Winter Climate Change in the Northern Forest: Scientific Synthesis and Practical Solutions

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- Changing winter temperatures and snow cover may have negative impacts on forest ecosystems and surrounding communities
- The way in which winter is defined can affect how trends in winter climate change are determined, with consequences for ecosystems and people

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http://www.nsrcforest.org

Project Summary

The goal of this project was to perform a synthesis to understand how changing winters impact people and ecosystems of the northern forest. We engaged with scientists and stakeholders throughout the region to develop questions of mutual interest for our synthesis. Using 100 years of climate data from stations across the northern forest region, we created indicators of winter climate change that illustrate impacts of changing winters on ecosystems and people. We found that winters are growing shorter, are ending earlier, and have lost many of the below-freezing temperatures and snow-covered conditions that support human activities and ecological processes. We communicated our findings with leaders of stakeholder groups throughout the region and will leverage our collaboration with the Hubbard Brook Research Foundation to develop translation products and broader outreach campaign.

Background and Justification

Winter is a key period for the ecology, economy, and cultures of the northern forest

Horsedrawn sled transporting pulpwood , Moosehead region, Maine, 1925

"Backyard" sugarbush, present day, New Hampshire

Background and Justification

Winter is a key period for the ecology, economy, and culture of the Northern Forest. During the colder months, low air temperatures promote forest health by killing insect pests that would otherwise proliferate during the growing season (Dukes et al. 2009). A deep snowpack insulates soil, preventing roots and burrowing animals from freezing and allowing biogeochemical cycling to occur (Campbell et al. 2005; Cleavitt et al. 2008; Rodenhouse et al. 2009). Sub-zero temperatures and deep snow cover are as important to the economy of the Northern Forest as they are to its ecology. Logging typically takes place during winter to minimize soil disturbance (Rittenhouse and Risman 2015). Maple sugaring depends on cold winters to prevent the sap from running too early in spring (Skinner et al. 2010). The ski industry requires a deep and persistent snowpack to attract skiers and reduce costs of making snow (Dawson and Scott 2013). Winter is also culturally important to recreation in Northern Forest, supporting snowmobiling, snow shoeing, and tracking (Scott et al. 2008).

The largest impacts of climate change in the Northern Forest may occur in winter. Across the region, winter air temperature has been warming and winter precipitation has been increasing at faster rates than annual air temperature and precipitation, with those trends expected to persist through 2100 (Hayhoe et al. 2007). Warmer winter air means that precipitation is more likely to fall as rain or sleet instead of snow, reducing seasonal snow cover. The snowpack has already decreased by 4.6 cm and 8.9 days per decade (Burakowski et al. 2008) and is anticipated to keep declining in depth and duration over the coming century (Hodgkins and Dudley 2013).

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https://northernwoodlands.org/articles/article/journal-logger
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Background and Justification: Some Key Questions

How do winter conditions impact water quality? Water quantity?

What goes on under snow? What happens when we lose snow cover?

How can we adapt to changing conditions?

Background and Justification: Some Key Questions

Despite the growing awareness of the importance of winter, we lack a synthetic understanding of how winter climate change may impact cold-season ecological and biogeochemical processes and may potentially undermine the economic and cultural activities they support.

Some questions that we have heard while engaging with both the scientific and stakeholder communities include:

- What goes on under the insulating blanket of snow? There's a lot we don't know about the functions and interactions of plants, fungi, microbes, insects, amphibians—you name it—that spend their winters hiding out under the snowpack. And then, thinking about climate change, we have to ask: what happens if that snowpack goes away for longer and longer periods of time?
- What is the role of winter conditions on the hydrology of our region? What do the interactions between snowpack and winter rain events mean for the provisioning of clean drinking water and for the cycling of nutrients through forests that are essential for forest growth?
- What is the geographic pattern of winter conditions and winter climate change? Can we all pack up our skis and escape to a corner of Quebec where the snowpack is more reliable?

Background and Justification: What is Winter?

We also need to define winter in order to understand how it is changing

Background and Justification: What is Winter?

What is winter? This question came up at a stakeholder meeting and is not trivial. If we are talking about winter climate change, then we should be able to describe what winter is. Most of the literature and winter or cold season phenomena do not explain what winter or cold season means, which could vary across scientific disciplines and/or among stakeholder groups.

Reckonings, or definitions of winter, include

- Astronomical: winter solstice to vernal equinox
- Meteorological: three coldest months of year
- Cultural: Thanksgiving to St Patrick's Day, ski season
- Ecological: hibernal period of biological dormancy
- All of the above? What winter means in the Northern Forest may differ from other areas

Our definition:

- Winter is a period characterized by sustained low temperatures **below freezing** and **snow accumulation** that together regulate **ecological processes** and the **services** they provide, both during winter and throughout the rest of the year.

- We like this definition because it captures the importance of coldness and snow. It framed the way we viewed the data for synthesis and the sorts of questions we asked.

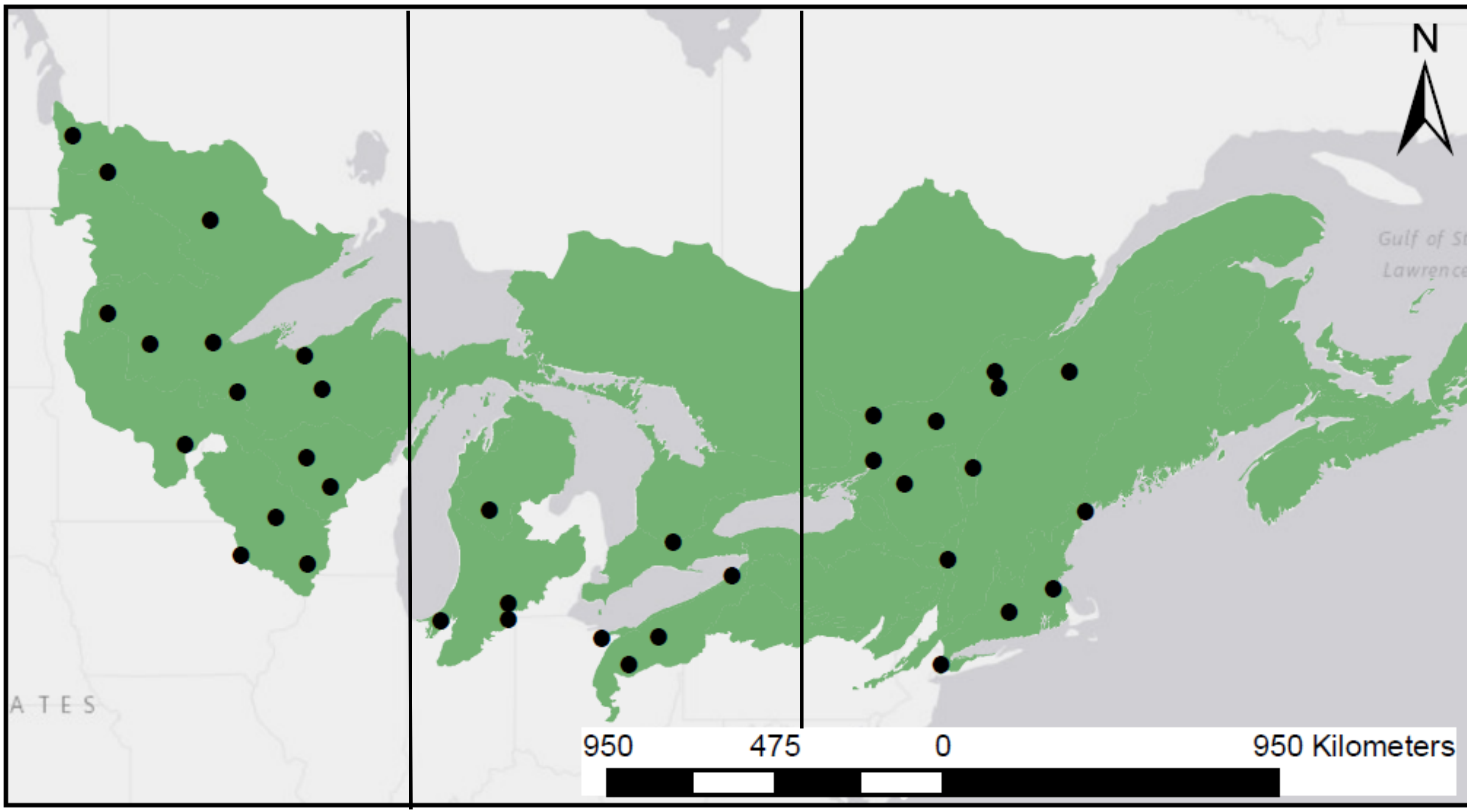
Methods: Our Data Synthesis

100 years of climate data across the Northern Forest to develop indicators of winter climate change and implications for ecosystems and people

Methods: Our Data Synthesis

Previous work examining the effects of winter climate change on ecological and biogeochemical processes have typically occurred at single sites or over short time spans that range from one to three years or in laboratory simulations and thus are difficult to scale over larger areas and longer periods. Prior studies that have included a broader spatiotemporal scope have typically examined indicators of winter climate change such as minimum temperatures and snow cover duration, and have not explicitly represented how changing conditions might affect both social and ecological systems. Here we take advantage of 100 years of meteorological observations across the northeastern U.S. and eastern Canada to develop a suite of indicators that enable a cross-cutting understanding of 1) how winter temperatures and snow cover have been changing across the northern forest region of northeastern North America; and 2) how these shifts may impact both ecosystems and surrounding human communities.

Methods: Northern Forest Study Area and Station Locations



Methods: Northern Forest Study Area and Station Locations

We focus this study on the northern forest region of the northeastern North America, which was identified using the hierarchical ecoregion classification system of Omernik and Griffith (2014). Level II (subcontinental) classification systems were used to delineate the study area that consisted of northern and eastern forest types. Within this area, weather stations were selected from the National Climate Data Archive of Environment Canada (NCDAEC; Mekis and Vincent, 2011; Vincent et al., 2012) and the United States Historical Climatology Network (U.S.HCN; Easterling et al., 1999; Williams et al., 2006). Only weather stations with ≥ 100 years of precipitation and/or temperature data were included in the analysis to facilitate trend detection.

The above figure shows the entire study area, colored in green, visually grouped into three geographic areas: the Midwest, Great Lakes, and Northeast to examine broad spatial differences among trends. We recognize that these spatial delineations do not strictly adhere to official regional designations for either Canada or the U.S. but nevertheless consider them a useful way to examine the spatial coherence of trends across the northern forest study region.

Methods: Data Analysis

- Data were daily temperature, precipitation, snowpack, snowfall
- Developed indicators to determine *timing*, *duration* and *condition* of winter
- Indicators are relevant for logging, recreation, human health, wildlife, and forest ecosystem processes

Methods: Data Analysis

We assessed long-term changes in winter conditions using a suite of indicators relevant for understanding both climatic changes and their impacts on ecosystems and human communities. Some of these indicators were previously defined by the joint World Meteorological Organization Commission on Climatology (CCl) and the Climate Variability and Prediction (CLIVAR) Expert Team on Climate Change Detection and Indices (ETCCDI) to standardize definitions and analyses of climate change (Karl et al., 1999; Peterson et al., 2001, Peterson et al., 2005, Brown et al., 2010, Donat et al., 2013). These include metrics such as Ice Days and Frost Days that are derived from daily maximum and minimum temperatures, respectively.

We supplemented these existing indicators with a new set of metrics that could explicitly consider how changing winter temperature, precipitation, snowfall, and snow depth might impact forested ecosystems and surrounding communities. This new set of metrics originated from the scientific literature and discussions with key stakeholders with whom we have long-standing partnerships. Metrics were grouped into categories related to coldness, snowpack, or both. For example, a "Snowmaking Day" represents conditions that are suitable for making artificial snow, which are necessary for winter recreation and tourism (Scott et al., 2003; Wilson et al., 2018). Because conditions appropriate for snowmaking have changed over recent decades as technology has improved, we calculated two different temperature thresholds: -5 °C and -2 °C (Scott et al., 2003; Wilson et al., 2018). For each of these thresholds, we evaluated changes in snowmaking opportunities for two time periods that represent historical visitation patterns of economic importance to ski areas: prior to December 25 and prior to February 28. These two snowmaking windows are necessary to ensure good ski conditions for the December holidays and for New England's February school vacation (Scott et al., 2006; Frumhoff et al., 2007; Wilson et al., 2018).

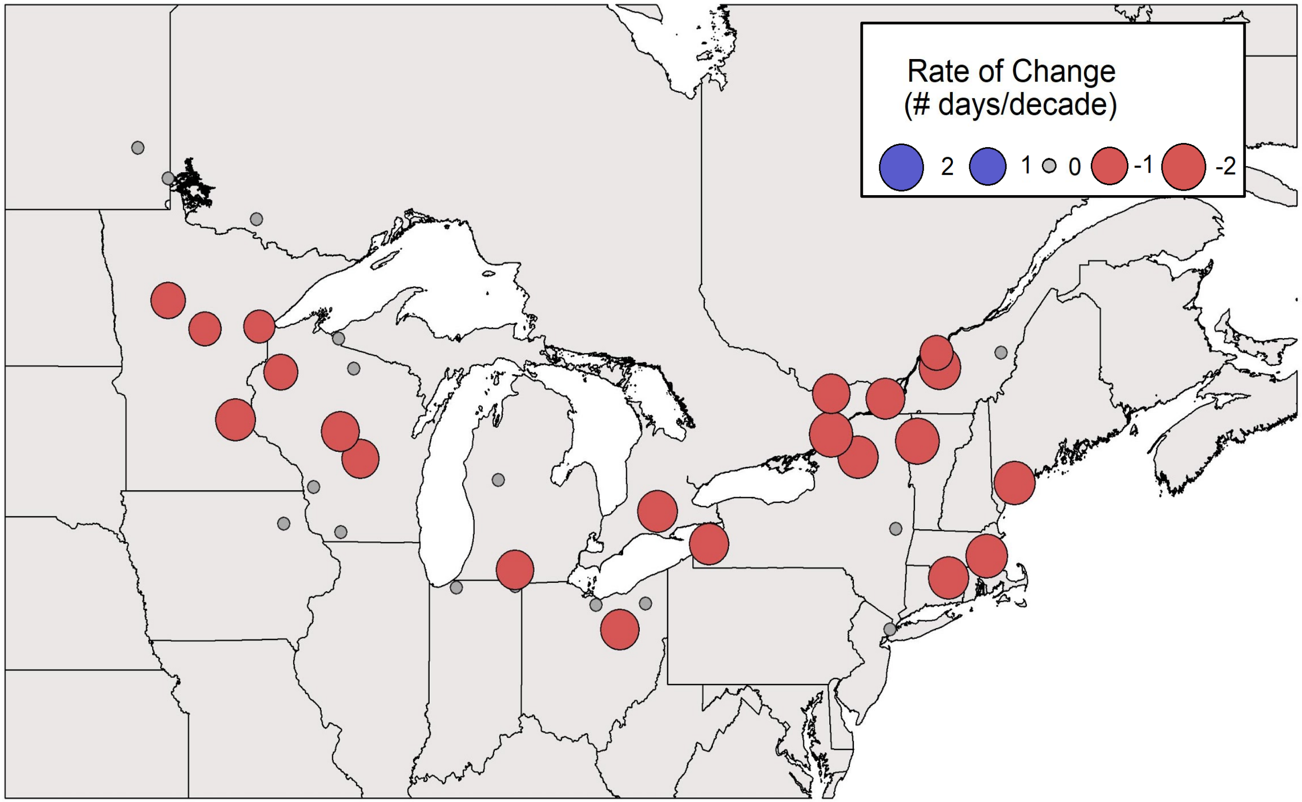
Methods: Data Analysis

In some cases, we developed multiple winter climate change indicators from a single threshold. For instance, snowmaking temperature thresholds of -5 °C are also lethal for some invasive, disease-carrying insects such as the Asian tiger mosquito (*Aedes albopictus*; Platanov et al., 2008; Rochlin et al., 2013; Ogden et al., 2014). Thus a Snowmaking Day of -5 °C could double as an indicator for both potential winter recreational activities and as a "Mosquito Kill Day," which is relevant for understanding how changing winters might impact human health. Likewise, Extreme Cold Days (ECD), in which air temperatures are less than -18 °C (0 °F), can negatively impact human health (e.g., frostbite, hypothermia). At the same time, these ECDs can positively affect forest health by preventing the northward advancement of forest insect pests such as the southern pine beetle (*Dendroctonus frontalis*) whose supercooling point (lower lethal temperatures) can range from -14 to -20 °C (Ungerer et al., 1999; Lombardero et al., 2000; Trân et al., 2007).

Indicators that featured both temperature and snowpack thresholds included "Bare Ground Ice Days" and "Bare Ground Thaw Days." A "Bare Ground Ice Day" illustrates a situation where the combination of an absent snowpack plus cold air temperatures might result in soil freezing, microbial and fine root mortality, and nutrient leaching (Groffman et al., 2001; Campbell et al., 2005; Cleavitt et al., 2008; Campbell et al. 2014; Tatariw et al., 2017; Sanders-DeMott et al., 2018; Patel et al. 2018). By contrast, a "Bare Ground Thaw Day" exemplifies a scenario in which the absence of snow plus warm air temperatures might result in conditions that reduce access to winter forest harvest sites (Stone, 2002; Rittenhouse and Risman, 2015), expose hiking trails to erosion risk, and limit opportunities for skiing, snowmobiling, and other winter sports (Scott et al., 2008).

We calculated the frequency with which each indicator occurred for each site by year combination, counting across the entire period from November 1 to May 31 annually to encapsulate the whole dormant season between senescence and leaf-out while also capturing early- and late-season snowfall and soil frost events. Within sites, we evaluated change over time for each climate variable using the Mann-Kendall test for trends in time series data, and determined the rate of change for each variable using nonparametric Sen slope analysis (Sen, 1968).

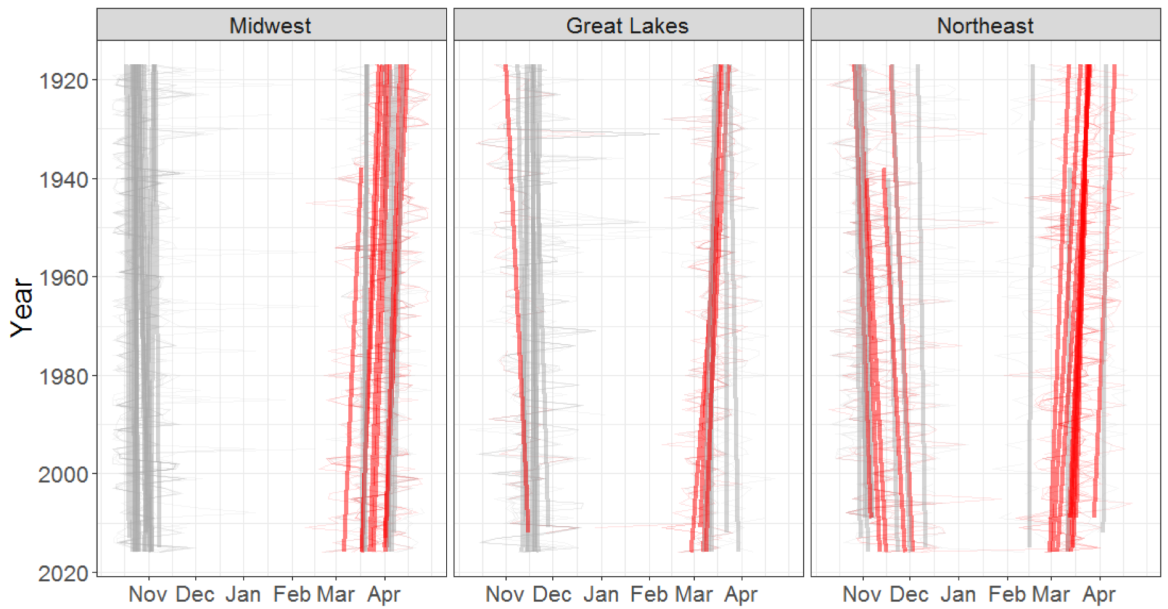
Results: Winters have been getting shorter (*duration*)



Trend analysis shows that winters, as defined by continuous temperatures below freezing, have generally become shorter, by a median of -2 days per decade.

The figure shows rates of change (in days per decade) in winter duration, as defined by daily air temperatures, for 37 stations across the study domain. Red dots indicate significant decreases in winter duration, and gray dots represent no significant change. The size of the dot illustrates the magnitude of change. We did not detect winter becoming longer at any station in the study area.

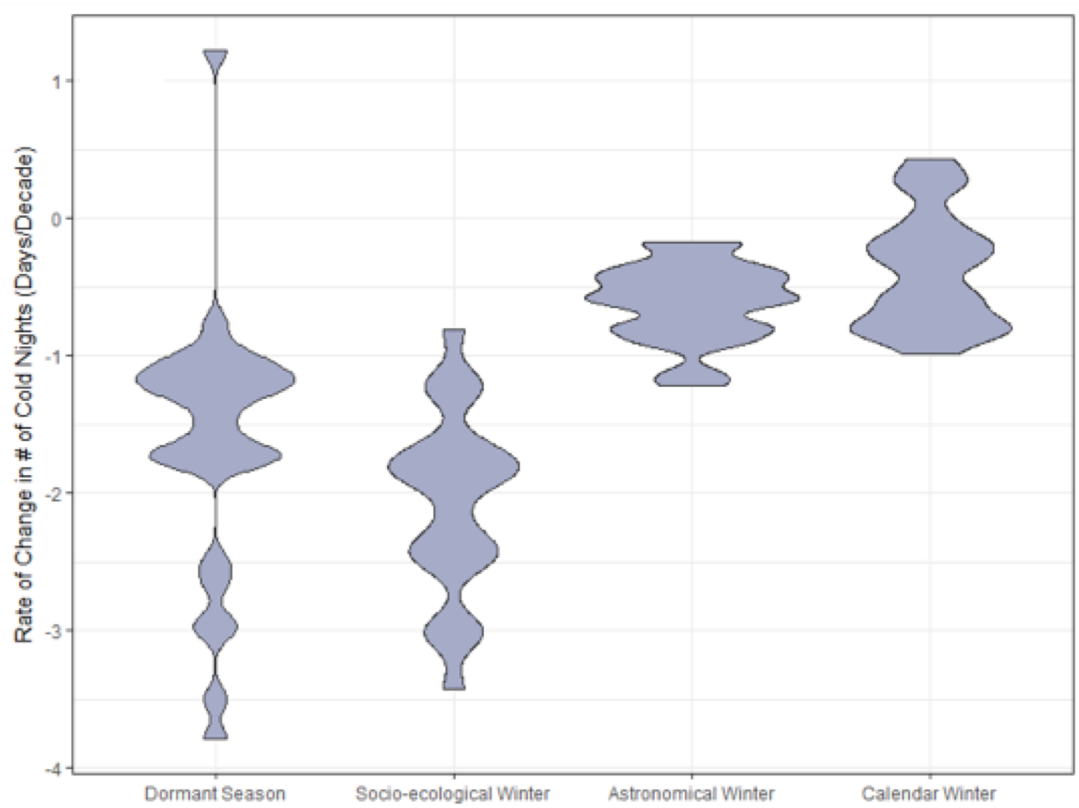
Results: Winters have been ending earlier (*timing*)



The overall shortening of winter, whether from a loss of continuous cold or snow cover, was largely due to an earlier spring onset, with many sites also showing trends toward a later end of fall.

The figure above shows “wedge plots” indicating the onset and end of winter, as defined by daily air temperature, from 1917 to 2016. Lighter-colored lines in the background are time series for each site showing the day of year of winter start and end, while darker-colored, straight lines in the foreground indicate trends. Red lines show trends toward later onset (autumn) and earlier end (spring), while gray lines indicate a lack of significant change over time. The intensity of the color represents the significance of the trend. Sites are grouped into three geographic areas, the Midwest, Great Lakes, and Northeast, to facilitate data visualization.

Results: How we define winter affects how we calculate change



This figure is a “violin” plot showing the distribution of rates of change in number of cold (< 0°C / < 32°F) nights for each of four reckonings (or definitions of winter): dormant season (Nov. 1-May 31), our newly defined social-ecological reckoning, as well as more traditional astronomical and meteorological reckonings.

The plot shows that way in we define winter influences how we calculate change in winter conditions. Although traditional ways of defining winter (astronomical and meteorological reckonings) generally show decreasing trends in the frequency of days with minimum temperatures below 0°C / 32°F, these reckonings are confined to an approximately 90 day period and thus may underestimate the loss of winter conditions that exist outside of this three-month window. The number of cold nights declined at rates approximately -1 day per decade slower when the meteorological reckoning was used to define winter than when the entire dormant season from November 1 to May 31 was considered.

Indicators and Implications for the Northern Forest Region

Image Credit: Integration and Application Network, University of Maryland Center for Environmental Science (ian.umces.edu/imagelibrary/)

Not only has the timing and duration of winter changed over the past 100 years, the conditions within winter have also changed, with implications for ecosystems and people of the northern forest.

Our presentation of winter climate change indicators includes the above pictures as a short-hand way of matching changes in indicators with specific impact.

The cloud with snowflakes represents general indicators of winter climate change.

The skier represents winter snow sports and recreation

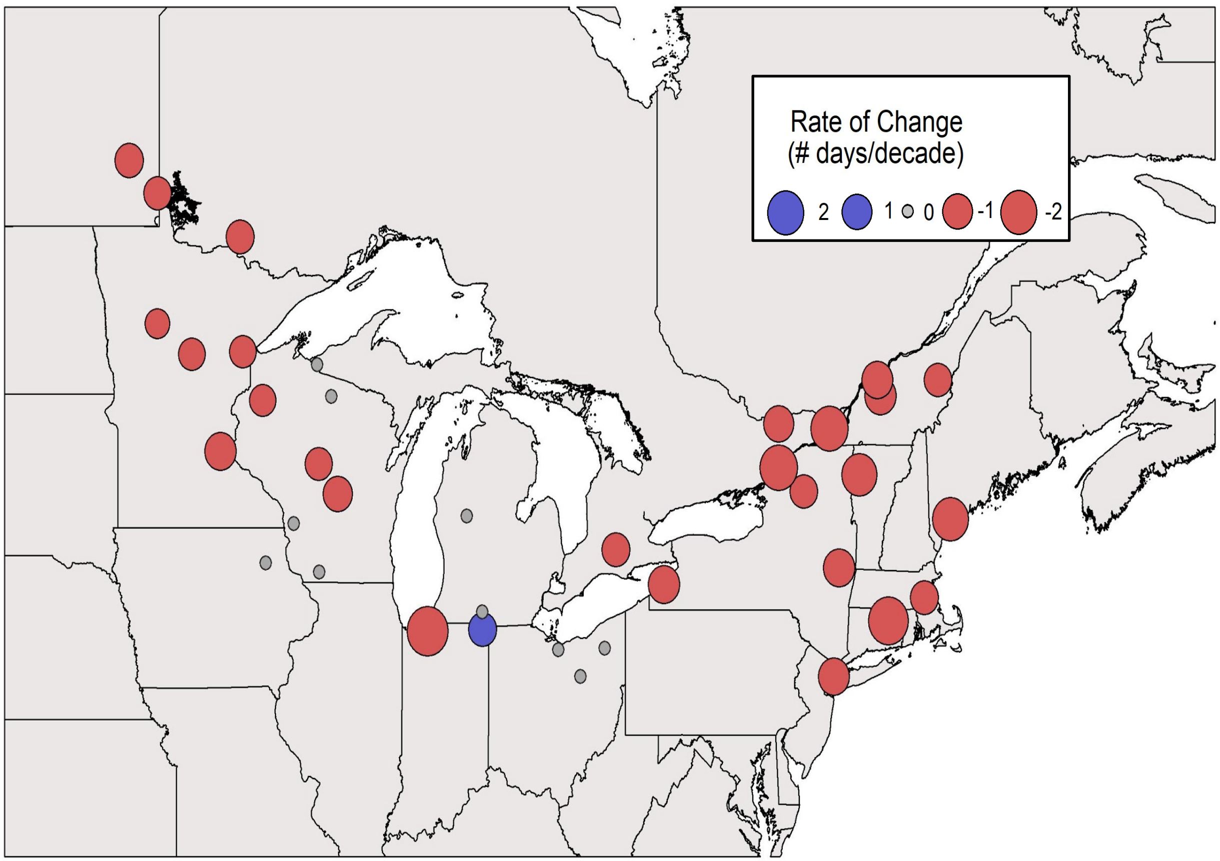
The tree represents ecosystems

The moose represents wildlife

The insect represents pests relevant for human health and forest health

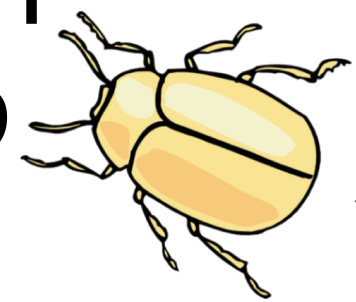
The person with a chainsaw represents logging and wood extraction

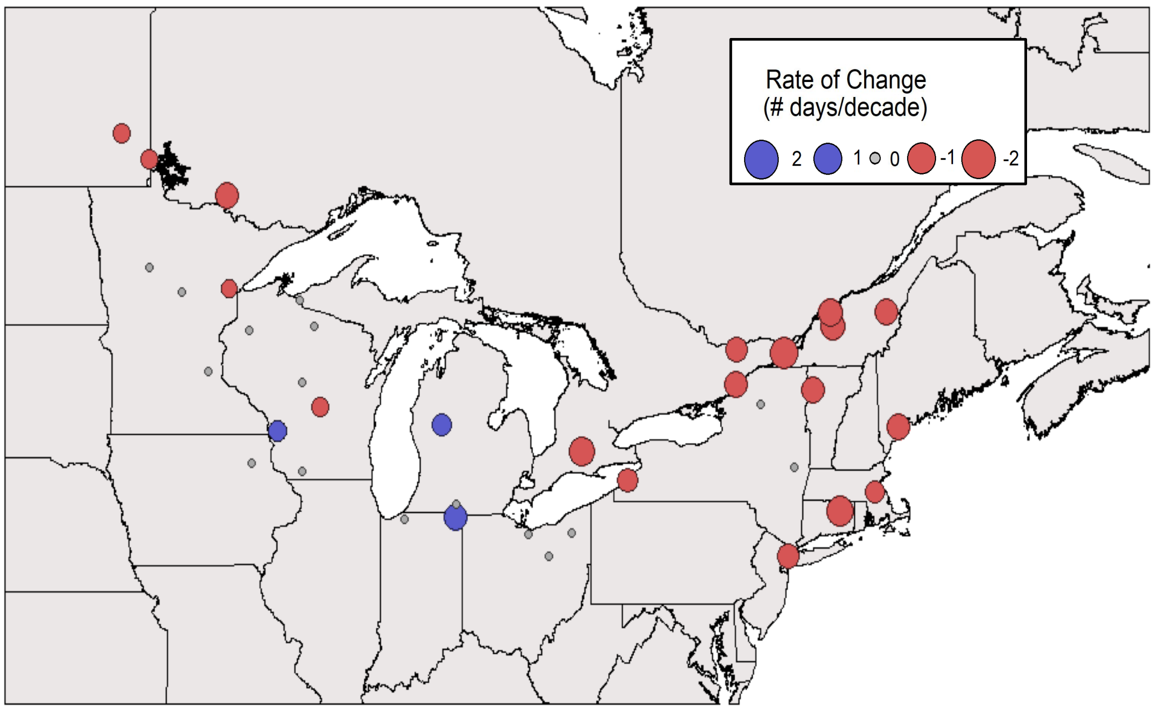
Implications: Changes in Frost Days (< 32°F)



Cold days when minimum temperatures are < 0°C or 32°F generally decreased over time across the study area. This loss of cold days may have a variety of impacts, likely affecting ecosystem processes (i.e., nutrient and water cycling), winter recreation, wildlife, insects, and forestry.

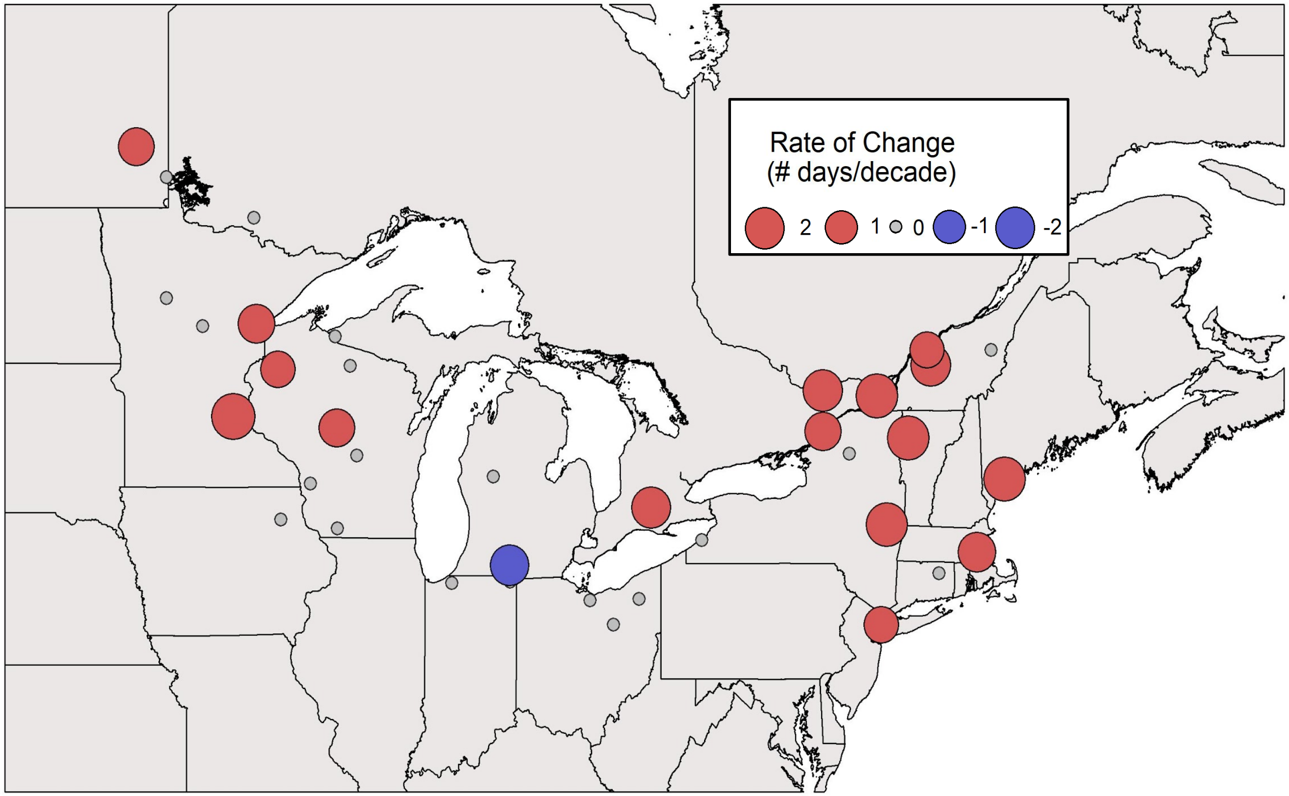
Implications: Changes in Snowmaking / Mosquito Kill Days





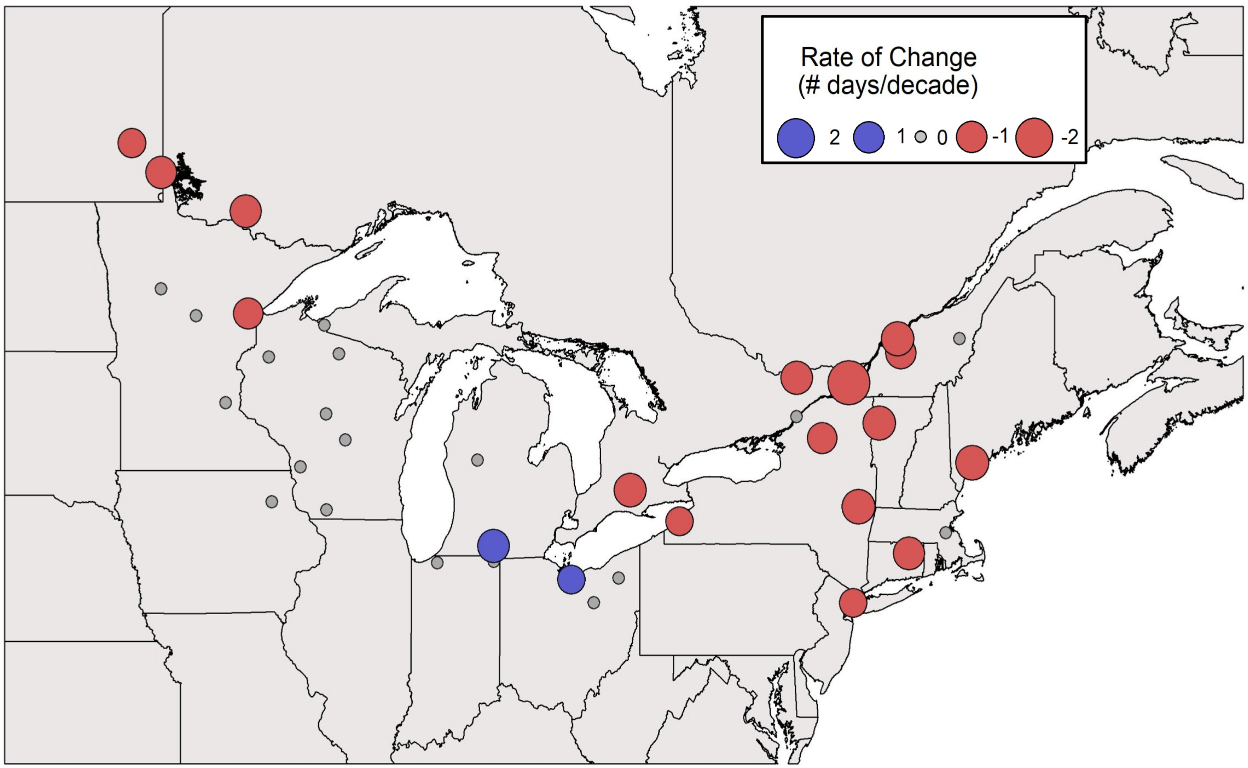
We also observed a loss of snowmaking days, primarily in the Northeast. These were defined by temperatures that are either < -5°C / < 23°F (old technology) or < -2°C / < 28°F (new technology). The above figure shows declines in snowmaking days at a temperature threshold of < -5°C / < 23°F. The disappearance of these days has implications both winter recreation and for the survival of insects such as the Asian tiger mosquito, which has a killing temperature threshold of < -5°C / < 23°F (limits range expansion).

Implications: Changes in Mud Days



Mud days are days when snow cover is absent and daily minimum temperatures are above freezing. A lot of prior research has examined the potential for low to no snow cover plus cold temperatures to cause soil freezing. Our analysis shows that these events are rare, and instead we have observed an increased frequency in days where there is no snow, and air temperatures are warm. This might be good news for vegetation and soils as soil frost can cause fine root mortality and nutrient losses. However, an increase in mud days likely has negative impacts on winter recreation and tourism by decreasing the number of days that ski areas and snowmobile trails are open. It also reduces access to timber harvest sites that can only be logged during winter when frozen ground prevents damage to roads and soils.

Implications: Changes in Snow Covered Days



A snow covered day is when snow > 0 inches. Changes in snow-covered days varied regionally, and tended to decrease in the Northeast and Midwest. Absence of snow can impact ecosystem properties and functions in a variety of ways and can also negatively affect wildlife, winter recreation, and winter forest harvest.

Project Outcomes: Outreach to North Forest Communities

- Six stakeholder meetings, four in NH and convening one each in ME and VT to identify questions of interest for synthesis (formative engagement)
- One dissemination event with leaders of stakeholder groups: “Confronting our Changing Winters: A View from 100 Years of Data and Dialogue”

Project Outcomes: Outreach to North Forest Communities

We held six stakeholder meetings, leveraging four previous meetings in New Hampshire and convening one meeting each in Maine and Vermont. Each featured semi-structured interviews prior to the gathering, a combination of scientific talks, plenary discussions, and break-out groups during the meeting, and evaluations at the end of the day that allowed us to improve the process at successive events. Attendees have included individuals from state, federal, and non-governmental organizations, industry representatives, scientists, and private citizens spanning a range of interests and expertise. From the insights we gained, we have devised a framework that identifies what people care about, why, and how scientific information might help inform decision-making.

We also held an outreach to discuss the results of our synthesis with stakeholder partners. The event, “Confronting our Changing Winters: A View from 100 Years of Data and Dialogue,” took place at the Hubbard Brook Experimental Forest on April 5, 2018. The goal of the meeting was to share our findings, talk about the questions and insights they inspire, and discuss how the results might be distributed, shared, and used within our respective networks and professions. We had 25 participants, many of whom engaged in earlier round table dialogues and represent similarly diverse views. This event enabled a two-way dialogue that both allowed us to communicate our findings while also seeking feedback about the most effective ways to disseminate our results to a broader audience. It also resulted in a new and exciting research collaboration that was the direct result of deliberations at our final outreach event. This new collaboration is among a climate scientist, a psychologist, and the director of the NH Ski Areas Association. The group is pursuing funding to explore how positive deviance (an approach to behavioral and social change) might be used to examine how and why ski areas might take steps to mitigate or adapt to climate change.

Project Outcomes: Engagement with Scientists

- One day-long workshop with northern forest scientists to identify research themes that align with stakeholder questions

Project Outcomes: Engagement with Scientists

We held a workshop the day prior to the biennial Northern Ecosystem Research Cooperative (NERC) meeting. This pre-NERC workshop occurred on March 27, 2017 at the USGS New York Water Science Center, Troy, NY. We engaged 20 scientists from across the northeastern North America, including researchers from the United States and Canada. The goals of the workshop were: 1) to define key questions to pursue with synthesis effort, determine the approach to answering these questions, and identify deliverables; and 2) to hold the first Northeastern Winter Working Group meeting to identify future research questions, new initiatives, and potential collaborators. We consider the workshop successful in achieving both goals, as were able to devise a framework for our NSRC-funded synthesis of winter climate change while at the same time outlining a future research agenda of broad interest to the group. We have even translated one of the ideas generated at the workshop into a formal research effort funded by the National Socio-Environmental Synthesis Center (SESYNC) to explore the coupled natural and human responses to extreme winter weather events.

Future directions

- Partnership with Hubbard Brook Research Foundation to develop translation products
- Media campaign to disseminate results
- New research directions that explore a “warmer soils in a warmer world” hypothesis focused on higher numbers of mud days and impacts on social and ecological systems
- New co-production of knowledge partnerships, working with regional stakeholders to explore questions of mutual interest

List of products

Peer-reviewed publications in prep

- Contosta, A.R., Casson, N.A., Nelson, S.J., Garlick, S., et al., in prep for Ecological Applications. The impacts of changing winters on forest ecosystems and surrounding communities. Expected submission date: 8/31/2018
- Contosta, A.R., Casson, N.A., Nelson, S.J., Garlick, S., et al., in prep for Nature Climate Change. What is Winter? A social-ecological reckoning. Expected submission date: 9/30/2018

Conference presentations

- Contosta, A.R., Nelson, S.J., Rezanezhad, F., and Sorenson, P. 2018. “Impacts of winter climate change on hydrobiogeochemical dynamics of terrestrial and aquatic systems during the winter and shoulder seasons.” American Geophysical Union Fall Meeting Session 54427 (Contosta et al. are session conveners)
- Contosta, A.R. Casson, N.J., Nelson, S.J., and Garlick, S. 2018. “What is winter? A socio-ecological reckoning.” Eastern Snow Conference, College Park, MD.

List of products

Websites

- https://changingwinters.wordpress.com

New Awards

- Winter Weather Whiplash: Developing Indices of Extreme Winter Weather Variability and Socio-Ecological Responses. A.R. Contosta, N.A. Casson, National Socio-Environmental Synthesis Center, 2017-2018.
- Winter Weather Whiplash. A.R. Contosta and E.A. Burakowski. Earth Systems Research Center Hubbard Endowment, 2018, $15,200.

References

Brown, P.J., Bradley, R.S. and Keimig, F.T., 2010. Changes in extreme climate indices for the northeastern United States, 1870–2005. *Journal of Climate*, *23*(24), pp.6555-6572.

Campbell, J.L., Mitchell, M.J., Groffman, P.M., Christenson, L.M. and Hardy, J.P., 2005. Winter in northeastern North America: a critical period for ecological processes. *Frontiers in Ecology and the Environment*, *3*(6), pp.314-322.

Campbell, J.L., Socci, A.M. and Templer, P.H., 2014. Increased nitrogen leaching following soil freezing is due to decreased root uptake in a northern hardwood forest. *Global change biology*, *20*(8), pp.2663-2673.

Cleavitt, N.L., Fahey, T.J., Groffman, P.M., Hardy, J.P., Henry, K.S. and Driscoll, C.T., 2008. Effects of soil freezing on fine roots in a northern hardwood forest. *Canadian Journal of Forest Research*, *38*(1), pp.82-91.

Dawson, J. and D. Scott (2013) Managing for climate change in the alpine ski sector, Tourism Management, 35: 244-254.

Donat, M.G., Alexander, L.V., Yang, H., Durre, I., Vose, R., Dunn, R.J.H., Willett, K.M., Aguilar, E., Brunet, M., Caesar, J. and Hewitson, B., 2013. Updated analyses of temperature and precipitation extreme indices since the beginning of the twentieth century: The HadEX2 dataset. *Journal of Geophysical Research: Atmospheres*, *118*(5), pp.2098-2118.

Dukes, J.S., J. Pontius, D. Orwig, J.R. Garnas, V.L. Rodgers, N. Brazee, B. Cooke, K.A. Theoharides, E.E. Stange, R. Harrington, J. Ehrenfeld, J. Gurevitch, M. Lerdau, K. Stinson, R. Wick, and M. Ayres (2009) Responses of insect pests, pathogens, and invasive plant species to climate change in the forests of northeastern North America: What can we predict? Canadian Journal of Forest Research, 39: 231–248.

Easterling, D. R., T. R. Karl, J. H. Lawrimore, and S. A. Del Greco. 1999. United States Historical Climatology Network Daily Temperature, Precipitation, and Snow Data for 1871-1997. ORNL/CDIAC-118, NDP-070. Carbon Dioxide Information Analysis Center, Oak Ridge National Laboratory, U.S. Department of Energy, Oak Ridge, Tennessee.

Frumhoff, P.C., McCarthy, J.J., Melillo, J.M., Moser, S.C., Wuebbles, D.J., Wake, C. and Spanger-Siegfried, E., 2008. An integrated climate change assessment for the Northeast United States. *Mitigation and adaptation strategies for global change*, *13*(5-6), pp.419-423.

Groffman, P.M., Driscoll, C.T., Fahey, T.J., Hardy, J.P., Fitzhugh, R.D. and Tierney, G.L., 2001. Colder soils in a warmer world: a snow manipulation study in a northern hardwood forest ecosystem. *Biogeochemistry*, *56*(2), pp.135-150.

Hayhoe, K., C.P. Wake, T.G. Huntington, L. Luo, M.D. Schwartz, J. Sheffield, E. Wood, B. Anderson, J. Bradbury, A. DeGaetano, T.J. Troy, and D. Wolf (2007) Past and future changes in climate and hydrological indicators in US Northeast, Climate Dynamics, 28: 381-407.

References

Hodgkins, G.A., and R.W. Dudley (2013) Modeled future peak streamflows in four coastal Maine rivers. U.S. Geological Survey Scientific Investigations Report 2013-5080, 18 pp.

Karl, T.R., Nicholls, N. and Ghazi, A., 1999. Clivar/GCOS/WMO workshop on indices and indicators for climate extremes workshop summary. In *Weather and Climate Extremes* (pp. 3-7). Springer, Dordrecht.

Lombardero, M.J., Ayres, M.P., Ayres, B.D. and Reeve, J.D., 2000. Cold tolerance of four species of bark beetle (Coleoptera: Scolytidae) in North America. *Environmental Entomology*, *29*(3), pp.421-432.

Mekis, É and L.A. Vincent, 2011: An overview of the second generation adjusted daily precipitation dataset for trend analysis in Canada. Atmosphere-Ocean 49(2), 163-177 doi:10.1080/07055900.2011.583910.

Ogden, N.H., Milka, R., Caminade, C. and Gachon, P., 2014. Recent and projected future climatic suitability of North America for the Asian tiger mosquito Aedes albopictus. *Parasites & vectors*, *7*(1), p.532.

Omernik, J.M. and G.E. Griffith. 2014. Ecoregions of the conterminous United States: evolution of a hierarchical spatial framework. Environmental Management 54(6):1249-1266.

Patel, K.F., Tatariw, C., MacRae, J.D., Ohno, T., Nelson, S.J. and Fernandez, I.J., 2018. Soil carbon and nitrogen responses to snow removal and concrete frost in a northern coniferous forest. *Canadian Journal of Soil Science*, *98*(0), pp.1-12.

Peterson, T., Folland, C., Gruza, G., Hogg, W., Mokssit, A. and Plummer, N., 2001. *Report on the activities of the working group on climate change detection and related rapporteurs*. Geneva: World Meteorological Organization.

Peterson, T.C., 2005. Climate change indices. *WMO bulletin*, *54*(2), pp.83-86.

Platonov, A.E., Fedorova, M.V., Karan, L.S., Shopenskaya, T.A., Platonova, O.V. and Zhuravlev, V.I., 2008. Epidemiology of West Nile infection in Volgograd, Russia, in relation to climate change and mosquito (Diptera: Culicidae) bionomics. *Parasitology Research*, *103*(1), pp.45-53.

Rittenhouse, C.D. and Rissman, A.R., 2015. Changes in winter conditions impact forest management in north temperate forests. *Journal of environmental management*, *149*, pp.157-167.

Rittenhouse, C.D. and A.R. Risman (2015) Changes in winter conditions impact forest management in north temperate forests, Journal of Environmental Management, 149: 157-167.

Rochlin, I., Ninivaggi, D.V., Hutchinson, M.L. and Farajollahi, A., 2013. Climate change and range expansion of the Asian tiger mosquito (Aedes albopictus) in Northeastern USA: implications for public health practitioners. *PloS one*, *8*(4), p.e60874.

References

Rodenhouse, N., Christesnen, L.M., Parry, D., and Green, L.E. (2009) Climate change effects on native fauna of northeastern forests, Canadian Journal of Forest Research, 39: 249-263.

Sanders-DeMott, R., Sorensen, P.O., Reinmann, A.B. and Templer, P.H., 2018. Growing season warming and winter freeze–thaw cycles reduce root nitrogen uptake capacity and increase soil solution nitrogen in a northern forest ecosystem. *Biogeochemistry*, *137*(3), pp.337-349.

Scott, D., McBoyle, G. and Mills, B., 2003. Climate change and the skiing industry in southern Ontario (Canada): exploring the importance of snowmaking as a technical adaptation. *Climate research*, *23*(2), pp.171-181.

Scott, D., McBoyle, G., Minogue, A. and Mills, B., 2006. Climate change and the sustainability of ski-based tourism in eastern North America: A reassessment. *Journal of sustainable tourism*, *14*(4), pp.376-398.

Scott, D., J. Dawson, and B. Jones (2008) Climate change vulnerability of the US Northeast winter recreation–tourism sector, Mitigation and Adaptation Strategies for Global Change, 13: 577-596.

Sen, P.K., 1968. Estimates of the regression coefficient based on Kendall's tau. *Journal of the American statistical association*, *63*(324), pp.1379-1389.

Skinner, C.B., A.T. DeGaetano, and B.F. Chabot (2010) Implications of twenty-first century

climate change on Northeastern United States maple syrup production: impacts and adaptations, Climatic Change, 100:685–702.

Stone, D.M., 2002. Logging options to minimize soil disturbance in the northern lake states. Northern Journal of Applied Forestry, 19: 115-121.

Tatariw, C., Patel, K., MacRae, J.D. and Fernandez, I.J., 2017. Snowpack Loss Promotes Soil Freezing and Concrete Frost Formation in a Northeastern Temperate Softwoods Stand. *Northeastern Naturalist*, *24*(sp7), pp.B42-B54.

Trân, J.K., Ylioja, T., Billings, R.F., Régnière, J. and Ayres, M.P., 2007. Impact of minimum winter temperatures on the population dynamics of Dendroctonus frontalis. *Ecological Applications*, *17*(3), pp.882-899.

Ungerer, M.J., Ayres, M.P. and Lombardero, M.J., 1999. Climate and the northern distribution limits of Dendroctonus frontalis Zimmermann (Coleoptera: Scolytidae). *Journal of Biogeography*, *26*(6), pp.1133-1145.

Williams, C. N., Jr., M. J. Menne, R. S. Vose, and D. R. Easterling (2006), United States Historical Climatology Network daily temperature, precipitation, and snow data, ORNL/CDIAC-118, NDP-070, http://cdiac.ornl.gov/epubs/ndp/ushcn/usa.html, Carbon Dioxide Inf. Anal. Cent., Oak Ridge Natl. Lab., U.S. Dep. of Energy, Oak Ridge, Tenn.

Wilson, G., Green, M., and Mack, K. 2018. Historical Climate Warming in the White Mountains of New Hampshire (USA): Implications for Snowmaking Water Needs at Ski Areas. Mountain Research and Development, 38: 164-171.