Supplement of

Meta-analysis of high-latitude nitrogen-addition and warming studies imply ecological mechanisms overlooked by land models

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**Supplemental Table**

Table S1: Compilation of the studies used in the meta-analysis.

**Supplemental Figure**

Figure S1: A complete list of response ratios for the variables included in the meta-analysis. The complete list of variables was considered to develop figure 5 a/ b.

Figure S2: The response ratio under nitrogen addition. The observational data is the same as that included in figure 2a and S1, however, the modeled response data has been broken down by the amount of nitrogen added (Collated refers to the aggregated nitrogen deposition concentrations, 0.2 – 3 kg ha\(^{-1}\) yr\(^{-1}\)).
References from table S1

1. Aerts, R., van Bodegom, P.M. & Cornelissen, J.H.C. (2012). Litter stoichiometric traits of plant species of high-latitude ecosystems show high responsiveness to global change without causing strong variation in litter decomposition. New Phytologist, 196, 181–188.
2. Allison, S., McGuire, K. & Treseder, K. (2010a). Resistance of microbial and soil properties to warming treatment seven years after boreal fire. Soil Biology and Biochemistry.
3. Allison, S.D. & Treseder, K.K. (2008). Warming and drying suppress microbial activity and carbon cycling in boreal forest soils. Global Change Biol, 14, 2898–2909.
4. Allison, S.D., Gartner, T.B., Mack, M.C., McGuire, K. & Treseder, K. (2010b). Nitrogen alters carbon dynamics during early succession in boreal forest. Soil Biology and Biochemistry, 42, 1157–1164.
5. Berendse, F., Van Breemen, N., Rydin, H.Å., Buttler, A., Heijmans, M., Hoosbeek, M.R., et al. (2001). Raised atmospheric CO2 levels and increased N deposition cause shifts in plant species composition and production in Sphagnum bogs. Global Change Biol, 7, 591–598.
6. Biasi, C., Meyer, H., Rusalimova, O., Hämmerle, R., Kaiser, C., Baranyi, C., et al. (2008). Initial effects of experimental warming on carbon exchange rates, plant growth and microbial dynamics of a lichen-rich dwarf shrub tundra in Siberia. Plant and Soil, 307, 191–205.
7. Björk, R.G., Majdi, H., Klemedtsson, L., Lewis-Jonsson, L. & Molau, U. (2007). Long-term warming effects on root morphology, root mass distribution, and microbial activity in two dry tundra plant communities in northern Sweden. New Phytol., 176, 862–873.
8. Boelman, N.T., Stieglitz, M., Griffin, K.L. & Shaver, G.R. (2005). Inter-annual variability of NDVI in response to long-term warming and fertilization in wet sedge and tussock tundra. Oecologia, 143, 588–597.
9. Boelman, N.T., Stieglitz, M., Rueth, H.M., Sommerkorn, M., Griffin, K.L., Shaver, G.R., et al. (2003). Response of NDVI, biomass, and ecosystem gas exchange to long-term warming and fertilization in wet sedge tundra. Oecologia, 135, 414–421.
10. Buckeridge, K.M., Cen, Y.-P., Layzell, D.B. & Grogan, P. (2009). Soil biogeochemistry during the early spring in low arctic mesic tundra and the impacts of deepened snow and enhanced nitrogen availability. Biogeochemistry, 99, 127–141.
11. Cahoon, S.M.P., Sullivan, P.F., Post, E. & Welker, J.M. (2011). Large herbivores limit CO2 uptake and suppress carbon cycle responses to warming in West Greenland. Global Change Biol, 18, 469–479.
12. Christiansen, T.R., Michelsen, A., Jonasson, S. & Schmidt, I.K. (1997). Carbon dioxide and methane exchange of a subarctic heath in response to climate change related environmental manipulations. Oikos, 34–44.
13. Christiansen, C.T., Schmidt, N.M. & MICHELSEN, A. (2012). High Arctic Dry Heath CO2 Exchange During the Early Cold Season. Ecosystems, 15, 1083–1092.
14. Churchland, C., Mayo-Bruinsma, L., Ronson, A. & Grogan, P. (2010). Soil microbial
and plant community responses to single large carbon and nitrogen additions in low arctic tundra. *Plant and Soil*, 334, 409–421.
16. Clemmensen, K.E., MICHELSEN, A., Jonasson, S. & Shaver, G.R. (2006). Increased ectomycorrhizal fungal abundance after long-term fertilization and warming of two arctic tundra ecosystems. *New Phytol.*, 171, 391–404.
17. Cornelissen, J.H.C., van Bodegom, P.M., Aerts, R., Callaghan, T.V., van Logtestijn, R.S.P., Alatalo, J., *et al.* (2007). Global negative vegetation feedback to climate warming responses of leaf litter decomposition rates in cold biomes. *Ecol Lett*, 10, 619–627.
18. DESLIPPE, J.R., HARTMANN, M., Mohn, W.W. & SIMARD, S.W. (2011). Long-term experimental manipulation of climate alters the ectomycorrhizal community of Betula nana in Arctic tundra. *Global Change Biol.*, 17, 1625–1636.
19. Dorrepaal, E., Toet, S., van Logtestijn, R.S.P., Swart, E., van de Weg, M.J., Callaghan, T.V., *et al.* (2009). Carbon respiration from subsurface peat accelerated by climate warming in the subarctic. *Nature*, 460, 616–619.
20. Gough, L., Wookey, P.A. & Shaver, G.R. (2002). Dry heath arctic tundra responses to long-term nutrient and light manipulation. *Arctic, Antarctic, and Alpine Research*, 211–218.
21. Grogan, P. & Chapin, F.S., III. (2000). Initial effects of experimental warming on above- and belowground components of net ecosystem CO 2 exchange in arctic tundra. *Oecologia*, 125, 512–520.
22. Guicharnaud, R., Arnalds, O. & Paton, G.I. (2010). Short term changes of microbial processes in Icelandic soils to increasing temperatures. *Biogeosciences*, 7.
23. Hartley, I.P., Hopkins, D.W., Sommerkorn, M. & Wookey, P.A. (2010). The response of organic matter mineralisation to nutrient and substrate additions in sub-arctic soils. *Soil Biology and Biochemistry*, 42, 92–100.
24. Haugwitz, M.S., MICHELSEN, A. & Schmidt, I.K. (2011). Long-term microbial control of nutrient availability and plant biomass in a subarctic-alpine heath after addition of carbon, fertilizer and fungicide. *Soil Biology and Biochemistry*, 43, 179–187.
25. Havström, M., Callaghan, T.V. & Jonasson, S. (1993). Differential growth responses of Cassiope tetragona, an arctic dwarf-shrub, to environmental perturbations among three contrasting high-and subarctic sites. *Oikos*, 389–402.
26. Hoosbeek, M.R., Van Breemen, N., Vasander, H., Buttler, A. & Berendse, F. (2002). Potassium limits potential growth of bog vegetation under elevated atmospheric CO2 and N deposition. *Global Change Biol.*, 8, 1130–1138.
27. HUDSON, J.M.G., HENRY, G.H.R. & Cornwell, W.K. (2011). Taller and larger: shifts in Arctic tundra leaf traits after 16 years of experimental warming. *Global Change Biol.*, 17, 1013–1021.
28. Illeris, L. & Jonasson, S. (1999). Soil and plant CO2 emission in response to variations in soil moisture and temperature and to amendment with nitrogen, phosphorus, and carbon in Northern Scandinavia. *Arctic, Antarctic, and Alpine Research*, 264–271.
29. Illeris, L., Michelsen, A. & Jonasson, S. (2003). Soil plus root respiration and microbial biomass following water, nitrogen, and phosphorus application at a high arctic semi desert. *Biogeochemistry*, 65, 15–29.
30. Jägerbrand, A.K., Alatalo, J.M., Chrimes, D. & Molau, U. (2009). Plant community responses to 5 years of simulated climate change in meadow and heath ecosystems at a subarctic-alpine site. *Oecologia*, 161, 601–610.
31. Johnson, L.C., Shaver, G.R., Cades, D.H., Rastetter, E., Nadelhoffer, K., Giblin, A., et al. (2000). Plant carbon-nutrient interactions control CO2 exchange in Alaskan wet sedge tundra ecosystems. *Ecology*, 81, 453–469.
32. Jonasson, S., Havström, M., Jensen, M. & Callaghan, T.V. (1993). In situ mineralization of nitrogen and phosphorus of arctic soils after perturbations simulating climate change. *Oecologia*, 95, 179–186.
33. Jonasson, S., MICHELSEN, A., SCHMIDT, I.K. & Nielsen, E.V. (1999). Responses in microbes and plants to changed temperature, nutrient, and light regimes in the arctic. *Ecology*, 80, 1828–1843.
34. Jones, M.H., Fahnestock, J.T., Walker, D.A., Walker, M.D. & Welker, J.M. (1998). Carbon dioxide fluxes in moist and dry arctic tundra during the snow-free season: responses to increases in summer temperature and winter snow accumulation. *Arctic and alpine research*, 373–380.
35. Kaarlejärvi, E., Baxter, R., Hofgaard, A., Hytteborn, H., Khitun, O., Molau, U., et al. (2012). Effects of Warming on Shrub Abundance and Chemistry Drive Ecosystem-Level Changes in a Forest–Tundra Ecotone. *Ecosystems*, 15, 1219–1233.
36. Lavoie, M., Mack, M.C. & Schuur, E.A.G. (2011). Effects of elevated nitrogen and temperature on carbon and nitrogen dynamics in Alaskan arctic and boreal soils. *J. Geophys. Res*, 116, G03013.
37. Marion, G.M. & Miller, P.C. (1982). Nitrogen mineralization in a tussock tundra soil. *Arctic and alpine research*, 287–293.
38. Michelsen, A., Jonasson, S., Sleep, D., Havström, M. & Callaghan, T.V. (1996). Shoot biomass, δ 13 C, nitrogen and chlorophyll responses of two arctic dwarf shrubs to in situ shading, nutrient application and warming simulating climatic change. *Oecologia*, 105, 1–12.
39. Nadelhoffer, K.J., Giblin, A.E., Shaver, G.R. & Laundre, J.A. (1991). Effects of temperature and substrate quality on element mineralization in six arctic soils. *Ecology*, 72, 242–253.
40. Natali, S.M., Schuur, E.A.G., Trucco, C., Hicks Pries, C.E., Crummer, K.G. & Baron Lopez, A.F. (2011). Effects of experimental warming of air, soil and permafrost on carbon balance in Alaskan tundra. *Global Change Biol*, 17, 1394–1407.
41. Nowinski, N.S., Trumbore, S.E., Schuur, E.A., Mack, M.C. & Shaver, G.R. (2008). Nutrient addition prompts rapid destabilization of organic matter in an arctic tundra ecosystem. *Ecosystems*, 11, 16–25.
42. Oberbauer, S.F., Tweedie, C.E., Welker, J.M., Fahnestock, J.T., HENRY, G.H.R., Webber, P.J., et al. (2007). Tundra CO2 fluxes in response to experimental warming across latitudinal and moisture gradients. *Ecological Monographs*, 77, 221–238.
43. Oechel, W.C., Vourlitis, G.L., Hastings, S.J., Ault, R.P. & Bryant, P. (1998). The effects of water table manipulation and elevated temperature on the net CO2 flux of wet sedge tundra ecosystems. *Global Change Biol*, 4, 77–90.
44. Olsson, P., Linder, S., Giesler, R. & Högberg, P. (2005). Fertilization of boreal forest reduces both autotrophic and heterotrophic soil respiration. *Global Change Biol*, 11, 1745–1753.
45. Press, M.C., Potter, J.A., Burke, M., Callaghan, T.V. & Lee, J.A. (1998). Responses of a subarctic dwarf shrub heath community to simulated environmental change. *Journal of Ecology*, 86, 315–327.
46. Richardson, S.J., Press, M.C., Parsons, A.N. & Hartley, S.E. (2002). How do nutrients and warming impact on plant communities and their insect herbivores? A 9-year study from a sub-Arctic heath. *Journal of Ecology*, 90, 544–556.
47. Rinnan, R., Michelsen, A. & Bååth, E. (2013). Fungi Benefit from Two Decades of Increased Nutrient Availability in Tundra Heath Soil. *PLoS ONE*, 8, e56532.
48. Rinnan, R., Michelsen, A. & Jonasson, S. (2008). Effects of litter addition and warming on soil carbon, nutrient pools and microbial communities in a subarctic heath ecosystem. *Applied Soil Ecology*, 39, 271–281.
49. Rinnan, R., Michelsen, A., Bååth, E. & Jonasson, S. (2007a). Fifteen years of climate change manipulations alter soil microbial communities in a subarctic heath ecosystem. *Global Change Biol*, 13, 28–39.
50. Rinnan, R., Michelsen, A., Bååth, E. & Jonasson, S. (2007b). Mineralization and carbon turnover in subarctic heath soil as affected by warming and additional litter. *Soil Biology and Biochemistry*, 39, 3014–3023.
51. Rinnan, R., Stark, S. & Tolvanen, A. (2009). Responses of vegetation and soil microbial communities to warming and simulated herbivory in a subarctic heath. *Journal of Ecology*, 97, 788–800.
52. Robinson, C.H., Wookey, P.A., Lee, J.A., Callaghan, T.V. & Press, M.C. (1998). Plant community responses to simulated environmental change at a high arctic polar semi-desert. *Ecology*, 79, 856–866.
53. Robinson, C.H., Wookey, P.A., Parsons, A.N., Potter, J.A., Callaghan, T.V., Lee, J.A., et al. (1995). Responses of plant litter decomposition and nitrogen mineralisation to simulated environmental change in a high arctic polar semi-desert and a subarctic dwarf shrub heath. *Oikos*, 503–512.
54. Ruess, L., Michelsen, A., Schmidt, I.K. & Jonasson, S. (1999). Simulated climate change affecting microorganisms, nematode density and biodiversity in subarctic soils. *Plant and Soil*, 212, 63–73.
55. Shaver, G.R., Johnson, L.C., Cades, D.H., Murray, G., Laundre, J.A., Rastetter, E.B., et al. (1998). Biomass and CO₂ flux in wet sedge tundras: responses to nutrients, temperature, and light. *Ecological Monographs*, 68, 75–97.
56. Sistla, S.A., Moore, J.C., Simpson, R.T., Gough, L., Shaver, G.R. & Schimel, J.P. (2013). Long-term warming restructures Arctic tundra without changing net soil carbon storage. *Nature*.
57. Sjögersten, S., Turner, B.L., Mahieu, N., Condron, L.M. & Wookey, P.A. (2003). Soil organic matter biochemistry and potential susceptibility to climatic change across the forest-tundra ecotone in the Fennoscandian mountains. *Global Change Biol*, 9, 759–772.
58. Sjögersten, S., Wal, R. & Woodin, S.J. (2012). Impacts of Grazing and Climate Warming on C Pools and Decomposition Rates in Arctic Environments. *Ecosystems*, 15, 349–362.
59. Smolander, A., Barnette, L., Kitunen, V. & Lumme, I. (2005). N and C transformations in long-term N-fertilized forest soils in response to seasonal drought. *Applied Soil Ecology*, 29, 225–235.
60. Sorensen, P.L., Michelsen, A. & Jonasson, S. (2008). Nitrogen uptake during one year in subarctic plant functional groups and in microbes after long-term warming and fertilization. *Ecosystems*, 11, 1223–1233.
61. Stapleton, L.M., Crout, N.M.J., Säwström, C., Marshall, W.A., Poulton, P.R., Tye, A.M., *et al.* (2005). Microbial carbon dynamics in nitrogen amended Arctic tundra soil: Measurement and model testing. *Soil Biology and Biochemistry*, 37, 2088–2098.
62. Stark, S., Eskelinen, A. & Männistö, M.K. (2011). Regulation of Microbial Community Composition and Activity by Soil Nutrient Availability, Soil pH, and Herbivory in the Tundra. *Ecosystems*, 15, 18–33.
63. Strebels, D., Elberling, B., Morger, E., Knicker, H.E. & Cooper, E.J. (2010). Cold-season soil respiration in response to grazing and warming in High-Arctic Svalbard. *Polar Research*, 29, 46–57.
64. T. Weedon, J., A Kowalchuk, G., Aerts, R., van Hal, J., van Logtestijn, R., Taş, N., *et al.* (2011). Summer warming accelerates sub-arctic peatland nitrogen cycling without changing enzyme pools or microbial community structure. *Global Change Biol*, 18, 138–150.
65. Trucco, C., Schuur, E.A.G., Natali, S.M., Belshe, E.F., Bracho, R. & Vogel, J. (2012). Seven-year trends of CO₂ exchange in a tundra ecosystem affected by long-term permafrost thaw. *J. Geophys. Res.*, 117, G02031.
66. Wahren, C.H.A., Walker, M.D. & Bret-Harte, M.S. (2005). Vegetation responses in Alaskan arctic tundra after 8 years of a summer warming and winter snow manipulation experiment. *Global Change Biol*, 11, 537–552.
67. Walker, M.D., Wahren, C.H., Hollister, R.D., Henry, G.H.R., Ahlquist, L.E., Alatalo, J.M., *et al.* (2006). Plant community responses to experimental warming across the tundra biome. *Proc Natl Acad Sci USA*, 103, 1342–1346.
68. Welker, J.M., Fahnestock, J.T., Henry, G.H.R., O’Dea, K.W. & Chimner, R.A. (2004). CO₂ exchange in three Canadian High Arctic ecosystems: response to long-term experimental warming. *Global Change Biol*, 10, 1981–1995.
69. Zamin, T.J. & Grogan, P. (2012). Birch shrub growth in the low Arctic: the relative importance of experimental warming, enhanced nutrient availability, snow depth and caribou exclusion. *Environ. Res. Lett.*, 7, 034027.