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Rapid CO_2 Release From Eroding Permafrost in Seawater

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Key Points:
- Permafrost was incubated in seawater to determine the amount of CO_2 potentially released by eroding permafrost coasts
- Observed CO_2 production after 4 months is up to 4.3 ± 1.0 mg/gdw at 4 °C and comparable to release rates from thawing permafrost on land
- Permafrost coasts and nearshore waters are potentially an important source of CO_2 that is neglected in carbon cycle budgets and models

Supporting Information:
- Supporting Information S1
- Figure S1
- Figure S2
- Figure S3
- Figure S4
- Figure S5
- Figure S6
- Data Set S1
- Data Set S2

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Abstract Permafrost is thawing extensively due to climate warming. When permafrost thaws, previously frozen organic carbon (OC) is converted into carbon dioxide (CO_2) or methane, leading to further warming. This process is included in models as gradual deepening of the seasonal non-frozen layer. Yet, models neglect abrupt OC mobilization along rapidly eroding Arctic coastlines. We mimicked erosion in an experiment by incubating permafrost with seawater for an average Arctic open-water season. We found that CO_2 production from permafrost OC is as efficient in seawater as without. For each gram (dry weight) of eroding permafrost, up to 4.3 ± 1.0 mg CO_2 will be released and 6.2 ± 1.2% of initial OC mineralized at 4 °C. Our results indicate that potentially large amounts of CO_2 are produced along eroding permafrost coastlines, onshore and within nearshore waters. We conclude that coastal erosion could play an important role in carbon cycling and the climate system.

Plain Language Summary The permanently frozen soils of the Arctic, known as permafrost, store large amounts of organic carbon, which accumulated over millennia due to slow decomposition in the cold Arctic regions. With climate warming this frozen organic carbon reservoir thaws and microbes recycle it quickly into greenhouse gases, which in turn support further warming. A slow and continuous thaw is currently used in models to project future greenhouse gas release from permafrost. Yet along the rapidly eroding coastlines of the Arctic Ocean, which make up 34% of the Earth's coastlines, whole stretches of the coast simply collapse, sink or slide into the ocean, including the previously frozen organic carbon. We simulated greenhouse gas release in response to coastline collapse in a laboratory experiment by simply mixing permafrost with seawater. We show that large amounts of carbon dioxide are being produced during the Arctic open-water season. Our study indicates that eroding permafrost coasts in the Arctic are potentially a major source of carbon dioxide. With increasing loss of sea ice, longer open-water seasons, and exposure of coasts to waves, we highlight the importance of coastal erosion for potential carbon dioxide emissions.

1. Introduction

Soils in the permafrost region of the Northern Hemisphere store an estimated 1,300 Pg (1.3×10^{18} g) of organic carbon (OC; Hugelius et al., 2014), an amount that exceeds the pool of carbon in the atmosphere (Ciais et al., 2013). With global warming, higher temperatures are causing permafrost to thaw and its OC to become subject to microbial turnover, producing greenhouse gases (GHGs; Knoblauch et al., 2013; Schädel et al., 2014), which further fuel global warming (Koven et al., 2015; Schuur et al., 2015). This process is represented in models as a one-dimensional (vertical) seasonal deepening of the active (non-frozen) layer. Although studies highlight the importance of abruptly thawing permafrost (Turetsky et al., 2019) and first attempts were made to include thermokarst (i.e., ground disturbance and subsidence caused by thawing of ice-rich permafrost; Schuur et al., 2015) and erosion processes on land in climate models (Lee et al., 2014; Von Deimling et al., 2015), this representation neglects the rapid mobilization of permafrost OC due to coastal erosion and thermokarst and thus OC turnover during lateral transport from land to sea (Figure 1). This process is likely to substantially increase GHG emissions from thawing permafrost (Fritz et al., 2017; Vonk & Gustafsson, 2013).

Permafrost coasts make up approximately 34% of the Earth's total coastline (Lantuit et al., 2012). Erosion of these coasts releases large amounts of permafrost OC directly into the Arctic Ocean (Couture et al., 2018;

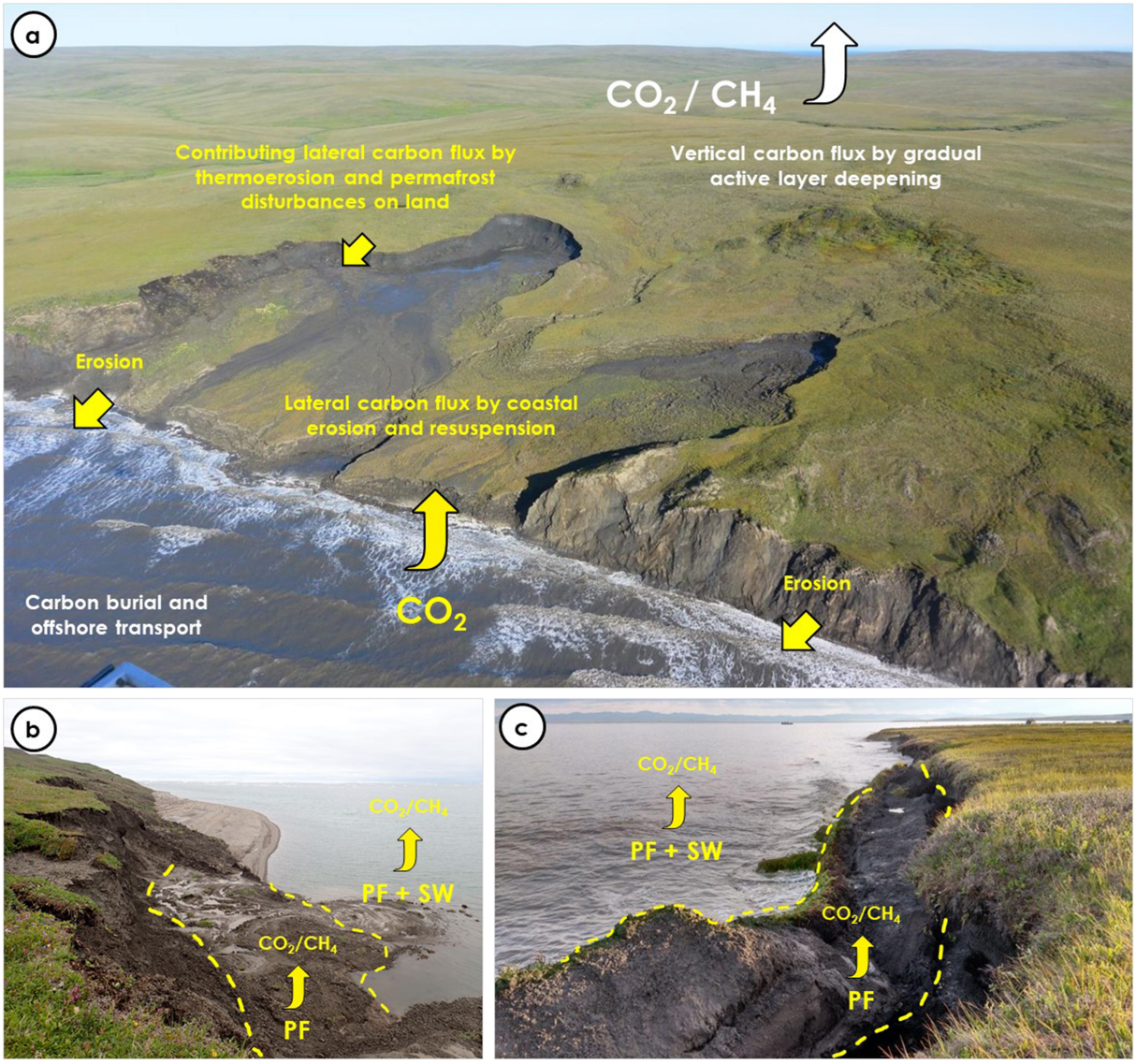

Figure 1. Lateral erosion of permafrost coasts in the Arctic. Coastal erosion rapidly mobilizes organic carbon pools from permafrost that can be quickly turned over into carbon dioxide onshore and within the nearshore zone (a). Figure 1a illustrates the lateral carbon flux from coastal erosion identified in this study (yellow vertical arrow) that is neglected in current models. Figures 1b and 1c give examples of erosion modes in form of mud lobes (b) and block failures (c) and conceive the experimental approach with permafrost (PF) and permafrost mixed with seawater (PF + SW) mimicking coastal erosion under laboratory conditions. Carbon dioxide (CO_2) and methane (CH_4) were measured during incubations of PF and PF + SW for the length of an average Arctic open-water season of 4 months. Pictures were taken on *Qikiqtaruk*—Herschel Island (Yukon Territory, Canada).

Wegner et al., 2015). Thermokarst and erosional features on land, which can occupy up to 20% of the permafrost landscape (Olefeldt et al., 2016), can further contribute to this OC flux by mobilizing deep permafrost carbon pools before waves erode the shore (see Figure 1). The most prominent features are retrogressive thaw slumps, thermoerosional gullies, and active layer detachment slides (Abbott et al., 2015) and are initiated by thaw of massive ice beds or degradation of ice wedges (Jorgenson et al., 2015; Ramage et al., 2017). The occurrence of thermoerosional features increases the amount of OC transported to the ocean but also leads to OC degradation prior to the release into the ocean (Tanski et al., 2017; Vonk et al., 2013; Ward & Cory, 2016). In short, the mechanisms of erosion at the Arctic coast are multifaceted but all contribute to the release of OC to the nearshore zone. The current mean circum-Arctic erosion rate is 0.57 m/year but can exceed 20 m/year at specific locations (Jones et al., 2018), inducing the transfer of large masses of sediment (430 Tg/year) and OC (up to 14 Tg/year; Wegner et al., 2015) to the nearshore

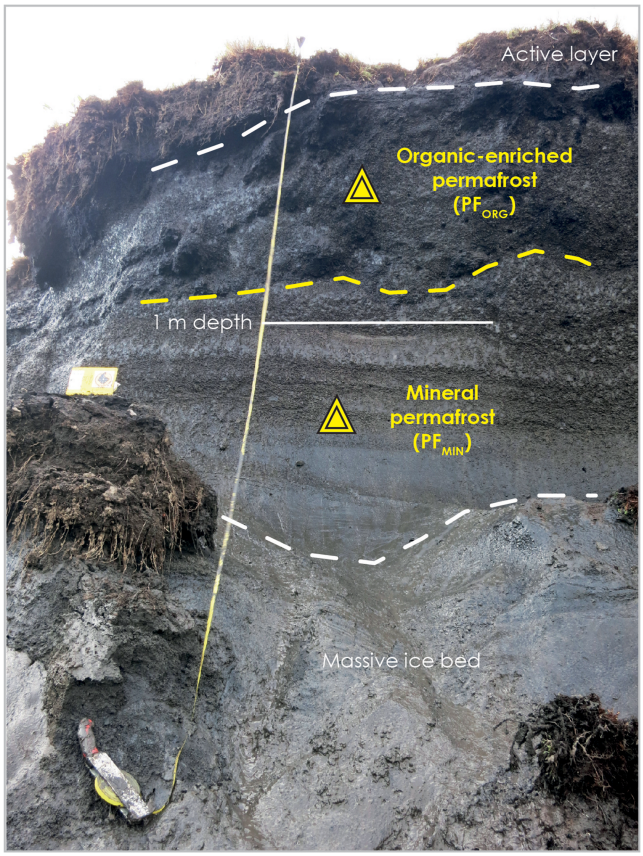

Figure 2. Exemplified sampling profile of exposed permafrost sediments. Sampling targeted the upper organic-enriched permafrost layer (PF_{ORG}), the deeper mineral permafrost layer (PF_{MIN}), and seawater ~1 km off the coast of the sampling location. Depth is given in meter below surface. For original sampling profiles and sampling locations see Figures S1 and S2.

zones of the Arctic Ocean. This carbon is potentially subject to mineralization into GHGs within the coastal realm upon release from permafrost (Semiletov et al., 2013; Vonk et al., 2012; Vonk & Gustafsson, 2013). Projected higher water temperatures and longer periods of open-water (ice-free) conditions will further promote the erosion of these coasts as cliffs will be exposed to wave action and storms during longer time spans (Barnhart et al., 2014; Dai et al., 2019; Overeem et al., 2011). Several studies already show that permafrost OC turnover in aquatic systems is substantial and important (Abbott et al., 2014; Vonk et al., 2012; Vonk et al., 2015). Yet in recent carbon budgets, OC from coastal erosion is assumed to be subject to turnover only at the cliff (Vonk et al., 2012) with the remainder exported offshore and buried in seafloor sediments (McGuire et al., 2009). Here, we hypothesize that a substantial part of this OC is not buried or exported but directly released from the coastal zones, onshore and within nearshore waters, as carbon dioxide (CO_2) in magnitudes relevant to the Arctic carbon budget and climate system.

2. Materials and Methods

2.1. Mimicking Coastal Erosion and GHG Production With Incubations

Insights on GHG emissions from eroding permafrost coasts in the Arctic are extremely rare. We developed a mechanistic approach to simulate erosion under laboratory conditions by mixing permafrost material with seawater and quantifying the subsequent GHG release. Sampling of permafrost (PF) and seawater (SW) took place on *Qikiqtaruk*—Herschel Island at the Yukon coast (Figure S1 in the supporting information). We targeted the upper (<1 m depth) organic-enriched layer ($PF_{ORG;}$ here defined as permafrost with a total OC (TOC) content of >5.0 wt%) and the lower (>1 m depth) mineral permafrost layer (PF_{MIN}; Figures 2 and S2). The average TOC content of our samples (4.7 ± 3.1 wt%) is slightly lower than carbon contents observed in continuous permafrost zones of Alaska and Siberia (10.5 ± 13.8% TOC; Schädel et al., 2014, and references therein) but is in the range of average TOC contents calculated for the entire Beaufort Sea and circum-Arctic coastline with 2.4–5.7 and 2.1 wt% OC, respectively (Lantuit et al., 2012). The seawater used for incubation was taken 1 km offshore the sampling site, where turbidity due to erosion or resuspension was not occurring. The Yukon Coast is strongly affected by erosion and thermokarst formation (Irrgang et al., 2019; Ramage et al., 2017; Figure 1). During a brief open-water period of approximately 4 months, coastal cliffs on *Qikiqtaruk*—Herschel Island erode at an average rate of 0.45 m/year (1970–2000; Lantuit & Pollard, 2005) and retrogressive thaw slumps are highly active (Ramage et al., 2017). The local erosion rate is slightly lower than for the adjacent Yukon Coast (0.7 m/year; Couture et al., 2018) and Beaufort Sea coast (1.1–1.2 m/year) but close to the circum-Arctic rate of 0.57 m/year (Lantuit et al., 2012).

Qikiqtaruk—Herschel Island is a moraine formed during the late Wisconsin glaciation and characterized by continuous permafrost (Pollard, 1990). Permafrost is covered by a seasonally non-frozen active layer varying between 40 and 60 cm in thickness during the summer season (Burn & Zhang, 2009). Sediment composition and ground ice contents (45–75 vol.%; Couture & Pollard, 2015) are similar to the rest of the western Canadian Arctic, Alaska, and most of Siberia. In these regions sediments are mainly composed of unconsolidated fine-grained deposits with high ground ice contents of 50–60 vol.% in the western Canadian Arctic (French, 1998), 44–89 vol.% in Alaska (Kanevskiy et al., 2013) and 65–90 vol.% in Siberia (Schirrmeister et al., 2011).

2.2. Experimental Setup and Incubation Conditions

To mimic GHG production during coastal erosion and in situ conditions at the coast, three aliquots of each PF_{ORG} ($n = 2$) and PF_{MIN} ($n = 2$) sample were incubated with seawater for an average Arctic open-water

Table 1
Summary of Incubation Setups, Cumulative CO_2 Production, and Associated TOC Loss

T	Sample	n	CO_2-C (mg/gdw)	std (±)	TOC loss (%)	std (±)
(4 °C)	PF_{ORG} + SW	6	4.3	1.0	1.5	0.2
	PF_{ORG} Control	2	3.1	0.3	1.1	0.0
	PF_{MIN} + SW	6	3.6	0.6	6.2	1.2
	PF_{MIN} Control	2	2.3	0.3	3.9	0.2
(16 °C)	PF_{ORG} + SW	6	5.5	0.7	1.9	0.1
	PF_{ORG} Control	2	6.4	1.4	2.4	0.3
	PF_{MIN} + SW	6	7.4	1.1	12.8	1.9
	PF_{MIN} Control	2	3.9	0.3	6.8	0.4

Note. Coastal erosion was mimicked by mixing representative permafrost deposits (see Figure 2) with seawater (SW) at different temperatures (T) under aerobic conditions for an average Arctic open-water season of 4 months, that is, 120 days. Organic-enriched and mineral permafrost (PF_{ORG} and PF_{MIN}, respectively) were incubated with SW and separately for control conditions (see supporting information Table S1). Total organic carbon (TOC) loss in percent is given as loss in form of CO_2 from initial TOC (mg C/gdw) measured prior to the incubations in PF sediments.

season of 4 months, that is, 120 days (Lantuit et al., 2012) (Table 1; see Figures S2, S3, and Text S1). Aerobic conditions were applied to mimic in situ conditions at the coast. Low and high temperatures (4 and 16 °C, respectively) were applied to study the effect of increased temperatures on OC decomposition. GHG emissions in form of CO_2 and methane (CH_4) were measured during the incubations (see Text S2) and complemented with analyses of TOC, dissolved organic carbon (DOC), stable carbon isotopes (δ^{13}C-TOC), and TOC/total nitrogen (TOC/TN) ratios (see Text S3) and measured before and after 4 months of incubation ($T = 1$) to determine carbon turnover (Knoblauch et al., 2013; Strauss et al., 2015). OC loss and turnover into CO_2 was estimated using initial TOC content and produced CO_2 (mg C/gdw) at the end of the incubation (see Text S4). We used the 4 °C temperature as reference for local temperatures in the study area, since it is in the range of temperatures observed along the Yukon Coast in summer and comparable to other incubation studies (Burn & Zhang, 2009; Lee et al., 2014; Schädel et al., 2014). We used the 16 °C scenario as the plume of the Mackenzie River can transport warm water masses to the Yukon Coast (Dunton et al., 2006) and to be comparable with previous studies that used a 15 °C temperature setting (e.g., Dutta et al., 2006; Lee et al., 2012).

3. Results and Discussion

3.1. CO_2 Production and Carbon Turnover

The experiment shows that substantial amounts of CO_2 are produced from thawing permafrost mixed with seawater and without, indicating CO_2 release along the land-ocean continuum of eroding permafrost coastlines. During an average open-water season of 4 months, between 3.6 ± 0.6 (PF_{MIN} + SW) and 4.3 ± 1.0

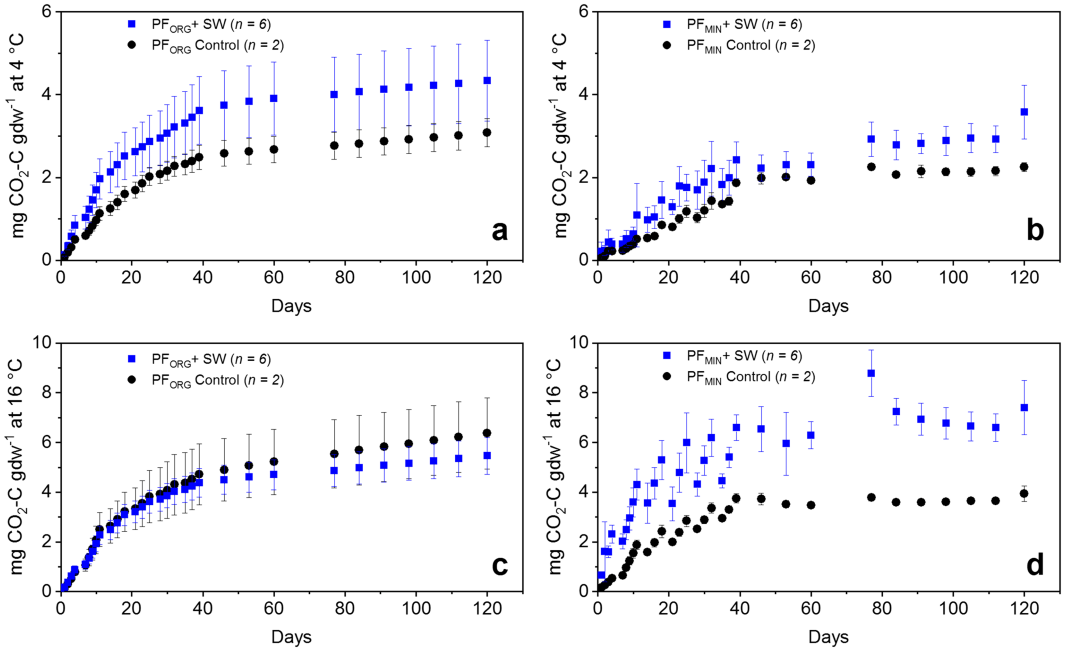

Figure 3. Cumulative aerobic CO_2 production from coastal permafrost during an incubation period of 120 days. Samples were incubated at 4 °C (a, b) and 16 °C (c, d). Cumulative aerobic CO_2 production is given ± standard deviation (error bars) for organic-enriched permafrost (PF_{ORG}; a, c) and mineral permafrost (PF_{MIN}; b, d) mixed with seawater (SW) and control conditions.

(PF_{ORG} + SW) mg CO_2-C/gdw are produced from thawing permafrost in seawater at 4 °C (Table 1 and Figure 3). The produced CO_2 from permafrost thaw in seawater outnumbered production from controls mimicking erosion onshore. In PF_{ORG} and PF_{MIN} Controls CO_2 production was 3.1 ± 0.3 and 2.3 ± 0.2 CO_2-C/gdw, respectively. In all incubation scenarios substantial amounts of initial OC were mineralized. The observed CO_2 production in PF_{ORG} and PF_{MIN} mixed with seawater corresponds to TOC (mg C/gdw) losses of 1.5 ± 0.2% and 6.2 ± 1.2%, respectively, whereas in PF_{ORG} and PF_{MIN} Controls, 1.1 ± 0.0% and 3.9 ± 0.2% TOC were lost, indicating quick mineralization of OC into CO_2 in the nearshore zone. The measured CO_2 release is in the range of or even greater than rates found in Alaska and Siberia, where productions of 1.07 to 3.42 mg CO_2-C/gdw (over 500 days; Lee et al., 2012) and 0.87 ± 0.56 to 1.6 ± 1.2 mg CO_2-C/gdw (over 1,200 days; Knoblauch et al., 2013) were observed for much longer incubation periods in aerated thawing terrestrial permafrost.

At higher temperatures (16 °C), total CO_2 production further increased by 21% (PF_{ORG} + SW) and 52% (PF_{MIN} + SW) when comparing the cumulated production at the end of the incubation (supporting information Figure S5). Only small amounts of methane were released (<10 μg CH_4-C/gdw; see supporting information Figure S6 and Table S1), potentially by outgassing from soil pore spaces or microbial production (Wagner et al., 1999). Organic matter decomposition is generally indicated by the decrease (given in percent change from initial measurements) of (1) DOC concentrations (28.0% in PF_{ORG} and 52.2% in PF_{MIN}), (2) TOC/TN ratios (12.8% in PF_{ORG} and 18.3% in PF_{MIN}), and an increase of δ^{13}C-TOC (0.9% in PF_{ORG} and 0.7% in PF_{MIN}) measured before and after incubations under control conditions at 4 °C (see Tables S2 and S3), which are all strong predictors for degradation and CO_2 production from permafrost OC (Knoblauch et al., 2013; Schädel et al., 2014; Strauss et al., 2015).

3.2. CO_2 Production Dynamics

The bulk of aerobic CO_2 was released quickly during the first 2 months of incubation most likely due to rapid removal of the most labile OC fractions of the fast carbon pool (Schädel et al., 2014), resulting in high CO_2 production rates over the first weeks of incubation (Dutta et al., 2006; Knoblauch et al., 2013). Maximum daily production rates peaked at 244.5 ± 57.4 μg CO_2-C/gdw/day for PF_{ORG} + SW and 188.4 ± 187.0 μg CO_2-C/gdw/day for PF_{MIN} after 11 days. Daily production rates observed at 16 °C were substantially higher than at 4 °C (supporting information Figure S5). Production rates decreased and plateaued after ~40 days at both temperatures. The cumulative CO_2 production and rates are in good agreement with existing permafrost incubation studies (Knoblauch et al., 2013; Lee et al., 2012; Schädel et al., 2014), where higher OC contents result in higher CO_2 production and production rates decrease toward baseline rates after 1 to 3 months (Knoblauch et al., 2013; Lee et al., 2012; Schädel et al., 2014).

The removal of OC during the course of our experiment was particularly efficient for the labile DOC fraction, typical for permafrost OC (Abbott et al., 2014; Vonk et al., 2013) shown for the Controls (see Table S2). The presence of saltwater potentially supported the mobilization of labile OC compounds from permafrost sediments as flocculation processes in seawater discriminate against less labile high molecular weight fractions in sediments (Dou et al., 2005). This might explain higher CO_2 production in permafrost incubated with seawater than without. Aerobic microbial communities with very high respiration rates found in aerated top layers of shallow coastal sediments are probably responsible for the quick CO_2 production in seawater (Arndt et al., 2013; Rasmussen & Jorgensen, 1992). The time required to completely convert the OC pool exceeds the duration of a single open-water period (Knoblauch et al., 2013) and was not accounted for in the experiment. Yet it implies that OC decomposition and CO_2 production could continue on longer timescales if not buried and preserved on the seafloor (Bröder et al., 2018; Schädel et al., 2014; Vonk et al., 2013).

Our results question the paradigm in current carbon budgets that OC is entirely transported offshore, utilized for primary production or buried in shelf sediments (Bröder et al., 2016; Dunton et al., 2006; Vonk & Gustafsson, 2013). We suggest an additional mechanism of GHG production from coastal permafrost degradation and collapse into the Arctic nearshore zone. We show that a fraction of eroded permafrost OC is quickly mineralized into CO_2, with or without seawater added, indicating potential CO_2 release to the atmosphere during coastal erosion. This corresponds with findings from Siberia that showed extensive outgassing of CO_2 from the coastal zone and oversaturated CO_2 conditions in coastal waters, potentially as a result of OC mineralization from terrestrial sources (Semiletov et al., 2013) or studies from the Yukon Coast, which show

that only ~13% of eroded OC is sequestered in nearshore sediments with the remainder being potentially available for turnover processes (Couture et al., 2018).

3.3. OC Pathways and CO_2 Dynamics in the Coastal Zone

Latest carbon budgets identify the coastal zone and the continental shelves of the Arctic Ocean as a CO_2 sink (Bates & Mathis, 2009; McGuire et al., 2009). However, we show that coastal permafrost thawing in seawater produces large amounts of CO_2 over a short period. Thus, eroding permafrost coasts and its nearshore waters may release substantial amounts of CO_2 during the open-water season onshore and within the nearshore waters. This carbon pathway and the associated GHG release is not accounted for in climate models yet and might have been already an important contributor during postglacial sea level rise and erosion of the former Beringian landmass (Wegner et al., 2015). To illustrate the potential significance of our findings at a circum-Arctic scale, we used a simple approach to estimate potential CO_2 emissions from coastal collapse on an annual basis. We projected the minimum and maximum observed TOC loss at 4 °C (1.1 ± 0.0 and 6.2 ± 1.2% over 120 days at 4 °C; Table 1) derived from our experiment to the most recent estimation of TOC fluxes from Arctic coasts (up to 14.0 Tg/year; Wegner et al., 2015). This calculation yields an annual CO_2 release rate between 0.2 ± 0.0 to 0.9 ± 0.2 Tg/year from permafrost erosion on land and in nearshore waters. The TOC loss of our study generally corresponds to findings from Dutta et al. (2006), who incubated permafrost over 90 days at 5 °C and showed an OC loss as GHG of 2.1 ± 0.2%. Our calculated CO_2 release compares with the 0.5–1 Pg OC/year projected to be released from vertical permafrost thaw (Schuur et al., 2008) and is in the same order of magnitude as other carbon fluxes in the permafrost environment such as OC fluxes from Arctic rivers into the ocean with 5.4 Tg POC/year and 25 Tg DOC/year (Macdonald et al., 2015; Raymond et al., 2007) or methane fluxes from northern and thermokarst lakes with 24.2 ± 10.5 Tg CH_4/year (Walter et al., 2007). Although our estimated number is only conservative, the calculated CO_2 release from coastal erosion onshore and within the seawater column is substantial and has not been considered for carbon budgets and climate simulations so far.

Our observed CO_2 production and calculated release from nearshore waters comes with several uncertainties. In the laboratory we had to neglect environmental parameters, which could not be mimicked but that most likely have a strong impact on CO_2 pathways in the coastal environment. This includes the environmental variability of OC stocks along Arctic coasts and its vulnerability to thaw and microbial turnover into GHGs, length of the open-water season, presence and duration of phytoplankton blooms, pH, water temperature, and oxygen availability as well as the depositional dynamics, bathymetry, water depth, and nearshore currents along Arctic coasts. Yet we believe that terrestrial OC turnover and potential CO_2 production is promoted along the coastal margins due to the combined effects of resuspension and supply of oxygen in shallow nearshore waters (Fritz et al., 2017; Macdonald et al., 2015; Vonk et al., 2012) or in lagoon systems and submerged areas of the Arctic (Brown et al., 2003; Dunton et al., 2006; Ruz et al., 1992; Schreiner et al., 2013). From the uncertainties mentioned, especially ice algae and primary production stimulated by nutrient supply from upwelling or terrestrial input (Ardyna et al., 2014; Tremblay et al., 2011) could promote the uptake of produced CO_2 stemming from permafrost erosion in coastal waters but turbidity caused by erosion and resuspension potentially may limit this uptake (Semiletov et al., 2013).

Terrestrial OC is being buried in large amounts directly in nearshore sediments (Couture et al., 2018; Vonk et al., 2014). Yet not the entire eroded OC is sequestrated in nearshore sediments and substantial portions are transported within the water column (Vonk et al., 2014). Stein and Macdonald (2004) estimated that ~33% of terrestrial-derived particulate OC is metabolized in the ocean. Heavier portions of mineral-bound terrestrial OC and older OC carbon fractions might quickly settle and accumulate upon release into coastal waters (Gustafsson et al., 2000; Karlsson et al., 2011; Vonk et al., 2014). Yet waves, longshore currents, and ice scouring can keep this OC in resuspension (Are, 1988; Macdonald et al., 2015; Vonk et al., 2012) making it available for further degradation into DOC and thus microbial uptake and decomposition into CO_2 (Battin et al., 2008; Dou et al., 2005). OC stemming from permafrost can contribute between <10% and almost 50% of OC in nearshore waters of the Arctic Ocean (Vonk et al., 2014). Labile terrestrial DOC fractions can be quickly mineralized within the water column and have been shown to have a short residence time of approximately 2–5 years on the shelf

(Alling et al., 2010; Letscher et al., 2011) during which approximately 30–50% of DOC is potentially being lost. Sunlight may further catalyze the turnover process in the upper water column by photooxidation (Cory et al., 2014; Ward et al., 2017). Eventually, resuspension and bioturbation also remobilize buried OC and slow carbon pools (Arndt et al., 2013; Rasmussen & Jorgensen, 1992), which decomposition can take up to decades (Schädel et al., 2014), postponing CO_2 production beyond one open-water season.

4. Conclusion

We show that substantial amounts of CO_2 are released from thawing permafrost in seawater during incubations. We conclude that potentially large amounts of CO_2 are being produced along eroding permafrost coasts, onshore during transit and within the nearshore water column, especially in the shallow water column where resuspension occurs. This carbon and GHG release pathway is not accounted for yet in climate models. We expect that coastal CO_2 production further increases due to the combined effects of accelerated coastal erosion, higher sea surface temperatures, and a longer open-water season which increases the time when cliffs are exposed to wave action and storm events. The high pace of environmental change along Arctic permafrost coasts could catalyze and increase the production of CO_2 in the coastal realm and thus strengthen permafrost carbon cycling.

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