Award # DE-FG02-07ER64456

Title:

Final Technical Report on Warming-Induced Biome Change at the Temperate-Boreal Ecotone: An Experimental Test of Key Regeneration Processes

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Project Period: 08/01/2007 – 07/31/2018

Abstract:

This project advanced our understanding of plants' key physiological and ecological processes that are essential to the survival, success, and carbon cycling of plants from the boreal-temperate forest ecotone in the future climate. A primary goal of the project was to test the effect of warming and water limitation on plants from the Boreal-Temperate Ecotone using a realistic outdoor long-term experiment. Plant at this ecotone are predicted to be particularly sensitive to future climate since the ecotone represents a relatively sharp boundary between many temperate species to the south and boreal species to the north. This work was important, as there was and still is a significant uncertainty surrounding the mechanisms of future climate effects on vegetation compositional and carbon cycling change, especially in forests mostly due to lack of experimental examination of response to warming and limited water availibility. Consequently, we tested our central objective, that was *to* assess the potential for projected climate to alter tree species composition and carbon cycling at the southern boreal-temperate forest ecotone by experimentally warming forest plots and documenting effects on establishment and juvenile performance for tree species near their warmer (boreal species) and colder (temperate species) range limits in northern Minnesota.

To accomplish our goals, we designed and built a successful highly manipulative experiment that implemented vegetation-soil warming and rainfall removal in both understory and open habitats at two sites in northern Minnesota (MN). The sites lie at different distances to the north of the ecotone between the southern boreal and northern temperate forest biomes. We focused on ten target species, all of which are near their warmer (*Pinus banksiana*, *Picea glauca*, *Abies balsamea*, *Populus tremuloides*, *Betula papyrifera*) or colder (*Pinus strobus*, *Quercus macrocarpa*, *Quercus rubra*, *Acer rubrum*, *Acer saccharum*) range edge in northern MN; we also studied other species such as a woody invader and native herbs and shrubs. Three temperature treatments (ambient, +1.7°C, +3.4°C) were imposed using infra-red heating lamps augmented with soil heating cables to simultaneously control soil and vegetation temperatures, enabling assessment of non-linear responses. These temperatures bracket the range of anticipated warming in the region during the next 75-100 years. In addition, we implemented summer rain removal treatment mimicking predicted distribution in precipitation patterns by future climate where we actively removed ~40% of rainfall. Measurements included germinant establishment, plant growth, phenology, physiology and survival; soil, plant and air temperature, soil moisture and nutrient status. These measures enabled us to assess how germination, growth and survival at the

establishment stage are influenced by direct climate effects and/or indirect effects of warming, soil resources such as water and nutrients availibility or other environmental variables that either directly or indirectly influence plant performance.

Project Activities Summary:

This research significantly increased our general understanding of the mechanisms by which future climatic change in a form of warming and soil water availibility might affect tree species performance, survival, carbon cycling physiology, growth and overall success and whether climatic changes will result in range shifts of species near their range boundaries. Our findings advance both specific projections about the impacts of future climate on the composition of southern boreal forest biome and improved understanding of carbon cycling physiology that can improve global land surface modeling. The full list of publications is provided below.

Accomplishments/Deliverables:

Research Papers

Published:

2018

Berini, J. L., Brockman, S. A., Hegeman, A. D., Reich, P. B., Muthukrishnan, R., Montgomery, R. A., & Forester, J. D. (2018). Combinations of abiotic factors differentially alter production of plant secondary metabolites in five woody plant species in the boreal-temperate transition zone. *Frontiers in plant science*, *9*.

Mucha, J., Peay, K. G., Smith, D. P., Reich, P. B., Stefański, A., & Hobbie, S. E. (2018). Effect of simulated climate warming on the ectomycorrhizal fungal community of boreal and temperate host species growing near their shared ecotonal range limits. *Microbial ecology*, *75*(2), 348-363.

Reich, P. B., Sendall, K. M., Stefanski, A., Rich, R. L., Hobbie, S. E., & Montgomery, R. A. (2018). Effects of climate warming on photosynthesis in boreal tree species depend on soil moisture. *Nature*, *562*(7726), 263.

Rice, K. E., Montgomery, R. A., Stefanski, A., Rich, R. L., & Reich, P. B. (2018). Experimental warming advances phenology of groundlayer plants at the boreal-temperate forest ecotone. *American journal of botany*, *105*(5), 851-861.

Thakur, M. P., Reich, P. B., Hobbie, S. E., Stefanski, A., Rich, R., Rice, K. E., ... & Eisenhauer, N. (2018). Reduced feeding activity of soil detritivores under warmer and drier conditions. *Nature climate change*, *8*(1), 75.

Wright, A. J., Fisichelli, N. A., Buschena, C., Rice, K., Rich, R., Stefanski, A., ... & Reich, P. B. (2018). Biodiversity bottleneck: seedling establishment under changing climatic conditions at the boreal–temperate ecotone. *Plant ecology*, *219*(6), 691-704.

2017

Fernandez, C. W., Nguyen, N. H., Stefanski, A., Han, Y., Hobbie, S. E., Montgomery, R. A., ... & Kennedy, P. G. (2017). Ectomycorrhizal fungal response to warming is linked to poor host performance at the boreal-temperate ecotone. *Global change biology*, *23*(4), 1598-1609

Martins, C. S., Nazaries, L., Delgado-Baquerizo, M., Macdonald, C. A., Anderson, I. C., Hobbie, S. E., ... & Singh, B. K. (2017). Identifying environmental drivers of greenhouse gas emissions under warming and reduced rainfall in boreal–temperate forests. *Functional ecology*, *31*(12), 2356-2368.

O'sullivan, O. S., Heskel, M. A., Reich, P. B., Tjoelker, M. G., Weerasinghe, L. K., Penillard, A., ... & Bahar, N. H. (2017). Thermal limits of leaf metabolism across biomes. *Global Change Biology*, *23*(1), 209-223.

Schwarz, B., Barnes, A. D., Thakur, M. P., Brose, U., Ciobanu, M., Reich, P. B., ... & Eisenhauer, N. (2017). Warming alters energetic structure and function but not resilience of soil food webs. *Nature climate change*, *7*(12), 895.

Thakur, MP, PB Reich, C Wagg, NA Fisichelli, M. Ciobanu, SE Hobbie, RL Rich, A Stefanski, N Eisenhauer. 2017. Effects of soil warming history on the performances of congeneric temperate and boreal herbaceous plant species and their associations with soil biota. J Plant Ecology 10(4): 670-680, doi: 10.1093/jpe/rtw066

Wei, X., Sendall, K. M., Stefanski, A., Zhao, C., Hou, J., Rich, R. L., ... & Reich, P. B. (2017). Consistent leaf respiratory response to experimental warming of three North American deciduous trees: a comparison across seasons, years, habitats and sites. *Tree physiology*, *37*(3), 285-300.

2016

Carey, J. C., Tang, J., Templer, P. H., Kroeger, K. D., Crowther, T. W., Burton, A. J., ... & Jiang, L. (2016). Temperature response of soil respiration largely unaltered with experimental warming. *Proceedings of the National Academy of Sciences*, *113*(48), 13797-13802.Crowther, TW, KEO Todd-Brown, CW Rowe, WR. Wieder, JC Carey, MB Machmuller, BL Snoek, S Fang, G Zhou, SD Allison, JM Blair, SD Bridgham, AJ Burton, Y Carrillo, PB Reich, JS Clark, AT Classen, FA Dijkstra, B Elberling, BA Emmett, M Estiarte, SD Frey, J Guo, J Harte, L Jiang, BR Johnson, G Kröel-Dulay, KS Larsen, H Laudon, JM Lavallee, Y Luo, M Lupascu, LN Ma, S Marhan, A Michelsen, J Mohan, S Niu, E Pendall, J Peñuelas, L Pfeifer-Meister, C Poll, S Reinsch, LL Reynolds, IK Schmidt, S Sistla, NW Sokol, PH Templer, KK Treseder, JM Welker, MA Bradford. 2016. Quantifying global soil carbon losses in response to warming. 2016. Nature 540:104-108. doi:10.1038/nature20150

Heskel, M. A., O'Sullivan, O. S., Reich, P. B., Tjoelker, M. G., Weerasinghe, L. K., Penillard, A., ... & Sinca, F. (2016). Convergence in the temperature response of leaf respiration across biomes and plant functional types. *Proceedings of the National Academy of Sciences*, *113*(14), 3832-3837.

Heskel, M. A., Atkin, O. K., O'Sullivan, O. S., Reich, P., Tjoelker, M. G., Weerasinghe, L. K., ... & Xiang, J. (2016). Reply to Adams et al.: Empirical versus process-based approaches to modeling temperature responses of leaf respiration. *Proceedings of the National Academy of Sciences*, *113*(41), E5996-E5997.

McCulloh, K. A., Petitmermet, J., Stefanski, A., Rice, K. E., Rich, R. L., Montgomery, R. A., & Reich, P. B. (2016). Is it getting hot in here? Adjustment of hydraulic parameters in six boreal and temperate tree species after 5 years of warming. *Global change biology*, *22*(12), 4124-4133.

Reich, P. B., Sendall, K. M., Stefanski, A., Wei, X., Rich, R. L., & Montgomery, R. A. (2016). Boreal and temperate trees show strong acclimation of respiration to warming. *Nature*, *531*(7596), 633.

Thakur, M. P., Reich, P. B., Wagg, C., Fisichelli, N. A., Ciobanu, M., Hobbie, S. E., ... & Eisenhauer, N. (2016). Effects of soil warming history on the performances of congeneric temperate and boreal herbaceous plant species and their associations with soil biota. *Journal of Plant Ecology*, *10*(4), 670-680.

Uelmen Jr, J. A., Lindroth, R. L., Tobin, P. C., Reich, P. B., Schwartzberg, E. G., & Raffa, K. F. (2016). Effects of winter temperatures, spring degree-day accumulation, and insect population source on phenological synchrony between forest tent caterpillar and host trees. *Forest Ecology and Management*, *362*, 241-250.

2015

Jacques, M. H., Lapointe, L., Rice, K., Montgomery, R. A., Stefanski, A., & Reich, P. B. (2015). Responses of two understory herbs, Maianthemum canadense and Eurybia macrophylla, to experimental forest warming: Early emergence is the key to enhanced reproductive output. *American journal of botany*, *102*(10), 1610-1624.

Jamieson, M. A., Schwartzberg, E. G., Raffa, K. F., Reich, P. B., & Lindroth, R. L. (2015). Experimental climate warming alters aspen and birch phytochemistry and performance traits for an outbreak insect herbivore. *Global change biology*, *21*(7), 2698-2710.

Reich, P. B., Sendall, K. M., Rice, K., Rich, R. L., Stefanski, A., Hobbie, S. E., & Montgomery, R. A. (2015). Geographic range predicts photosynthetic and growth response to warming in co-occurring tree species. *Nature Climate Change*, *5*(2), 148.

Rich, R. L., Stefanski, A., Montgomery, R. A., Hobbie, S. E., Kimball, B. A., & Reich, P. B. (2015). Design and performance of combined infrared canopy and belowground warming in the B4Warm ED (Boreal Forest Warming at an Ecotone in Danger) experiment. *Global Change Biology*, *21*(6), 2334-2348.

Sendall, K. M., Reich, P. B., Zhao, C., Jihua, H., Wei, X., Stefanski, A., ... & Montgomery, R. A. (2015). Acclimation of photosynthetic temperature optima of temperate and boreal tree species in response to experimental forest warming. *Global change biology*, *21*(3), 1342-1357.

Vanderwel, M. C., Slot, M., Lichstein, J. W., Reich, P. B., Kattge, J., Atkin, O. K., ... & Kitajima, K. (2015). Global convergence in leaf respiration from estimates of thermal acclimation across time and space. *New Phytologist*, *207*(4), 1026-1037.

2014

Eisenhauer, N., Stefanski, A., Fisichelli, N. A., Rice, K., Rich, R., & Reich, P. B. (2014). Warming shifts 'worming': effects of experimental warming on invasive earthworms in northern North America. *Scientific reports*, *4*, 6890.

Fisichelli, N., Wright, A., Rice, K., Mau, A., Buschena, C., & Reich, P. B. (2014). First-year seedlings and climate change: species-specific responses of 15 North American tree species. *Oikos*, *123*(11), 1331-1340.

Schwartzberg, E. G., Jamieson, M. A., Raffa, K. F., Reich, P. B., Montgomery, R. A., & Lindroth, R. L. (2014). Simulated climate warming alters phenological synchrony between an outbreak insect herbivore and host trees. *Oecologia*, *175*(3), 1041-1049.

Thakur, M. P., Reich, P. B., Eddy, W. C., Stefanski, A., Rich, R., Hobbie, S. E., & Eisenhauer, N. (2014). Some plants like it warmer: increased growth of three selected invasive plant species in soils with a history of experimental warming. *Pedobiologia*, *57*(1), 57-60.

Thakur, M. P., Reich, P. B., Fisichelli, N. A., Stefanski, A., Cesarz, S., Dobies, T., ... & Eisenhauer, N. (2014). Nematode community shifts in response to experimental warming and canopy conditions are associated with plant community changes in the temperate-boreal forest ecotone. *Oecologia*, *175*(2), 713-723.

2012

Brzostek, E. R., Blair, J. M., Dukes, J. S., Frey, S. D., Hobbie, S. E., Melillo, J. M., ... & Stefanski, A. (2012). The effect of experimental warming and precipitation change on proteolytic enzyme activity: positive feedbacks to nitrogen availability are not universal. *Global Change Biology*, *18*(8), 2617-2625.

In Revision:

Stefanski, A., Bermudez, R., Sendall, K. M., Montgomery, M. A., Reich, P. B., (in review): Surprising lack of sensitivity of biochemical limitation of photosynthesis of nine tree species to open-air experimental warming and reduced rainfall in southern boreal forest.

In Preparation:

Bermudez et al., Effect of warming and rainfall reduction on temperature response of photosynthetic capacity of trees from boreal-temperate ecotone

Heskel et al., Climate and species range influence high temperature physiology at the temperate-boreal ecotone

Montgomery et al., Phenological responses of temperate-boreal trees to experimental warming depend on ambient spring temperatures, leaf habit and species geographic range

Van Nuland et al., Warming and disturbance alters soil microbiome diversity and function in a northern forest ecotone

Dissertations: University of Minnesota

2016

Rice, K. (2016). Phenological responses of herbaceous plants, shrubs, and tree seedlings to experimental climate change conditions in northern Minnesota. MS Thesis.

2015

Eddy III, W. C. (2015). Experimental warming effects on soil organic matter dynamics at the temperate-boreal forest ecotone. PhD dissertation.

2012

Pinahs, C. A. (2012). Experimental warming: how temperature affects germination and survival of Minnesota tree species. MS Thesis.

Selected Presentations and Posters:

2016

Reich, Peter (May 2015). Eight Years of Lessons from B4WarmED: Tree Responses to Warming and Rainfall Manipulation in a Boreal Ecotone. DOE-TES/SBR Joint Investigators Meeting

2015

Reich, Peter (May 2015). Functional trait work in? DOE-TES/SBR Joint Investigators Meeting

Reich, Peter (May 2015). B4WarmED: Experimental warming and rainfall manipulation in a boreal ecotone reveal key responses and adjustments at plant, soil, and ecosystem scales. DOE-TES/SBR Joint Investigators Meeting

2014

Reich, Peter (May 2014). B4WarmED: Warming X Rainfall Manipulation Shifts Integrated Soil and Plant Community Processes in a Boreal Ecotone Experiment. DOE-TES/SBR Joint Investigators Meeting

2013

Eddy III, W. C., Hobbie, S. E., Reich, P. B., Rich, R., & Stefanski, A. (August 2013). Will warming enhance soil organic matter decomposition? Evidence from an in situ warming experiment and process-based soil laboratory incubations. *The 98th ESA Annual Meeting.*

Rich, R. L., Stefanski, A., Montgomery, R. A., Hobbie, S. E., & Reich, P. B. (August 2013). forest warming experiment: Design and implementation of four years of concurrent above-and below-ground warming at the temperate-boreal ecotone. *The 98th ESA Annual Meeting.*

Reich, P. B., Rich, R., Stefanski, A., Sendall, K. M., Montgomery, R. A., Zhao, C. M., ... & Rice, K. (August 2013). forest warming experiment: Species geographic distributions predict photosynthetic responses of local ecotypes to climate warming. *The 98th ESA Annual Meeting.*

Reich, Peter (May 2013). B4WarmED: An open-air process-oriented experiment exploring southern boreal forest response to future climate warming and precipitation shifts. DOE-TES/SBR Joint Investigators Meeting

Rice, K., Montgomery, R. A., Rich, R., Fisichelli, N., Jacques, M. H., Stefanski, A., & Reich, P. B. (August 2013). forest warming experiment: Increased temperature effects on herbaceous plant phenology. *The 98th ESA Annual Meeting.*

Sendall, K. M., Montgomery, R. A., Rich, R. L., Stefanski, A., Rice, K., Jihua, H., ... & Reich, P. B. (August 2013). forest warming experiment: Effects on photosynthetic temperature optima of temperate and boreal tree species. *The 98th ESA Annual Meeting.*

Smith, D. P., Reich, P. B., Hobbie, S. E., Stefanski, A., & Peay, K. G. (August 2013). forest warming experiment: Effects on diversity, community structure and function of soil fungi and bacteria. *The 98th ESA Annual Meeting.*

Thakur, M. P., Reich, P. B., Fisichelli, N., Stefanski, A., Cesarz, S., Dobies, T., ... & Eisenhauer, N. (August 2013). forest warming experiment: shifts in nematode community influence plant cover and composition. *The 98th ESA Annual Meeting.*

Wong, V. L., Schwebach, C., Arnold, A. E., U'Ren, J. M., Montgomery, R. A., Reich, P. B., ... & May, G. (August 2013). Effects of climate warming on the occurrence of endophytic fungi in boreal Picea and Populus. *The 98th ESA Annual Meeting.*

2012

Eddy III, W. C., Hobbie, S. E., Stefanski, A., Rice, K., Rich, R. L., & Reich, P. B. forest warming experiment: Effects of soil moisture on soil organic matter decomposition.

2011

Montgomery, R. A., Reich, P. B., Rich, R. L., & Stefanski, A. (2011, December). Spring Temperatures Alone Cannot Explain Timing of Budburst of Boreal-Temperate Tree Species under Experimental Warming. In *AGU Fall Meeting Abstracts*.