nature geoscience

Article

https://doi.org/10.1038/s41561-023-01354-5

Dominance of particulate organic carbon in top mineral soils in cold regions

In the format provided by the authors and unedited

Supplementary Information

Appendix S1. List of the articles included in the meta-analysis of soil carbon fractions distribution in cold systems.

1. Chang, R. *et al.* Soil organic carbon becomes newer under warming at a permafrost site on the Tibetan Plateau. *Soil Biol. Biochem.* **152**, (2021).
2. Chen, Y., Liu, X., Hou, Y., Zhou, S. & Zhu, B. Particulate organic carbon is more vulnerable to nitrogen addition than mineral-associated organic carbon in soil of an alpine meadow. *Plant Soil* (2019) doi:10.1007/s11104-019-04279-4.
3. Diochon, A., Gregorich, E. G. & Tarnocai, C. Evaluating the quantity and biodegradability of soil organic matter in some Canadian Turbic Cryosols. *Geoderma* **202**–**203**, 82–87 (2013).
4. Dong, S. *et al.* Effect of grassland degradation on aggregate-associated soil organic carbon of alpine grassland ecosystems in the Qinghai-Tibetan Plateau. *Eur. J. Soil Sci.* **71**, 69–79 (2020).
5. Dörfer, C., Kühn, P., Baumann, F., He, J. S. & Scholten, T. Soil organic carbon pools and stocks in permafrost-affected soils on the Tibetan Plateau. *PLoS One* **8**, 1–9 (2013).
6. Fang, H. J. *et al.* Nitrogen deposition impacts on the amount and stability of soil organic matter in an alpine meadow ecosystem depend on the form and rate of applied nitrogen. *Eur. J. Soil Sci.* **65**, 510–519 (2014).
7. Fang, K., Qin, S., Chen, L., Zhang, Q. & Yang, Y. Al/Fe Mineral controls on soil organic carbon stock across tibetan alpine grasslands. *J. Geophys. Res. Biogeosciences* **124**, 247–259 (2019).
8. Gentsch, N. *et al.* Properties and bioavailability of particulate and mineral-associated organic matter in Arctic permafrost soils, Lower Kolyma Region, Russia. *Eur. J. Soil Sci.* **66**, 722–734 (2015).
9. Gentsch, N. *et al.* Temperature response of permafrost soil carbon is attenuated by mineral protection. *Glob. Chang. Biol.* **24**, 3401–3415 (2018).
10. Guan, S. *et al.* Climate warming impacts on soil organic carbon fractions and aggregate stability in a Tibetan alpine meadow. *Soil Biol. Biochem.* **116**, 224–236 (2018).
11. Herndon, E. *et al.* Influence of iron redox cycling on organo-mineral associations in Arctic tundra soil. *Geochim. Cosmochim. Acta* **207**, 210–231 (2017).
12. Höfle, S., Rethemeyer, J., Mueller, C. W. & John, S. Organic matter composition and stabilization in a polygonal tundra soil of the Lena Delta. *Biogeosciences* **10**, 3145–3158 (2013).
13. Jung, J. Y. *et al.* Responses of surface SOC to long-term experimental warming vary between different heath types in the high Arctic tundra. *Eur. J. Soil Sci.* **71**, 752–767 (2020).
14. Kane, E. S., Valentine, D. W., Schuur, E. A. G. & Dutta, K. Soil carbon stabilization along climate and stand productivity gradients in black spruce forests of interior Alaska. *Can. J. For. Res.* **35**, 2118–2129 (2005).
15. Karhu, K *et al.* Temperature sensitivity of soil carbon fractions in boreal forest soil. *Ecology* **91**, 370–376 (2010).
16. Lugato, E., Lavallee, J. M., Haddix, M. L., Panagos, P. & Cotrufo, M. F. Different

climate sensitivity of particulate and mineral-associated soil organic matter. *Nat. Geosci.* **14**, 295–300 (2021).
17. Luo, R. *et al.* Nutrient addition reduces carbon sequestration in a Tibetan grassland soil: Disentangling microbial and physical controls. *Soil Biol. Biochem.* **144**, 107764 (2020).
18. Mueller, C. W. *et al.* Microscale soil structures foster organic matter stabilization in permafrost soils. *Geoderma* **293**, 44–53 (2017).
19. Mueller, C. W. *et al.* Large amounts of labile organic carbon in permafrost soils of northern Alaska. *Glob. Chang. Biol.* **21**, 2804–2817 (2015).
20. Paré, M. & Bedard-Haughn, A. Surface soil organic matter qualities of three distinct canadian arctic sites. *Arctic, Antarct. Alp. Res.* **45**, 88–98 (2013).
21. Poeplau, C., Kätterer, T., Leblans, N. I. W. & Sigurdsson, B. D. Sensitivity of soil carbon fractions and their specific stabilization mechanisms to extreme soil warming in a subarctic grassland. *Glob. Chang. Biol.* **23**, 1316–1327 (2017).
22. Poeplau, C., Sigurdsson, P. & Sigurdsson, B. D. Depletion of soil carbon and aggregation after strong warming of a subarctic Andosol under forest and grassland cover. *Soil* **6**, 115–129 (2020).
23. Prater, I. *et al.* From fibrous plant residues to mineral-associated organic carbon - The fate of organic matter in Arctic permafrost soils. *Biogeosciences* **17**, 3367–3383 (2020).
24. Shang, W. *et al*. Soil organic matter fractions under different vegetation types in permafrost regions along the Qinghai-Tibet Highway, north of Kunlun Mountains, China. *J Mt Sci* **12**, 1010–1024 (2015).
25. Shen, D. *et al.* Increased chemical stability but decreased physical protection of soil organic carbon in response to nutrient amendment in a Tibetan alpine meadow. *Soil Biol. Biochem.* **126**, 11–21 (2018).
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27. Teklay, T. & Chang, S. X. Temporal changes in soil carbon and nitrogen storage in a hybrid poplar chronosequence in northern Alberta. *Geoderma* **144**, 613–619 (2008).
28. Tian, Y. Q. *et al.* Carbon sequestration in two alpine soils on the Tibetan Plateau. *J. Integr. Plant Biol.* **51**, 900–905 (2009).
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31. Yuan, Z. Q. *et al.* Pasture degradation impact on soil carbon and nitrogen fractions of alpine meadow in a Tibetan permafrost region. *J. Soils Sediments* **20**, 2330–2342 (2020).
32. Yuan, X. *et al.* Sensitivity of soil carbon dynamics to nitrogen and phosphorus enrichment in an alpine meadow. *Soil Biol. Biochem.* **150**, 107984 (2020).
33. Yuan, X. *et al.* Plateau pika offsets the positive effects of warming on soil organic

carbon in an alpine swamp meadow on the Tibetan Plateau. *Catena* **204**, 105417 (2021).

34. Xu, H. *et al.* Soil enzyme response to permafrost collapse in the Northern Qinghai-Tibetan Plateau. *Ecol. Indic.* **85**, 585–593 (2018).

35. Zollinger, B. *et al.* Effect of permafrost on the formation of soil organic carbon pools and their physical-chemical properties in the Eastern Swiss Alps. *Catena* **110**, 70–85 (2013).

Appendix S2. List of the articles included in the meta-analysis of warming effects on soil carbon fractions in cold systems vs. other biomes.

1. Bai, T. *et al.* Interactive global change factors mitigate soil aggregation and carbon change in a semi-arid grassland. *Glob. Chang. Biol.* **26**, 5320–5332
2. Chang, R. *et al.* Soil organic carbon becomes newer under warming at a permafrost site on the Tibetan Plateau. *Soil Biol. Biochem.* **152**, (2021).
3. Cheng, X., Luo, Y., Xu, X., Sherry, R. & Zhang, Q. Soil organic matter dynamics in a North America tallgrass prairie after 9 yr of experimental warming. *Biogeosciences* **8**, 1487–1498 (2011).
4. De Feudis, M. *et al.* Small altitudinal change and rhizosphere affect the SOM light fractions but not the heavy fraction in European beech forest soil. *Catena* **181**, 104091 (2019).
5. Guan, S. *et al.* Climate warming impacts on soil organic carbon fractions and aggregate stability in a Tibetan alpine meadow. *Soil Biol. Biochem.* **116**, 224–236 (2018).
6. He, N., Chen, Q., Han, X., Yu, G. & Li, L. Warming and increased precipitation individually influence soil carbon sequestration of Inner Mongolian grasslands, China. *Agric. Ecosyst. Environ.* **158**, 184–191 (2012).
7. Díaz-Martínez, Panettieri, M., García-Palacios, P., Moreno, E., Plaza, C. & Maestre, F.T. Biocrusts modulate climate change effects on soil organic carbon pools: insights from a 9-year experiment. *Ecosystems*, in press (2022).
8. Jung, J. Y. *et al.* Responses of surface SOC to long-term experimental warming vary between different heath types in the high Arctic tundra. *Eur. J. Soil Sci.* **71**, 752–767 (2020).
9. Link, S. O., Smith, J. L., Halvorson, J. J. & Bolton, H. A reciprocal transplant experiment within a climatic gradient in a semiarid shrub-steppe ecosystem: Effects on bunchgrass growth and reproduction, soil carbon, and soil nitrogen. *Glob. Chang. Biol.* **9**, 1097–1105 (2003).
10. Liu, X. J. A. *et al.* Soil aggregate-mediated microbial responses to long-term warming. *Soil Biol. Biochem.* **152**, 108055 (2021).
11. Pendall, E., Osanai, Y., Williams, A. L. & Hovenden, M. J. Soil carbon storage under simulated climate change is mediated by plant functional type. *Glob. Chang. Biol.* **17**, 505–514 (2011).
12. Poeplau, C., Kätterer, T., Leblans, N. I. W. & Sigurdsson, B. D. Sensitivity of soil carbon fractions and their specific stabilization mechanisms to extreme soil warming in a subarctic grassland. *Glob. Chang. Biol.* **23**, 1316–1327 (2017).
13. Poeplau, C., Sigurdsson, P. & Sigurdsson, B. D. Depletion of soil carbon and aggregation after strong warming of a subarctic Andosol under forest and grassland cover. *Soil* **6**, 115–129 (2020).
14. Puissant, J. *et al.* Climate change effects on the stability and chemistry of soil organic carbon pools in a subalpine grassland. *Biogeochemistry* **132**, 123–139 (2017).
15. Schnecker, J., Borken, W., Schindlbacher, A. & Wanek, W. Little effects on soil organic matter chemistry of density fractions after seven years of forest soil warming. *Soil Biol. Biochem.* **103**, 300–307 (2016).
16. Song, B. *et al.* Light and heavy fractions of soil organic matter in response to

climate warming and increased precipitation in a temperate steppe. *PLoS One* **7**, 1–8 (2012).
17. Soong, J. L. *et al.* Five years of whole-soil warming led to loss of subsoil carbon stocks and increased CO2 efflux. *Sci. Adv.* **7**, 1–9 (2021).
18. Thaysen, E. M., Reinsch, S., Larsen, K. S. & Ambus, P. Decrease in heathland soil labile organic carbon under future atmospheric and climatic conditions. *Biogeochemistry* **133**, 17–36 (2017).
19. Tian, J. *et al.* Microbial metabolic response to winter warming stabilizes soil carbon. *Glob. Chang. Biol.* **27**, 2011–2028 (2021).
20. Zhang, C., Tang, G. & Sun, Y. Asymmetric and Symmetric Warming–Induced Stability of Organic Carbon in a Calcareous Soil. *Soil Sci. Soc. Am. J.* **83**, 1200–1208 (2019).

Appendix S3. List of the articles cited in Table S2.

1. Gurevitch, J. & Hedges, L.V. Statistical issues in ecological meta-analyses. *Ecology* **80**, 1142-1149 (1999).
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3. García-Palacios, P. *et al.* Are there links between responses of soil microbes and ecosystem functioning to elevated CO2, N deposition and warming? A global perspective. *Glob. Change Biol.* **21**, 1590-1600 (2015).
4. Karst, J. *et al.* The mutualism-parasitism continuum in ectomycorrhizas: a quantitative assessment using meta-analysis. *Ecology* **89**, 1032-1042 (2008).