Reconciling carbon-stock estimates for the Yedoma region

Katey Walter Anthony[1], Guido Grosse[2], Peter Anthony[1], Miriam Jones[3], Sergei Davydov[4], & Sergey A. Zimov[4]

[1] *University of Alaska Fairbanks*
[2] *Alfred Wegener Institute Helmholtz Centre for Polar and Marine Research, Potsdam, Germany*
[3] *United States Geological Survey*
[4] *Pacific Institute of Geography Russian Academy of Sciences*

Permafrost soil organic carbon (C) in the Yedoma region comprises a large fraction of the total circumpolar permafrost C pool, yet estimates based on different approaches during the past decade have led to disagreement in the size and composition of the Yedoma region permafrost C pool. This research aims to reconcile different approaches and show that after accounting for thermokarst and fluvial erosion processes of this interglacial period, the Yedoma region C pool (456 $\pm$ 45 Pg C) is the sum of 172 $\pm$ 19 Pg Holocene-aged C and 284 $\pm$ 40 Pg Pleistocene-aged C.

The size of the present-day Pleistocene-aged yedoma C pool was originally estimated to be 450 Pg based on a mean deposit thickness of 25 m, 1$\times$106 km^2 areal extent, 2.6% total organic C content, 1.65$times$103 kg m^{-3}dry bulk density, and 50% volumetric ice wedge content (Zimov et al. 2006). This estimate assumed that 17% of the Last Glacial Maximum yedoma C stock was lost to greenhouse gas production and emission when 50% of yedoma thawed beneath lakes during the Holocene. However, the regional scale yedoma C pool estimate of Zimov et al. (2006) did not include any Holocene C and assumed that all of the 450 Pg C was Pleistocene-aged.

In subsequent global permafrost C syntheses, soil organic C content (SOCC, kg C m^{-2}) data from the Northern Circumpolar Soil C Database (NCSCD) and Zimov et al. (2006) were used to estimate the soil organic C pool for the Yedoma region (450 Pg), assuming only Pleistocene-aged yedoma C from 3 to 25 m (407 Pg), and a mixture of C ages in the 0 to 3 m interval (43 Pg).

A more recent synthesis of Yedoma-region C stocks based on extensive sampling by Strauss et al. (2013) took into account lower C bulk density values of yedoma, higher organic C concentrations of yedoma, a larger landscape fraction of thermokarst (70% of Yedoma region area), the larger C concentration of thermokarst, and remote-sensing based quantification of ice-wedge volumes. This synthesis produced lower mean- and median-based estimates of Yedoma-region C, 348+73 Pg and 211 +160/-153 Pg respectively. However, Strauss et al. (2013) focused on the remaining undisturbed yedoma and refrozen surface thermokarst deposits and thus did not include taberite deposits, which are the re-frozen remains of yedoma previously thawed beneath thermokarst lakes and still present in large quantities on the landscape.

In our study (Walter Anthony et al. 2014), we measured the dry bulk density directly on 89 yedoma and 311 thermokarst-basin samples, including taberites, collected in four yedoma subregions of the North Siberian Kolyma Lowlands. Multiplying the organic matter content of an individual sample by the same sample's measured bulk density yielded an organic C bulk density data set for yedoma samples that was normally distributed. Combining our subregion-specific organic C bulk density results with those of Strauss et al. (2013) for other yedoma subregions extending to the far western extent of Siberian yedoma, we determined a mean organic C bulk density of yedoma for the total Yedoma region (26 $\pm$ 1.5 kg C m-3), which is similar to that previously suggested by Strauss et al. (2013) (27 kg C m-3 mean based approach; 16 kg C m-3 median based approach). Our estimate of the organic C pool size of undisturbed yedoma permafrost (129 $\pm$ 30 Pg Pleistocene C) in the 396,600 $\pm$ 39,700 km^2 area that has not been degraded by thermokarst since the Last Glacial Maximum (Table 1) is based on this regional-mean C bulk density value. Our calculation also assumes an average yedoma deposit thickness of 25 m and 50% volumetric massive ice wedge content, as in previous estimates (Zimov et al. 2006, NCSCD; Table 1).

Similar results found in the recent study of the Yedoma-region C inventory by Strauss et al.(2013) corroborate our estimate of the undisturbed yedoma

C inventory. The size of the remaining yedoma C pool was estimated by Strauss et al. (2013) to be 112 Pg (vs. 129 Pg, this study) based on mean parameter values: organic C bulk density 27 kg C cm-3 (vs. 26.2 kg C cm-3 in this study), yedoma deposit thickness 19.4 m (vs. 25 m in this study), yedoma volumetric ice wedge content 48% (vs. 50% in this study), and thermokarst extent (70% in both studies). The two studies took different approaches for estimating yedoma deposit thicknesses: Strauss et al. (2013) used 22 field sites from Siberia and Alaska with a mean thickness of 19.4 m; our calculations used a thickness value determined from Russian literature (25 ± 5m, references in Walter Anthony et al. 2014). The mean derived from our limited (n=17) field sites was 38 m in the Kolyma region. The two studies further differ slightly in calculating Yedoma-region area: Strauss et al. (2013), which focused on still frozen deposits vulnerable to future thaw, did not include thawed deposits in present-day lakes, but did include deposits in known smaller yedoma occurrences outside the core Yedoma region such as valleys of NW Canada, Chukotka, and the Taymyr Peninsula. Our study focused on the extent of core-yedoma deposits as well as organic-C stored in present-day yedoma lake deposits. While differences in yedoma thickness and area values can impact upscaling calculations, efforts are underway by the Yedoma region synthesis IPA Action Group (Strauss and colleagues) to analyze more comprehensive data sets and better constrain the values.

Based on our approach that includes a differentiation of thermokarst-lake facies, we estimate that 155 Pg Pleistocene-aged organic C is stored in thermokarst-lake basins and thermoerosional gullies in the Yedoma region of Beringia [155 Pg is the sum of 114 Pg in taberite deposits and 41 Pg in various lacustrine facies]. This 155 Pg Pleistocene-aged C represents the remains of yedoma that thawed and partially decomposed beneath and in thermokarst lakes and streams. Altogether we estimate a total Pleistocene-C pool size of 284 ± 40 Pg for the Beringian Yedoma region in the present day as the sum of Pleistocene C in undisturbed yedoma (129 Pg) and in thermokarst basins (155 Pg, Table 1).

Separately, Holocene-aged organic C assimilated and sequestered in deglacial thermokarst basins in the Yedoma-region is 159 ± 24 Pg. Our upscaling is based on the mean C stocks of individual permafrost exposures (Fig. 2e in Walter Anthony et al. 2014), which were normally distributed. To our knowledge, this is the first study to combine a geomorphologic classification of alas facies with C content, including the deeper lacustrine deposits, for the purpose of systematically upscaling to a regional alas C inventory.

We did not measure the C content of Holocene terrestrial soils overlying undisturbed yedoma permafrost; however, applying values from the NCSCD in Siberia for Histels (44.3 kg C m-2, 9% of Yedoma region area), Orthels (26.0 kg C m-2, 17% of Yedoma region area) and Turbels (38.4 kg C m-2, 63% of Yedoma region area) to the extent of 1-m surface deposits overlying the area of undisturbed yedoma permafrost (396,000 ± 39,600 km^2), results in 12.9 ± 1.3 Pg of Holocene C. This calculation assumes that the 70/30 ratio of thermokarst to undisturbed yedoma applies across the Histel, Orthel and Turbel cover classes.

Altogether, we estimate the Holocene and Pleistocene organic C pool size in the Yedoma region of Beringia as 456 ± 45 Pg (38% Holocene, 62% Pleistocene) (Table 1). Despite the differences in approaches and locations of study sites, similarities in the mean-based estimates of the Yedoma-region organic C pool size between Strauss et al. (2013) and this study corroborate our findings. Not accounting for diagenetically altered organic C from yedoma thawed in situ beneath lakes (taberites), Strauss et al. (2013) estimated 348 Pg C for the regional pool size. Without taberite C, our estimate would be similar (342 Pg C). For our study, focusing on the C balance shifts from the Pleistocene to the end of the Holocene, we show that taberite deposits are an important component and need to be included in the budget as these deposits are a large C pool that represents diagenetically-altered organic C from yedoma thawed in situ beneath lakes (Table 1b). Our estimate of yedoma-derived taberite deposits underlying thermokarst basins (114 Pg C), would bring the Yedoma-region C pool estimate by Strauss et al. (2013) up to 462 Pg C, which is similar to our estimate of 456 Pg C.

In summary, the Yedoma-region organic C value (456 ± 45 Pg C, consisting of Pleistocene and Holocene C) determined by this study is similar to that calculated originally by Zimov et al. (2006) to represent only the Pleistocene yedoma C pool (450 Pg). Subsequently, the Pleistocene-aged yedoma C was considered to be 450 Pg C. Pleistocene-aged yedoma carbon was considered to be >90% of the regional pool by the subsequent NCSCD syntheses for quantification of circumpolar permafrost carbon. The primary difference between the Yedoma-region C pool estimate presented here versus Zimov et al. (2006), which entered the NCSCD syntheses, is that in this study net C gains associated with a widespread thermokarst process are taken into account. The component of Pleistocene yedoma C was reduced in this study by 38% and a new Holocene-thermokarst C pool (159 Pg) was introduced. We lowered the Pleistocene-aged yedoma C pool based on larger, more recent data sets on yedoma's dry bulk density by this study and Strauss et al. (2013) and based on our more recent map-based analysis showing a 20% larger areal extent of deep thermokarst activity in the Yedoma region.

The major implications of this study pertain to the nature and fate of greenhouse gas emissions associated with permafrost thaw in the Yedoma region. Differentiation of the C pool in the Yedoma region (yedoma vs. thermokarst basins) is critical to understanding past and future C dynamics and climate feedbacks. Since a larger fraction of the yedoma landscape has already been degraded by thermokarst during the Holocene (70% instead of 50%), the size of the anaerobically-vulnerable yedoma C pool for the production of methane is 40% lower than that previously calculated. Second, there is concern that permafrost thaw will mobilize and release 'ancient' organic C to the atmosphere. Assuming average radiocarbon ages of Pleistocene-yedoma and Holocene deposits of 30 kya and 6.5 kya respectively, accounting for the new Holocene-aged thermokarst C pool (159 Pg C) lowers the average age of the current Yedoma-region C pool by about one third. This result is important to global C-cycle modeling since C isotope signatures provide valuable constraints in models. Finally, given differences in permafrost soil organic matter origins for the Pleistocene-aged steppe-tundra yedoma C pool [accumulated under aerobic conditions; froze within decades to centuries after burial; and remained frozen for tens of thousands of years] and the lacustrine Holocene-aged C pool [accumulated predominately under anaerobic conditions and remained thawed for centuries to millennia prior to freezing after lakes drained], it is likely that organic matter degradability differs substantially between these two pools. This has implications for differences in their vulnerability to decomposition and greenhouse gas production under scenarios of permafrost thaw in the future.

References

Strauss J., Schirrmeister L, Grosse G, Wetterich W, Ulrich M, Herzschuh U, Hubberten H-W. 2013. The deep permafrost carbon pool of the Yedoma region in Siberia and Alaska. Geophys. Res. Lett. 40, 6165–6170.

Walter Anthony K M, Zimov SA, Grosse G, Jones MC, Anthony P, Chapin III FS, Finlay JC, Mack mC, Davydov S, Frenzel P, Frolking S. 2014. A shift of thermokarst lakes from carbon sources to sinks during the Holocene epoch. Nature, 511, 452-456, DOI 10.1038/nature13560

Zimov,SA, Schuur EAG, Chapin FS. 2006. Permafrost and the global carbon budget. Science 312: 1612–1613.