

Supplementary Materials: Thawing Permafrost as a Nitrogen Fertiliser: Implications for Climate Feedbacks

S1. Soil Carbon Observations

There are several soils databases available which can be used to determine the soil organic carbon content (SOC) in kg m^{-2} . The SOC is typically calculated using the following relationship:

$$\text{SOC} = 1000f_{org}\rho_b(1 - f_C)z \quad (\text{S1})$$

where f_{org} is the organic carbon mass fraction in g kg^{-1} , ρ_b is the soil bulk density in kg m^{-3} , f_C is volumetric fraction of coarse fragments (>2 mm) and z is the thickness of the soil layer (m). Bulk density is hard to measure and can be highly uncertain. Therefore one way of calculating it is from the organic carbon content. Figure S1 shows two of the relationships from the literature which relate the bulk density to the organic carbon content.

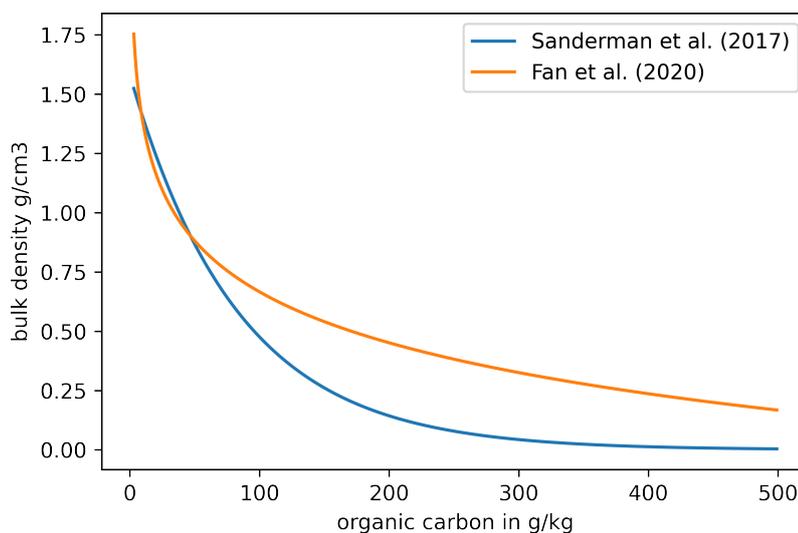


Figure S1. Bulk density derived from the organic carbon by [1,2]

The SOC used in this paper was calculated from a variety of different sources highlighted in Table S1. In all cases the data sets were regridded to 0.5 degrees.

Table S1. Observations of soil organic carbon with information over the permafrost region. The bulk density column defines the source of the bulk density if we needed to derive the SOC from f_{org} .

Data set	ρ_b	Global total (Gt)	Layer thickness (m)	Max depth (m)	Reference
Organic Carbon content					
NCSCD	-	-	0.3, 0.7, 1.0, 1.0	3.0	[3]
WISE30sec	[2]	2064	0.2, 0.2, 0.2, 0.2, 0.2, 0.5, 0.5	2.0	[4]
WISE30sec	[1]	2424	0.2, 0.2, 0.2, 0.2, 0.2, 0.5, 0.5	2.0	[4]
WISE30sec	WISE30sec	2824	0.2, 0.2, 0.2, 0.2, 0.2, 0.5, 0.5	2.0	[5]
S2017	-	3260	0.3, 0.7, 1.05	2.0	[1]
IGBP-DIS	-	1501	1.0	1.0	[6]
GSDE (SOCDfilled.nc)	-	2016	0.05, 0.05, 0.07, 0.12, 0.20, 0.34, 0.55, 0.91	2.3	[7]
GSDE (gapfilled)	GSDE (gapfilled)	2914	0.05, 0.05, 0.07, 0.12, 0.20, 0.34, 0.55, 0.91	2.3	[7]
GSDE (SOCD5min.nc)	-	1874	0.05, 0.05, 0.07, 0.12, 0.20, 0.34, 0.55, 0.91	2.3	[7]
Carvahlais	-	2450	maximum soil depth	-	[8]
Organic Nitrogen content					
GSDE	-	148	0.05, 0.05, 0.07, 0.12, 0.20, 0.34, 0.55, 0.91	2.3	[7]
IGBP-DIS	-	148	1.0	1.0	[6]
WISE30sec	[2]	145	0.2, 0.2, 0.2, 0.2, 0.2, 0.5, 0.5	2.0	[4]
WISE30sec	[1]	147	0.2, 0.2, 0.2, 0.2, 0.2, 0.5, 0.5	2.0	[4]
WISE30sec	WISE30sec	163	0.2, 0.2, 0.2, 0.2, 0.2, 0.5, 0.5	2.0	[4]

S2. Observational Constraint on Permafrost Carbon

In order to evaluate the amount of labelled permafrost soil carbon represented by the JULES-IMOGEN simulations we need an observational based estimate of the total permafrost carbon. In general the large scale observational data sets of soil carbon in the permafrost region give the amount of soil carbon in the whole soil profile rather than the amount of carbon within the permanently frozen soil. However, this can be quantified given an estimate of the top of the permafrost table. Figure S2 shows an observational based relationship between the maximum summer thaw depth (a proxy for the top of the permafrost table) and the annual mean air temperature (MAAT). The soil-based observations were taken from the Circumpolar Active Layer Monitoring Network [CALM: [9]] and the Global Terrestrial Network for Permafrost [GTN-P; [10,11]] and used by [12]. The air temperature observations were taken from the WFDEI gridded global data set [13]. The box and whiskers plots in Figure S2 show the mean and 5th to 95th percentile confidence interval. The solid lines show the fitted relationships for these statistics. The uncertainty in the relationship is much larger at the warmer air temperatures where the active layer is more sensitive to the local environmental conditions such as the soil type, aspect and land cover type. Using the MAAT for the period 2000-2009 derived from the WFDEI gridded global data set these relationships were extrapolated to give an estimate of the multi-annual mean maximum summer thaw depth for the pan-arctic region along with its uncertainties. These extrapolated thaw depths were superimposed on the profiles of soil carbon for the top 3 m from the Northern Circumpolar Soil Carbon Database (NCSCD, [3]) which were interpolated to 10 cm thick layers.

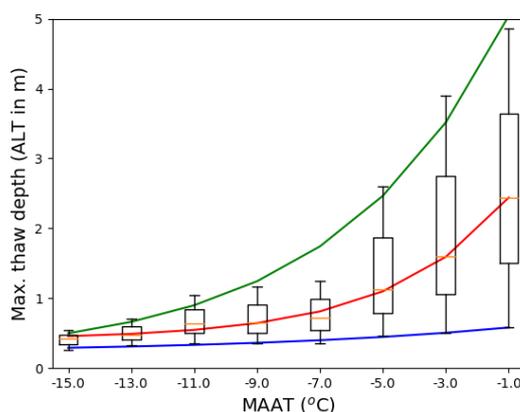


Figure S2. Observational-based relationship between maximum summer thaw depth and local annual mean air temperature (MAAT).

Figure S3 shows the spatial distribution of soil carbon in the permanently frozen soils for the mean and 5th and 95th percentile confidence intervals of the relationship shown in Figure S2. The total estimated permafrost carbon ranges from 454 to 889 Gt (5th to 95th percentile) with a median of 673 Gt C. The methodology described here is initially a simple framework for approximately estimating permafrost carbon which could be revised in the future by using additional environmental information in order to reduce uncertainties.

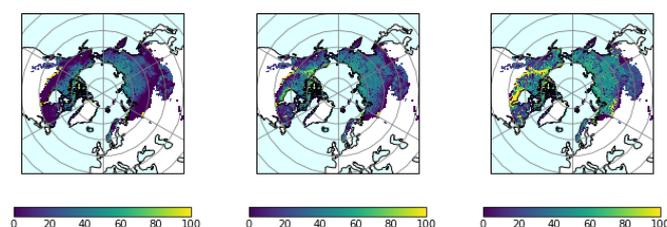


Figure S3. Spatial distribution of the estimated permafrost carbon (Gt C) using the fitted 5th (left plot), 50th (middle plot) and 95th (right plot) percentile confidence intervals from Figure S2.

References

1. Sanderman, J.; Hengl, T.; Fiske, G.J. Soil carbon debt of 12,000 years of human land use. *Proceedings of the National Academy of Sciences* **2017**, *114*, 9575–9580.
2. Fan, N.; Koirala, S.; Reichstein, M.; Thurner, M.; Avitabile, V.; Santoro, M.; Ahrens, B.; Weber, U.; Carvalhais, N. Apparent ecosystem carbon turnover time: uncertainties and robust features. *Earth System Science Data* **2020**, *12*, 2517–2536.
3. Hugelius, G.; Strauss, J.; Zubrzycki, S.; Harden, J.W.; Schuur, E.; Ping, C.L.; Schirmer, L.; Grosse, G.; Michaelson, G.J.; Koven, C.D.; et al. Estimated stocks of circumpolar permafrost carbon with quantified uncertainty ranges and identified data gaps. *Biogeosciences (Online)* **2014**, *11*, 6573–6593.
4. Batjes, N.H. Harmonized soil property values for broad-scale modelling (WISE30sec) with estimates of global soil carbon stocks. *Geoderma* **2016**, *269*, 61–68.
5. Batjes, N. Harmonized soil profile data for applications at global and continental scales: updates to the WISE database. *Soil Use and Management* **2009**, *25*, 124–127.
6. IGBP. Global Gridded Surfaces of Selected Soil Characteristics (IGBP-DIS).[Global Gridded Surfaces of Selected Soil Characteristics (International Geosphere-Biosphere Programme-Data and Information System)]. *ORNL DAAC* **2000**. doi:10.3334/ORNLDAAC/569.
7. Shangquan, W.; Dai, Y.; Duan, Q.; Liu, B.; Yuan, H. A global soil data set for earth system modeling. *Journal of Advances in Modeling Earth Systems* **2014**, *6*, 249–263.
8. Carvalhais, N.; Forkel, M.; Khomik, M.; Bellarby, J.; Jung, M.; Migliavacca, M.; Mu, M.; Saatchi, S.; Santoro, M.; Thurner, M.; et al. Global covariation of carbon turnover times with climate in terrestrial ecosystems. *Nature* **2014**, *514*, 213–217.
9. Brown, J. Circumpolar Active-Layer Monitoring (CALM) Program: Description and data. *Circumpolar active-layer permafrost system, version 2.0. (ed.) M. Parsons and T. Zhang, (comp.) International Permafrost Association Standing Committee on Data Information and Communication* **1998**. National Snow and Ice Data Center.
10. Biskaborn, B.K.; Lanckman, J.P.; Lantuit, H.; Elger, K.; Dmitry, S.; William, C.; Vladimir, R. The new database of the Global Terrestrial Network for Permafrost (GTN-P). *Earth System Science Data* **2015**, *7*, 245–259.
11. Biskaborn, B.; Smith, S.; Noetzli, J.; Matthes, H.; Vieira, G.; Streletskiy, D.; Schoeneich, P.; Romanovsky, V.; Lewkowicz, A.; Abramov, A.; et al. Permafrost is warming at a global scale. *Nature communications* **2019**, *10*, 1–11.
12. Burke, E.J.; Zhang, Y.; Krinner, G. Evaluating permafrost physics in the Coupled Model Intercomparison Project 6 (CMIP6) models and their sensitivity to climate change. *The Cryosphere* **2020**, *14*, 3155–3174.
13. Weedon, G.P.; Balsamo, G.; Bellouin, N.; Gomes, S.; Best, M.J.; Viterbo, P. The WFDEI meteorological forcing data set: WATCH Forcing Data methodology applied to ERA-Interim reanalysis data. *Water Resources Research* **2014**, *50*, 7505–7514.