

High biolability of ancient permafrost carbon upon thaw

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[1] Ongoing climate warming in the Arctic will thaw permafrost and remobilize substantial terrestrial organic carbon (OC) pools. Around a quarter of northern permafrost OC resides in Siberian Yedoma deposits, the oldest form of permafrost carbon. However, our understanding of the degradation and fate of this ancient OC in coastal and fluvial environments still remains rudimentary. Here, we show that ancient dissolved OC (DOC, >21,000 ¹⁴C years), the oldest DOC ever reported, is mobilized in stream waters draining Yedoma outcrops. Furthermore, this DOC is highly biolabile: 34 ± 0.8% was lost during a 14 day incubation under dark, oxygenated conditions at ambient river temperatures. Mixtures of Yedoma stream DOC with mainstem river and ocean waters, mimicking in situ mixing processes, also showed high DOC losses (14 days; 17 ± 0.8% to 33 ± 1.0%). This suggests that this exceptionally old DOC is among the most biolabile DOC in any previously reported contemporary river or stream in the Arctic. **Citation:** Vonk, J. E., et al. (2013), High biolability of ancient permafrost carbon upon thaw, *Geophys. Res. Lett.*, 40, doi:10.1002/grl.50348.

1. Introduction

[2] The northern soil carbon (C) pool contains approximately 1672 Pg C [Tarnocai et al., 2009] of which more than a quarter (>500 Pg C) is stored in frozen Yedoma [Zimov et al., 2006] deposits in the Siberian-Arctic (Figure 1). This is approximately equal to the amount of C stored in total global forest biomass [Pan et al., 2011]. Yedoma deposits formed during the late Pleistocene [Zimov et al., 2006; Schirrmeister et al., 2011] in unglaciated Siberia and cover ca. 1 million km² (Figure 1a). Due to a lack of processing and survival of bacteria [Dutta et al., 2006; Rivkina et al., 1998] during formation, organic carbon (OC) held in

Yedoma deposits has been hypothesized to be highly biolabile upon thaw. Formation of Yedoma is initiated by accumulation of sediments [Zimov et al., 2006], and is therefore not as much exposed to repetitive freeze-thaw cycles, that process and degrade OC, in comparison to other soil ecosystems. As climate warms, permafrost soils (including Yedoma) will thaw and decompose leading to the production of greenhouse gases, in turn accelerating climate warming [Dutta et al., 2006; Schaefer et al., 2011]. This is referred to as the “permafrost carbon feedback” (PCF). Initial estimates suggest that the PCF can be substantial [Zimov et al., 2006; Schuur et al., 2008; Schaefer et al., 2011], but remarkably, this process is not included in any Intergovernmental Panel on Climate Change (IPCC) [IPCC, 2007] scenario of future climate change. Understanding how frozen OC pools are processed upon thaw is therefore crucial for understanding future climate change and C dynamics in the Arctic and globally.

[3] Four physical mechanisms release OC from permafrost to the atmosphere [Schuur et al., 2008]: active layer deepening, talik formation, thermokarst development, and erosion. Coastal and riverbank erosion of Yedoma deposits can occur over vast distances (e.g., along the >5000 km East Siberian Arctic coastline) [Vonk et al., 2012] and may release OC from entire soil depth profiles (up to ca. 40 m) directly to aquatic environments. A deepening of the active layer—the seasonally thawed surface soil, may also lead to an increased supply of permafrost derived OC to inland waters over regional scales. After thawing, the crucial current unknowns are how much, and how rapidly does OC held within these deposits enter the contemporary C cycle. Inland and coastal waters are increasingly recognized as important processors of terrestrial organic carbon (OC), generating a substantial flux of CO₂ to the atmosphere [Aufdenkampe et al., 2011; Battin et al., 2008; Bianchi, 2011]. Carbon processing during coastal release in the Siberian Arctic has been shown to be substantial [Alling et al., 2010; Sánchez-García et al., 2011]. This study investigates the “hydrological biolability”, i.e., the potential biodegradability within the residence time of the aquatic system, of OC from recently thawed Yedoma deposits introduced to aquatic ecosystems.

[4] The “Duvannyi Yar” exposure on the banks of Kolyma River in Northeast Siberia (Figure 1) is a classical and relatively well-studied Yedoma site [e.g., Vasil’chuk and Vasil’chuk, 1997; Dutta et al., 2006]. Radiocarbon ages of the ca. 40 m high deposits range between 13,000 and 45,000 years [Vasil’chuk and Vasil’chuk, 1997]. Permafrost thaw and/or riverbank erosion result in mean retreat rates of 3–5 m/yr. Water from melting ice wedges feed streams that carry recently thawed Yedoma off the cliff into the Kolyma River (Figure 2). These sediment-laden, first-order streams represent an integrated signal of recently thawed Yedoma.

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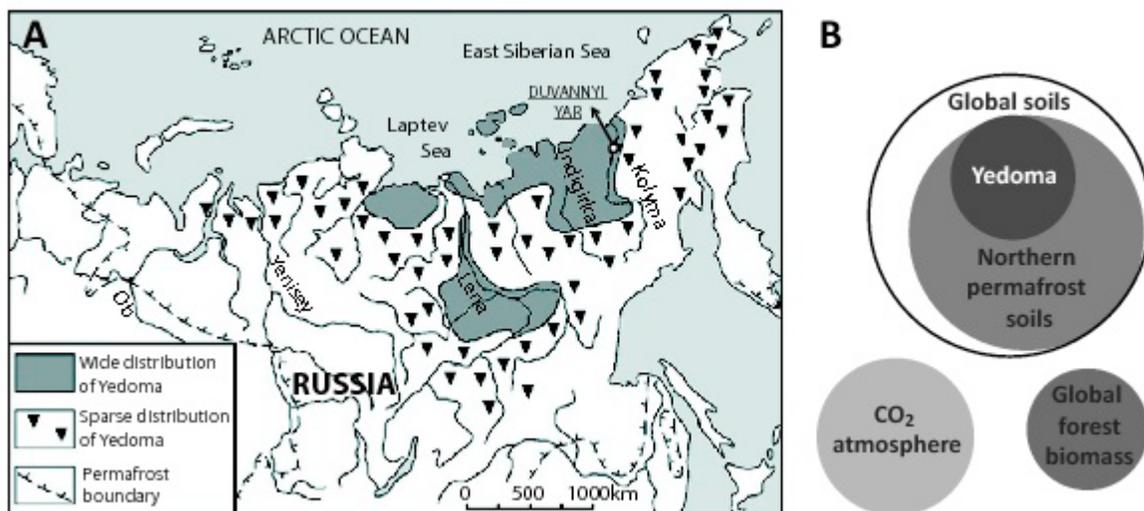


Figure 1. (a) Yedoma extent in the Siberian Arctic [Romanovskii, 1993], overlain with major rivers and our study site Duvannyi Yar. (b) Relative carbon pool sizes of Yedoma (500 Pg) [Zimov *et al.*, 2006; Tarnocai *et al.*, 2009] in comparison with other major global carbon pools (global soils 2400 Pg, northern permafrost soils 1672 Pg, global forest biomass 450 Pg and atmospheric CO₂ 750 Pg) [IPCC, 2007; Tarnocai *et al.*, 2009; Pan *et al.*, 2011].

These first-order streams are formed early in the summer when ice wedges start to melt, and their course and magnitude depends on local riverbank collapse, thaw rates and relief. We used the stream dissolved OC (DOC) for incubations and mixing experiments with Kolyma River and East Siberian Sea-water (see section 2), with the goal to estimate biolability during fluvial and coastal processing of ancient permafrost OC.

2. Methods

[s] In July 2010, we sampled six thaw streams along the Duvannyi Yar exposure (on a line from 68.631°N–159.156°E

to 68.631°N–159.143°E, Figure 2) on the Kolyma River. The streams have all freshly formed from thawing ice-rich Yedoma permafrost, and meander down the cliff in a course that is dependent on local bank collapse, thaw rates and relief. Estimated flow rates on our sampling day were ca. 2.5–10 L/s, stream temperatures just above 0 °C and transport time from thaw to entry into Kolyma River < 1 h. The water was filtered through precombusted 0.7 μm glass fiber filters (Whatman) and analyzed at the Northeast Science Station in Cherskii (Russia), for DOC on a Shimadzu TOC-V analyzer using established protocols [Mann *et al.*, 2012]. Frozen water samples were exported, acidified (to remove inorganic carbon)

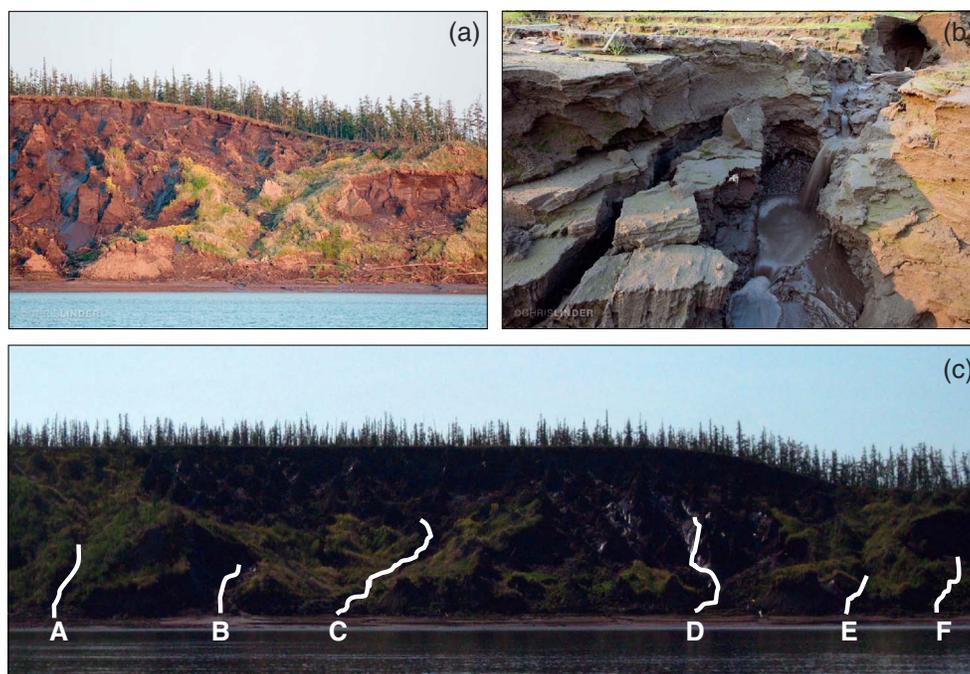


Figure 2. (a) Duvannyi Yar exposure on the Kolyma river bank containing (b) freshly thawed Yedoma organic matter is exported down the cliffs merging in mud streams that drain into Kolyma River. (c) Location of thaw streams sampled in 2010. (photos © Chris Linder).

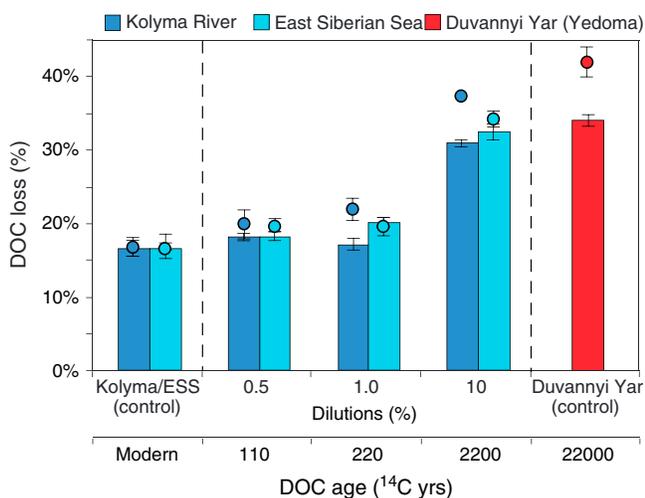


Figure 3. Dissolved organic carbon loss (%) after 14 days (bars) and 28 days (points) dark incubations at 20°C for Kolyma River (light blue), East Siberian Sea (dark blue), Yedoma streams (red), and three dilutions of Yedoma water with Kolyma River or East Siberian Sea water. The ¹⁴C age of DOC (years) (x-axis) represents the proportion of Duvannyi Yar (Yedoma) stream water added to Kolyma River or East Siberian Sea water. Standard deviations represent errors from triplicate experiments.

[7] Our biolability study focused on DOC instead of POC, because it is the most important intermediary in the global C cycle. Only low-molecular weight dissolved compounds can be transported through microbial cell membranes, and are thus readily available for microbial metabolism [Battin *et al.*, 2008]. Thaw streams originating in Pleistocene Yedoma deposits lost $34 \pm 0.8\%$ of their DOC after 14 days and $41 \pm 3\%$ after 28 days incubation (see section 2 and Figure 3). With an initial DOC concentration of 155 mg/L, these losses convert to a remarkable decrease in DOC concentration of 52 mg/L in 14 days, or 63 mg/L in 28 days. Additionally, samples of Kolyma River and East Siberian Sea water (salinity 26) that were spiked with Yedoma-DOC showed an increase in DOC loss with increasing Yedoma additions (Figure 3), from ca. 18% loss for a 0.5% Yedoma addition to ca. 32% loss for a 10% Yedoma addition after 14 days. Higher percent OC losses were observed in both fresh and saline waters with increasing additions of Yedoma OC (Figure 3) suggesting that Yedoma OC may enhance, or even prime, remineralization of contemporary DOC [Bianchi, 2011]. We propose that the high biolability of this >21,000 year old DOC can be explained by the following: (i) a lack of pre-processing of DOC prior to thaw [e.g., Dutta *et al.*, 2006], (ii) the presence of more low-molecular-weight compounds or fewer aromatics [Waldrop *et al.*, 2010], (iii) nutrient availability, and (iv) an abrupt spike in the activity of Yedoma's intrinsic bacteria, having survived for thousands of years [Rivkina *et al.*, 1998], but now exposed to temperatures above zero and availability of (liquid) water. Previous reports on Arctic stream or river biolability report percent DOC losses up to 42% (3 months at 20°C; Alaska) [Holmes *et al.*, 2008], up to 35% (40 days at 25°C; Alaska) [Balcarczyk *et al.*, 2009], up to 53% for under-ice waters (28 days, 15°C; Alaska) [Wickland *et al.*, 2012], up to 28% (97 days, temperature not given; W-Siberia) [Kawahigashi *et al.*, 2004], and up

to 20% (28 days, room temperature; Kolyma River) [Mann *et al.*, 2011]. Variable incubation conditions make direct comparisons challenging, yet a 34% loss of ancient (>21,000 ¹⁴C years) DOC after only 14 days is among the highest ever reported for pristine, non-glacier-fed, rivers or streams.

[8] The conventional way to calculate and globally-upscale greenhouse gas release fluxes from thawing permafrost is typically based on direct CO₂ and CH₄ emission measurements from thawing tundra soils [Dorrepaal *et al.*, 2009]. Here, we show that a substantial portion of greenhouse gases may be generated during stream, river and shelf transport. One should note here that we only examined release of Yedoma OC in the dissolved phase; the dynamics of POC, with fluxes that are likely orders of magnitude higher (Table 1), and that may breakdown (also photochemically) to release substantial amounts of DOC, remain undetermined. Our results further indicate that differences in the reactivity of contemporary versus old OC, and associated fluxes need to be accounted for in future studies. The strong degradation of Yedoma-DOC in the stream network could also explain why significant seasonal DOC aging in the Kolyma River main-stem has not been observed [Neff *et al.*, 2006]. Increased contributions of permafrost-derived C may not be easy to detect at the mouth of large Arctic rivers as it is removed rapidly over short incubation times likely comparable to water residence times within the headwaters (~3–7 days from Duvannyi Yar to river mouth, assuming average river velocities of 0.5–1.5 m/s, Holmes *et al.* [2012]). Furthermore, the flux of terrestrial-derived OC to the Arctic Ocean, estimated from measurement at the river mouth, may misrepresent the actual mobilization and turnover of the DOC in the watershed, as processing of DOC within the catchment, prior to arrival at the river mouth is not included in these estimates. Similar to recent studies that revealed the presence of biolabile ancient OC being liberated from glaciers [Hood *et al.*, 2009], our data also contrasts to the prevailing paradigm of age versus reactivity of OC.

4. Conclusions

[9] We show here that Yedoma DOC, with >21,000 ¹⁴C years the oldest ever reported, is highly biolabile upon release, both in fluvial (i.e., Kolyma River) and in coastal environments (i.e., East Siberian Sea) (Figure 3). Estimates of the exact contribution of Yedoma OC in Arctic C cycling are improving [Vonk *et al.*, 2012], but are still subject to considerable uncertainties, e.g., due to a lack of adequate spatial coverage of Yedoma deposits [Romanovskii, 1993], and accurate estimates of delta and riverbank erosion. Ongoing Arctic climate warming is expected to further increase the thermal exposure, thaw and erosion of Yedoma, particularly along the extensive East Siberian Arctic coastline, where Yedoma deposits are ubiquitously present and increasingly exposed to wave fetch and storms due to recent reductions in sea ice [IPCC, 2007; Stroeve *et al.*, 2007]. Yedoma OC, hosting ca. 25% of the total belowground permafrost soil OC [Zimov *et al.*, 2006; Tarnocai *et al.*, 2009] is very old, yet highly biologically reactive upon mobilization. The high biolability of this material seems likely to amplify the effect of the PCF scenario in the Arctic. Furthermore, examining permafrost degradation through ¹⁴C-DOC measurements at river mouths may not be representative for the actual mobilization and turnover of permafrost C, as extensive

processing of permafrost derived-C *within* the watershed may be masking the river mouth signal. It is apparent that further studies are needed to address the magnitude of the flux of thawing Yedoma OC, but also, importantly, to incorporate the reactivity of this material in regional and global C budgets.

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