive
PAGE21, All sites	0.52 (232)	0.45 (232)	0.34 (228)
CryoCarb 1-Kolyma	0.52 (404)	0.47 (406)	0.54 (406)
CryoCarb 2-Taymyr	0.41 (480)	0.33 (484)	0.48 (484)
CryoCarb 3-Seida	0.81 (78)	0.43 (78)	0.38 (70)

Table 3

a

	Pt	Min/CE	Min Mtn	Min Pty	Min Lowl	Alluv	Eol	Pl Yed
PAGE21, All sites	0.24	0.29	0.99	1.51	1.44	1.44	1.68	
CryoCarb-Kolyma	4.83	6.72	17.8	15.3	19.7	22.0		11.5
CryoCarb-Taymyr	6.24			29.3	24.7	26.2		
CryoCarb-Seida	2,40			5.76	7.92			

b

	Pt	Min/CE	Min Mtn	Min Pty	Min Lowl	Alluv	Eol	Pl Yed
PAGE21, All sites	0.17	0.20	0.69	1.05	1	1.00	1.17	
CryoCarb-Kolyma	0.25	0.34	0.90	0.78	1	1.12		0.58
CryoCarb-Taymyr	0.26			1.18	1	1.06		
CryoCarb-Seida	0.30			0.73	1			
Mean relative lability	0.24	0.27	0.80	0.94	1	1.06	1.17	0.58
S.D. relative lability	0.05	0.10	0.15	0.22		0.06		

Table 4

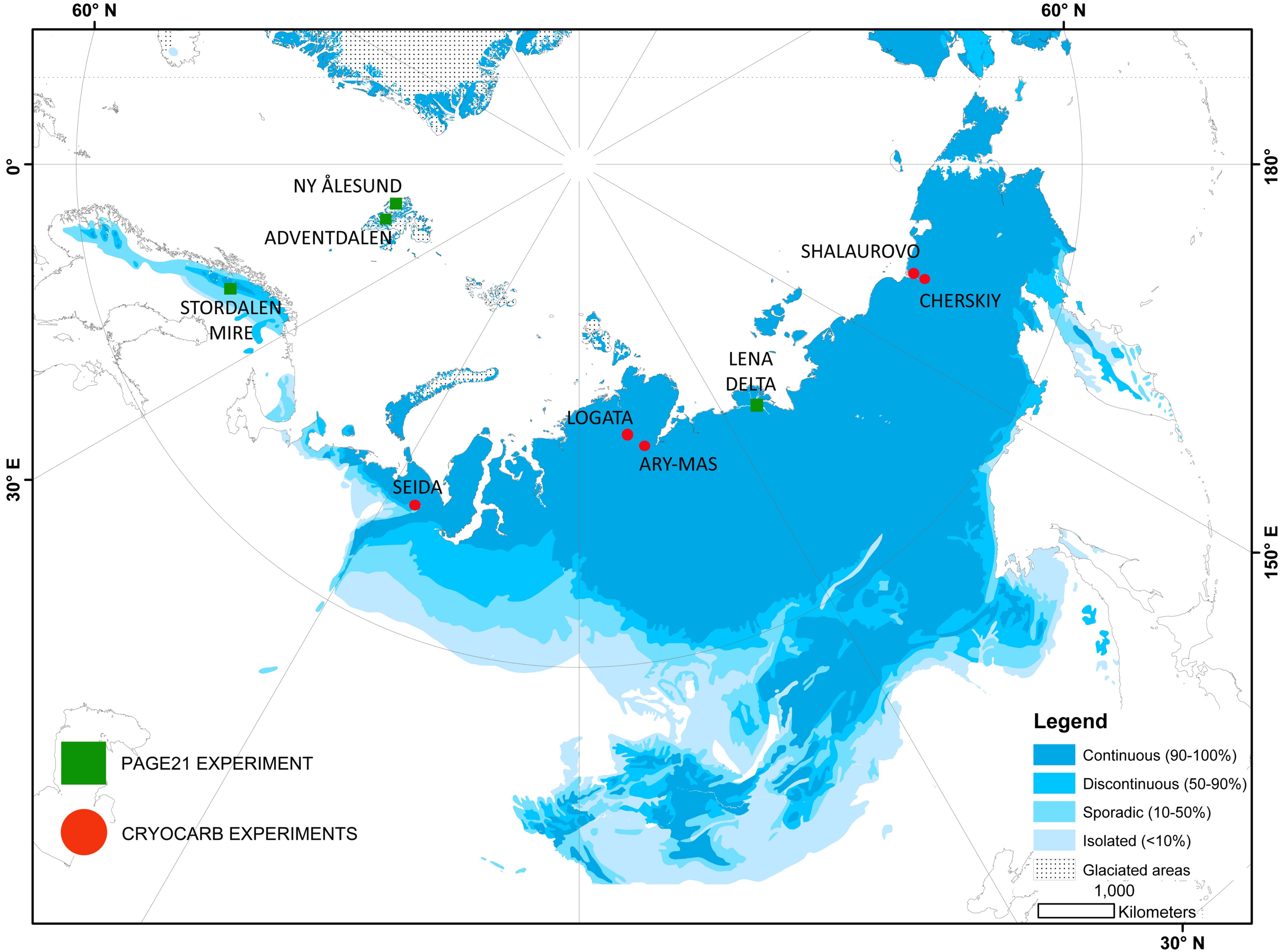
a

	AL_Min	AL_Ce	P_Min	P_Ce	AL_Pt	OL Ls	Min Ls	Min Ls	
AL_OL	< 0.001	0.0072	< 0.001	< 0.001	< 0.001	0.0493	< 0.001	< 0.001	AL_OL
AL_Min		0.5761	0.2217	0.5360	0.1887	< 0.001	0.6598	0.5682	AL_Min
AL_Ce			0.1464	0.1387	0.5186	0.0160	0.1956	0.7096	AL_Ce
P_Min				0.5570	0.0119	< 0.001	0.7353	0.0809	P_Min
P_Ce					0.0119	< 0.001	1.0000	0.1828	P_Ce
AL_Pt						0.0018	0.0518	0.1103	AL_Pt
AL_OL Ls							< 0.001	< 0.001	AL_OL Ls
AL_Min Ls								0.2500	AL_Min Ls

b

	AL_Min	AL_Ce	P_Min	P_Ce	AL_Pty	AL_Pt	P_Pt	Fr_Yed	Th_Yed	
AL_OL	0.3800	0.0027	0.0658	< 0.001	0.0255	< 0.001	< 0.001	< 0.001	< 0.001	AL_OL
AL_Min		< 0.001	0.011	< 0.001	0.0174	< 0.001	< 0.001	< 0.001	< 0.001	AL_Min
AL_Ce			0.1178	0.2318	0.8849	0.0083	< 0.001	0.3428	0.1653	AL_Ce
P_Min				< 0.001	0.1656	< 0.001	< 0.001	0.0017	< 0.001	P_Min
P_Ce					0.4539	0.0098	< 0.001	0.9258	0.2751	P_Ce
AL_Pty						0.0168	< 0.001	0.5059	0.2036	AL_Pty
AL_Pt							0.0440	< 0.001	0.0034	AL_Pt
P_Pt								< 0.001	< 0.001	P_Pt
Fr_Yed									0.1448	Fr_Yed

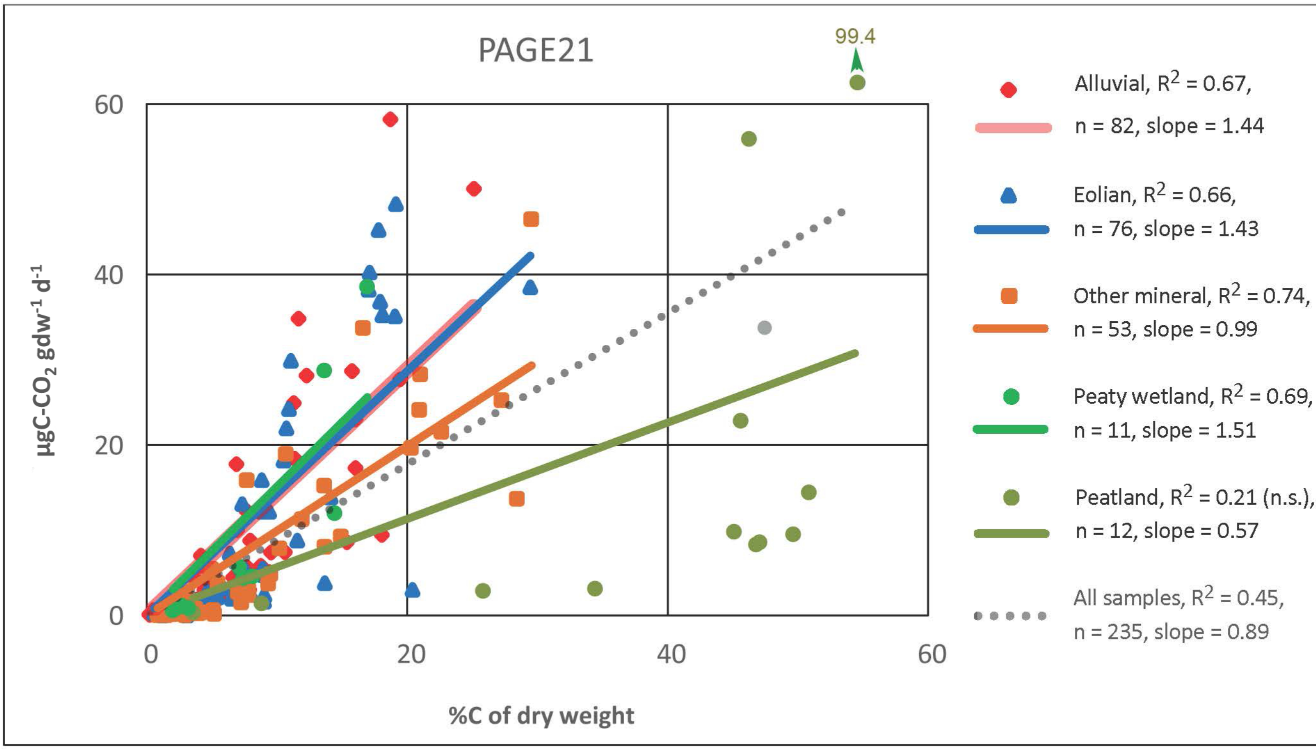
Figure 1



60° N
60° N
0°
180°
30° E
150° E
30° N
NY ÅLESUND
ADVENTDALEN
STORDALEN MIRE
SHALAUROVO
CHERSKIY
LENA DELTA
LOGATA
ARY-MAS
SEIDA
PAGE21 EXPERIMENT
CRYOCARB EXPERIMENTS
Legend
Continuous (90-100%)
Discontinuous (50-90%)
Sporadic (10-50%)
Isolated (<10%)
Glaciated areas
1,000
Kilometers

Figure 2

a


PAGE21
99.4
60
40
20
0
0
20
40
60
µgC-CO2 gdw-1 d-1
%C of dry weight
Alluvial, R2 = 0.67,
n = 82, slope = 1.44
Eolian, R2 = 0.66,
n = 76, slope = 1.43
Other mineral, R2 = 0.74,
n = 53, slope = 0.99
Peaty wetland, R2 = 0.69,
n = 11, slope = 1.51
Peatland, R2 = 0.21 (n.s.),
n = 12, slope = 0.57
All samples, R2 = 0.45,
n = 235, slope = 0.89

b

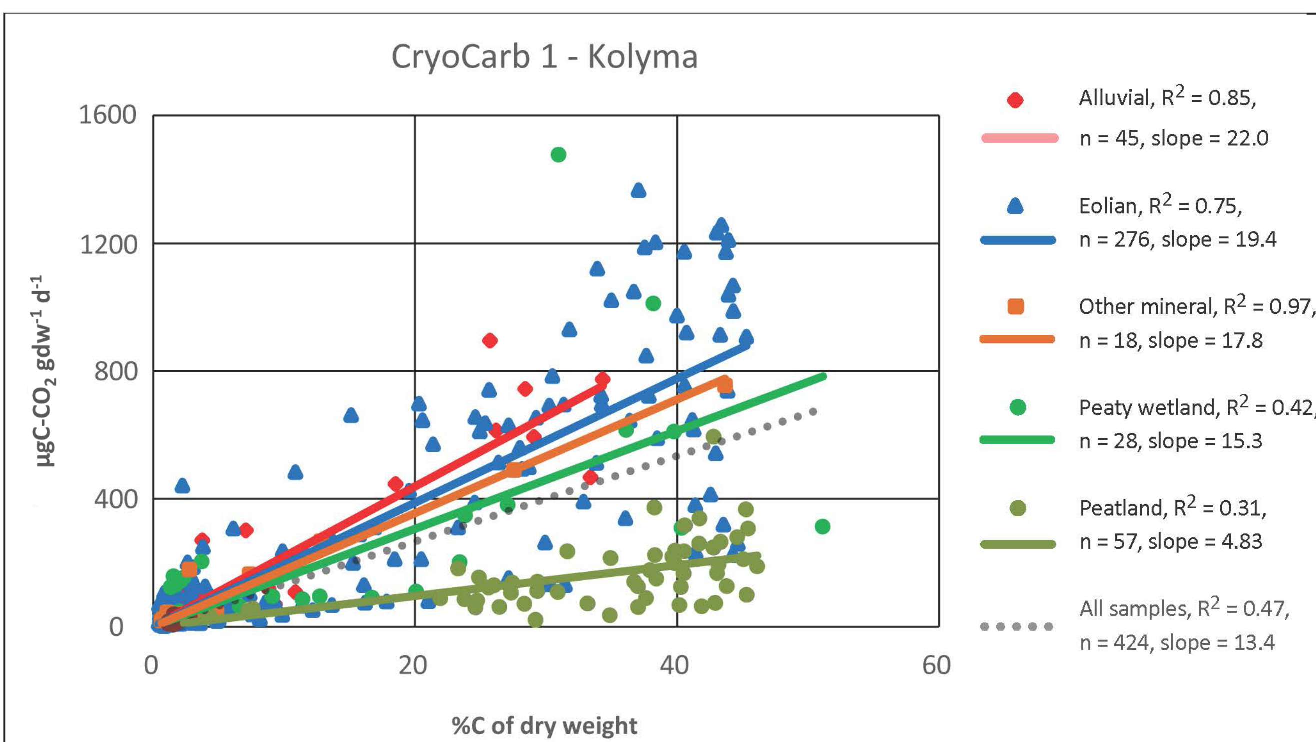

CryoCarb 1 - Kolyma
1600
1200
800
400
0
0
20
40
60
µgC-CO2 gdw-1 d-1
%C of dry weight
Alluvial, R2 = 0.85,
n = 45, slope = 22.0
Eolian, R2 = 0.75,
n = 276, slope = 19.4
Other mineral, R2 = 0.97,
n = 18, slope = 17.8
Peaty wetland, R2 = 0.42,
n = 28, slope = 15.3
Peatland, R2 = 0.31,
n = 57, slope = 4.83
All samples, R2 = 0.47,
n = 424, slope = 13.4

Figure 3

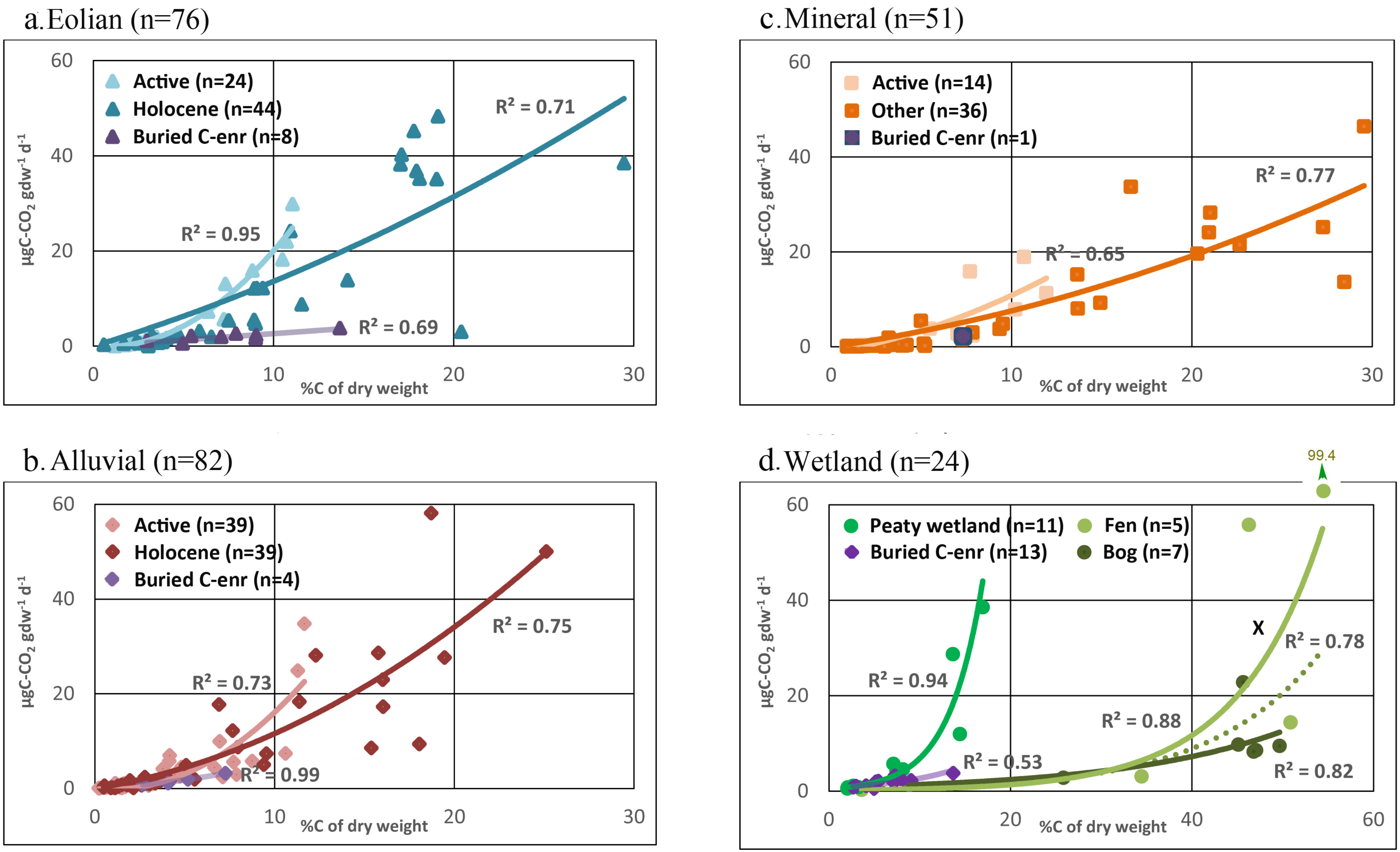
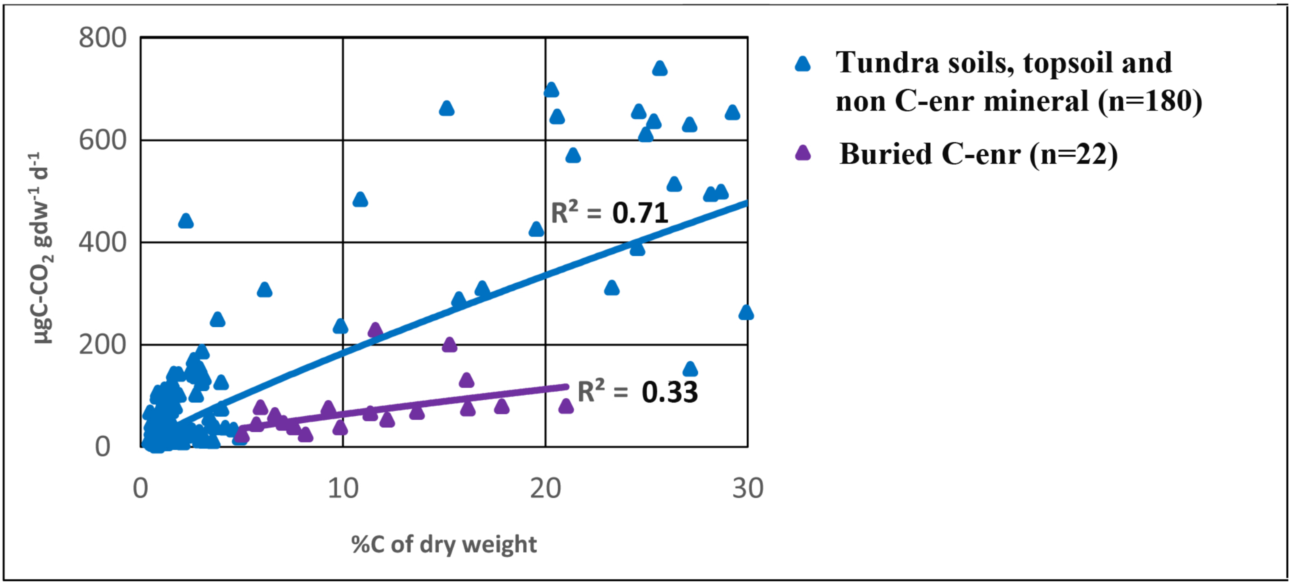

a. Eolian (n=76)
Active (n=24)
Holocene (n=44)
Buried C-enr (n=8)
R² = 0.71
R² = 0.95
R² = 0.69
μgC-CO2 gdw-1 d-1
%C of dry weight
c. Mineral (n=51)
Active (n=14)
Other (n=36)
Buried C-enr (n=1)
R² = 0.77
R² = 0.65
μgC-CO2 gdw-1 d-1
%C of dry weight
b. Alluvial (n=82)
Active (n=39)
Holocene (n=39)
Buried C-enr (n=4)
R² = 0.75
R² = 0.73
R² = 0.99
μgC-CO2 gdw-1 d-1
%C of dry weight
d. Wetland (n=24)
99.4
Peaty wetland (n=11)
Fen (n=5)
Buried C-enr (n=13)
Bog (n=7)
X
R² = 0.78
R² = 0.94
R² = 0.88
R² = 0.53
R² = 0.82
μgC-CO2 gdw-1 d-1
%C of dry weight

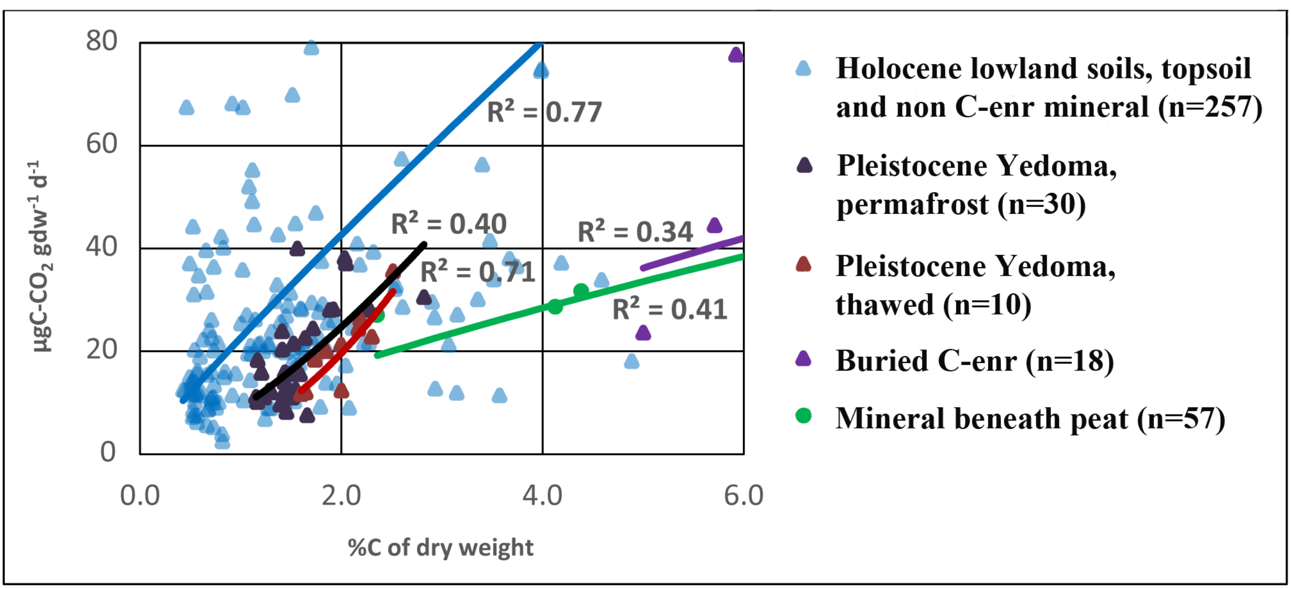
Figure 4

a



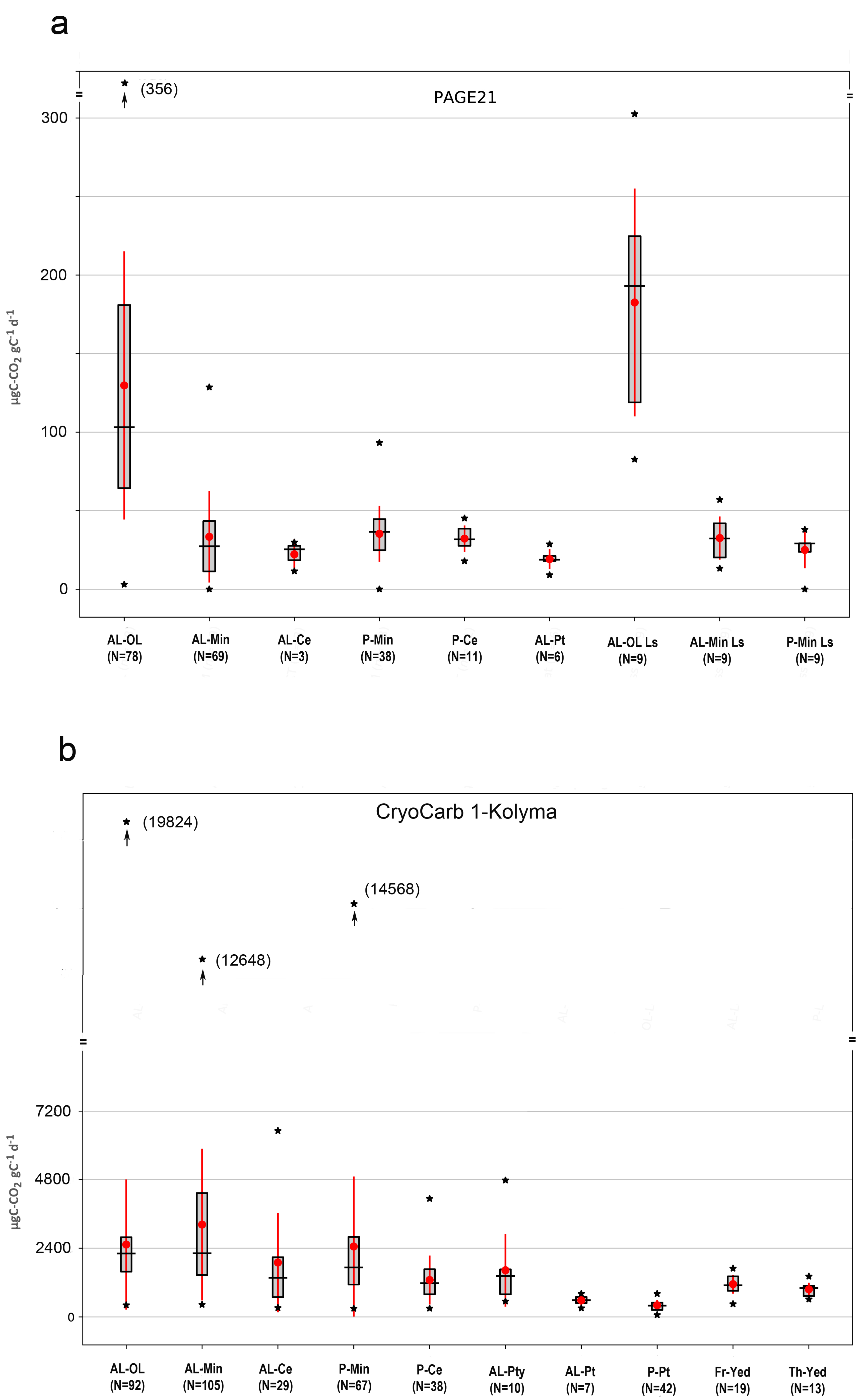
800
600
400
200
0
0
10
20
30
µgC-CO2 gdw-1 d-1
%C of dry weight
R² = 0.71
R² = 0.33
Tundra soils, topsoil and non C-enr mineral (n=180)
Buried C-enr (n=22)

b



80
60
40
20
0
0.0
2.0
4.0
6.0
µgC-CO2 gdw-1 d-1
%C of dry weight
R² = 0.77
R² = 0.40
R² = 0.71
R² = 0.34
R² = 0.41
Holocene lowland soils, topsoil and non C-enr mineral (n=257)
Pleistocene Yedoma, permafrost (n=30)
Pleistocene Yedoma, thawed (n=10)
Buried C-enr (n=18)
Mineral beneath peat (n=57)

Figure 5



a
PAGE21
(356)
300
200
100
0
μgC-CO2 gC-1 d-1
AL-OL (N=78)
AL-Min (N=69)
AL-Ce (N=3)
P-Min (N=38)
P-Ce (N=11)
AL-Pt (N=6)
AL-OL Ls (N=9)
AL-Min Ls (N=9)
P-Min Ls (N=9)
b
CryoCarb 1-Kolyma
(19824)
(14568)
(12648)
7200
4800
2400
0
μgC-CO2 gC-1 d-1
AL-OL (N=92)
AL-Min (N=105)
AL-Ce (N=29)
P-Min (N=67)
P-Ce (N=38)
AL-Pty (N=10)
AL-Pt (N=7)
P-Pt (N=42)
Fr-Yed (N=19)
Th-Yed (N=13)