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Changes in winter conditions impact forest management in north temperate forests

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ABSTRACT

Climate change may impact forest management activities with important implications for forest ecosystems. However, most climate change research on forests has focused on climate-driven shifts in species ranges, forest carbon, and hydrology. To examine how climate change may alter timber harvesting and forest operations in north temperate forests, we asked: 1) How have winter conditions changed over the past 60 years? 2) Have changes in winter weather altered timber harvest patterns on public forestlands? 3) What are the implications of changes in winter weather conditions for timber harvest operations in the context of the economic, ecological, and social goals of forest management? Using meteorological information from Climate Data Online and Autoregressive Integrated Moving Average (ARIMA) models we document substantial changes in winter conditions in Wisconsin, including a two- to three-week shortening of frozen ground conditions from 1948 to 2012. Increases in minimum and mean soil temperatures were spatially heterogeneous. Analysis of timber harvest records identified a shift toward greater harvest of jack pine and red pine and less harvest of aspen, black spruce, hemlock, red maple, and white spruce in years with less frozen ground or snow duration. Interviews suggested that frozen ground is a mediating condition that enables low-impact timber harvesting. Climate change may alter frozen ground conditions with complex implications for forest management.

1. Introduction

Based on global climate change models, studies at global and regional scales anticipate that changes in temperature and precipitation will affect supporting and regulating services of forest ecosystems, including carbon sequestration and storage potential (van Mantgem et al., 2009; Yvon-Durocher et al., 2010), climate regulation (Foley et al., 2007), and hydrology (Meyer et al., 1999; Stewart, 2013). Studies of provisioning services of forest ecosystems have largely focused on anticipated changes in timber supply through species range shifts (Iverson and Prasad, 1998) and changes in vegetation growth and length of growing seasons (Saxe et al., 2001; Tullus et al., 2012), atmospheric CO_2 concentrations (Norby et al., 1999; Hyvönen et al., 2007), disturbance regimes (Dale et al., 2001), and invasive plants, insect and disease dynamics Ayers and Lombardero 2000, Dukes et al., 2009). Less well studied are the impacts of climate change on forest operations, including changing access to stands, timing of harvest and transport, and selection of forests for harvest based on operability (Spittlehouse, 2005; Ogden and Innes, 2007; Gauthier et al., 2014). Changes in provisioning services due to climate change may also have interacting effects on supporting and regulating services (Alig et al., 2002). The dynamic interactions of humans and their environments, at local to global scales, produce these interrelated effects (Chapin et al., 2006).

Climate change portends changes in the timing, frequency, duration, and intensity of weather events. When assessing impacts, vulnerabilities, and adaptations, researchers often cannot discern a priori which climate change impacts produce vulnerabilities of greatest concern to communities of interest. Therefore a participatory process is needed to define vulnerabilities, narrow into the most relevant impacts and vulnerabilities, and examine related adaptations (Smit and Wandel, 2006). This process led us to focus on winter weather and frozen ground conditions, which are not widely discussed in the literature on forest management and

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climate change (Spittlehouse, 2005) despite anticipated changes in winter temperatures, precipitation type, extent of snow cover, and snow depth.

The majority of temperate forests are managed for timber and non-timber forest products (Food and Agriculture Organization, 2010). In north-temperate regions, winter weather conditions are primary factors affecting forest operations, including the ability to access sites, harvest within sites, and transport equipment and products away from sites. Reduced access to timber on wet, unfrozen soils is expected to threaten the forest industry (Lindner et al., 2010). Forest operations conducted on partially frozen or thawed soils can cause rutting and soil compaction (Stone, 2002), which have long-term impacts on soil productivity (Corns, 1988; Grigal, 2000). While local meteorological records indicate a trend toward warmer winters in the north-central United States (Serbin and Kucharik, 2009; Kucharik et al., 2010; Sinha et al., 2010), the effects on frozen ground conditions depend on several factors. Snow insulates soils from cold air temperatures in winter, so reduced snow in the absence of temperature change can result in greater depth of frozen soil (Groffman et al., 2001, 2011). However, empirical observations from Canada indicate that warmer winters and reduced snow depth result in fewer soil freezing days (Henry, 2008; Sinha and Cherkauer, 2008). Reduction in albedo leads to increased absorption of solar energy and hence warming of exposed soils (Chapin et al., 2000), as does increases in winter temperatures (Mellander et al., 2007). We were particularly interested in trends over time in duration and variability in frozen ground conditions.

This research aims to document climate impacts on forest management and contextualize those impacts with an assessment of multiple goals and stressors. We asked: 1) How have winter conditions changed over the past 60 years? 2) Have changes in winter weather altered timber harvest patterns on public forestlands? 3) What are the implications of changes in winter weather conditions for timber harvest operations in the balance of economic, ecological, and social goals of forest management? To answer our questions we first quantified changes in winter conditions. We then associated changes in winter conditions with tree harvest amounts. Finally, we examined the context of climate change impacts based on document analysis and interviews with forest managers. We focus on Wisconsin, the United States' leading producer of paper products.

2. Methods

We used a mixed-methods approach to link quantitative evidence of trends with rich contextual description of the drivers and implications of these trends (Johnson and Onwuegbuzie, 2004). Our mixed-methods analysis combined historical analysis of climate data and timber harvesting trends with qualitative interviews that provided context and meaning for changes in winter conditions. Wisconsin's north and eastern temperate forests support a \$20 billion timber industry. Loggers secure contracts to harvest timber on public and private lands, and most contracts provide a two-year period for conducting harvests, so loggers have some flexibility in determining what to harvest at any time. Logs and chips are then transported to mills; one study in this region estimated a 240 km mean round trip distance, of which 3% was on private logging roads including unpaved forest roads, 16% was on minor county roads, and 81% was on major state roads (Stewart et al., 2012). Sustainable harvests are encouraged through government policy and nongovernmental certification programs. For instance, loggers are encouraged to follow Best Management Practices for water quality. County and state forests and private lands enrolled in the forest tax program are certified by the Sustainable Forestry Initiative (SFI) and/or Forest Stewardship Council (FSC).

2.1. Historical analysis of winter conditions, 1948–2012

We obtained meteorological records for eight weather stations in Wisconsin (Fig. 1; Supplementary material, Appendix 1) from Climate Data Online provided by the National Climatic Data Center, National Oceanic and Atmospheric Administration. All stations in the analysis had nearly complete daily records and at least 60 years of continuous observations. The meteorological records consisted of daily records of maximum air temperature (Tmax; °C), minimum air temperature (Tmin; °C), precipitation amount (Prec; mm), snowfall amount (Snow; mm), and snow depth (Snwd; mm). From those weather observations, we calculated the daily mean air temperatures:

$$T\text{mean}_i = \frac{(T\text{max}_i - T\text{min}_i)}{2} \tag{1}$$

for each day i. We then calculated an 11-day running mean (Trun) of the daily mean air temperatures for each day where the mean for day 11 was the mean value of daily mean air temperature for the 11 days from day (i−10) to day i. Values of Trun on the first 10 days were calculated using 1-day to 10-day running means respectively. We estimated daily soil temperature (Ts) at 10-cm depth (Zheng et al., 1993):

$$T\text{s} = 0.78 \times T\text{run}_i + 2.87 \tag{2}$$

where $T\text{run}_i$ was an 11-day mean of daily mean air temperature.

We considered the soil frozen if the soil temperature at 10-cm depth was ≤ 0 °C. This depth of soil freezing approximated the point between being able to operate lighter logging equipment ($\geq$7.5 cm frozen soil) vs. heavier logging equipment ($\geq$15 cm frozen soil; Stone, 2002). We then adjusted Ts based on presence (Snwd > 0 mm; Eq. (3)) or absence (Snwd = 0 mm; Eq. (4)) of snow cover:

$$T\text{sa} = [(T\text{avg}_i - T\text{avg}_{i-1}) \times M_1] + T\text{s}_{i-1} \tag{3}$$

$$T\text{sa} = [(T\text{avg}_i - T\text{avg}_{i-1}) \times M_2] + T\text{s}_i \tag{4}$$

where $M_1 = 0.1$ and $M_2 = 0.25$ were constant scalers derived from regressing Trun against observed soil temperatures (Zheng et al., 1993). We applied these equations to weather information obtained from airport locations with little or no topographic relief. Local forest soil conditions are influenced by soil type, topography, subsurface water dynamics, and vegetative cover, which can impact the onset, depth, and duration of frozen soil. Thus, we considered the soil temperatures obtained in Eqs. (3) and (4) as estimates of local forest soil conditions and not observed values.

We calculated several metrics of changes in winter conditions for each winter season, defined as November 1 to April 30 (Table 1). These metrics included frozen ground days (Tsa ≤ 0 C), thawed ground days (Tsa > 0 C), soil temperature, and snow melt. To analyze each time series of winter conditions, we fit Autoregressive Integrated Moving Average (ARIMA) models (Box and Jenkins, 1976). ARIMA models decompose a time series into trend and irregular components, while accounting for potential correlations in the irregular component. Specifically, an ARIMA (p,d,q) model, specifies an autoregressive model of order p, a moving average model of order q, or a mixed model with p and q greater than 0. ARIMA models assume constant mean and variance over time (i.e., a stationary time series) so time series were differenced d times to

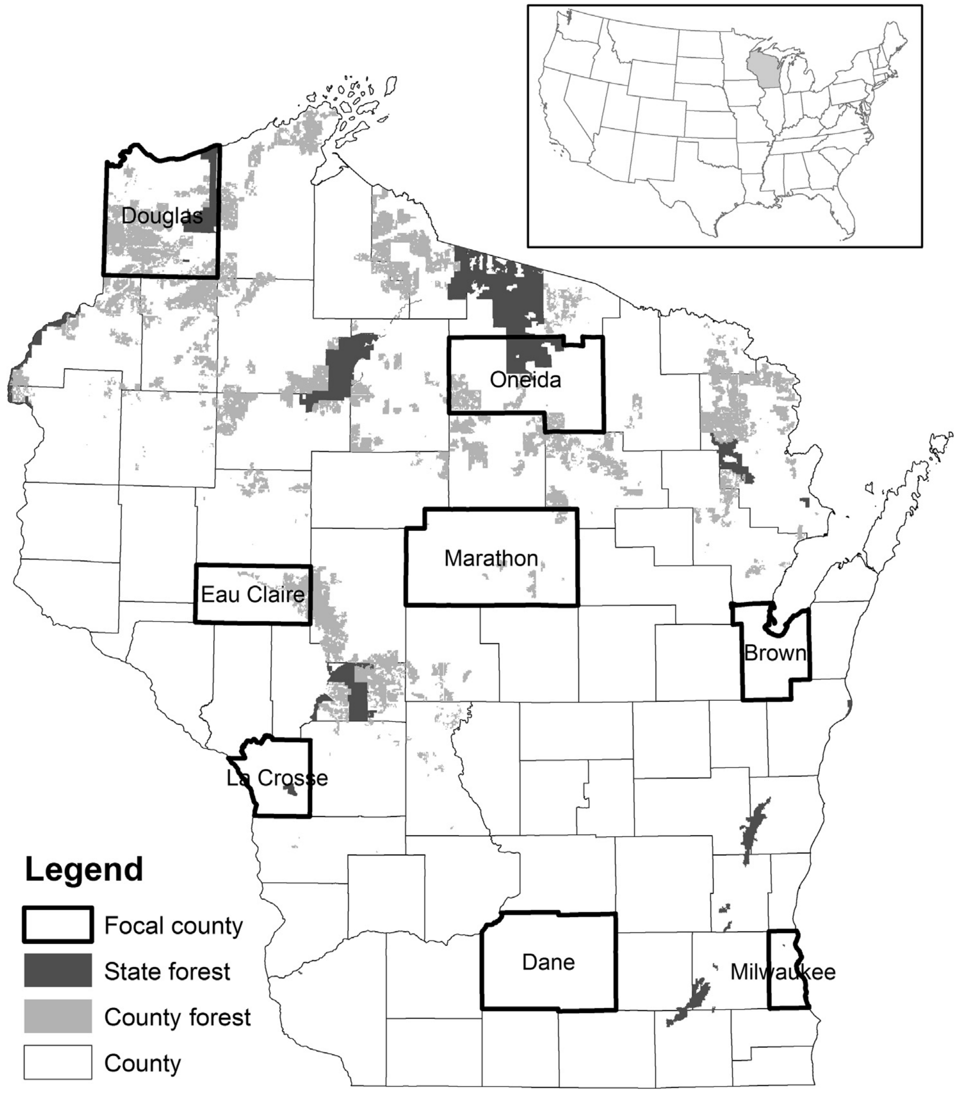

Fig. 1. Location of state and county forests in Wisconsin, USA. Meteorological station records obtained from the focal counties indicated.

meet the assumption of stationarity when necessary. Models with $d > 0$ had a trend with slope μ, which was the estimated mean of the differenced data. Statistical significance of the trend was assessed by evaluating the standard error of μ to ensure the slope was significantly different from zero. This procedure was the equivalent of a t-test, after adjusting for autocorrelation. We used the auto.arima() function in the forecast library of the R language and environment for statistical analyses (version 2.15.2) (R Core Development Team, 2012) to identify the appropriate ARIMA (p,d,q) model. We used residuals from ARIMA models as independent variables when associating forest harvest and winter conditions.

2.2. Association between forest harvest and winter conditions, 1996–2012

We used data from the Wisconsin Forest Inventory and Reporting System (WisFIRS, http://dnr.wi.gov/topic/CountyForests/wisfirs.html) to obtain forest harvest information from 4 county forests (Douglas, Eau Claire, Marathon, and Oneida), and 15 state forest units (Black River, Brule River, Coulee Experimental, Flambeau River, Governor Knowles, Kettle Moraine Lapham, Loew, Mukwanago, Northern, Pike, and Southern units, Northern Highland, American Legion, Peshtigo River, and Point Beach; state forests, hereafter). We removed state forests without forest harvest from analysis.

The WisFIRS database provided information on harvest amount (hectares), by forest type, for all harvests conducted from 1996 to 2012 on county and state forests. We obtained harvest information for 15 forest cover types: aspen (*Populus grandidentata*, *Populus tremuloides*), birch (*Betula papyrifera*, *Betula nigra*, and *Betula lutea*), black spruce (*Picea mariana*), fir-spruce (predominantly *Abies balsamea* or *Picea glauca*, or both species), hemlock (*Tsuga canadensis*), jack pine (*Pinus banksiana*), northern hardwoods (predominantly *Acer saccharum*, *Fagus grandifolia*, *Tilia americana*, *Fraxinus americana*, and *Betula alleghaniensis*), oaks (*Quercus* spp.), red maple (*Acer rubrum*), red pine (*Pinus resinosa*), scrub oak (*Quercus* spp.), swamp hardwoods (predominantly *Fraxinus nigra*, *Ulmus americana*, and *Acer rubrum*), tamarack (*Larix laricina*), white pine (*Pinus strobus*), and white spruce (*Picea glauca*).

We summed harvest amount by species within each county and state forest for the period July 1 to June 30 to obtain 12-month harvest amounts associated with winter conditions of each year. More detailed information on timing of harvest was not available so we were unable to partition harvest by seasons. We also were unable to account for spatial variability in stand productivity and

Table 1
Description of metrics for winter conditions derived from meteorological station data in Wisconsin.

Variable	Explanation of terms
Frozen ground season	Season of frozen ground, from start to end of frozen ground
Frozen ground duration	Total number of days with soil temperature ≤0 °C per winter
Start of frozen ground	Start day of frozen ground, days since November 1
End of frozen ground	End day of frozen ground, days since November 1
Freeze-thaw cycles	Number of freeze–thaw cycles per winter
Mean ground thaw duration	Mean duration of consecutive thaw days for each winter
SD ground thaw duration	Standard deviation of consecutive thaw days for each winter
Mean soil temperature	Mean soil temp per winter
SD soil temperature	Standard deviation of soil temp per winter
Min. soil temperature	Minimum soil temp per winter
Max. soil temperature	Maximum soil temp per winter
Soil temp 1st snow	Soil temp at first snow depth >15 cm
Snow season	Season of snow depth >15 cm, from start to end
Snow duration	Total number of days with snowdepth >15 cm per winter
Start of snow	Start day of snowdepth >15 cm
End of snow	End day of snowdepth >15 cm
Snow depth 1st freeze	Snow depth at first instance of frozen ground
Mean snow melt duration	Mean duration of snow depth <15 cm for each winter
SD snow melt duration	Standard deviation of duration of snow depth <15 cm for each winter

Table 2
Mean minimum (Tmin), mean (Tmean), and maximum (Tmax) air temperature (in °C), total snowfall (Snow, in cm), and total winter rainfall (Rain, in mm) observed during the frozen ground season at meteorological stations in Wisconsin. Means calculated for the 10-year period ending in the year indicated.

Station	County	Metric	1960[a]	1970	1980	1990	2000	2010
14898	Brown	Tmin	−26.9	−30.7	−28.8	−27.9	−27.6	−25.9
		Tmean	−6.9	−8.2	−8.0	−7.2	−6.3	−6.2
		Tmax	11.3	8.7	9.9	8.9	11.2	11.3
		Snow	78.9	89.6	100.2	89.1	107.8	123.0
		Rain	30.1	30.1	37.3	22.4	28.0	26.8
14837	Dane	Tmin	−26.8	−30.2	−27.8	−28.2	−25.9	−25.2
		Tmean	−5.9	−7.7	−7.2	−6.5	−5.5	−5.6
		Tmax	12.7	11.7	13.1	12.7	12.2	12.8
		Snow	72.9	69.9	80.9	80.6	103.1	103.2
		Rain	34.2	29.7	31.0	27.1	35.6	33.1
14991	Eau Claire	Tmin	−33.1	−34.2	−32.8	−31.9	−29.2	−27.6
		Tmean	−8.7	−9.2	−9.8	−8.8	−7.7	−7.6
		Tmax	12.1	9.8	10.2	12.3	11.2	10.4
		Snow	86.7	104.4	90.8	96.4	121.2	88.6
		Rain	6.1	8.8	16.6	22.9	17.9	19.7
14920	La Crosse	Tmin	−32.7	−34.1	−32.0	−32.0	−29.7	−28.5
		Tmean	−8.4	−9.0	−9.1	−8.6	−7.4	−7.5
		Tmax	11.8	11.1	11.7	10.9	10.8	11.3
		Snow	69.2	112.3	104.2	77.5	115.3	97.2
		Rain	20.0	16.3	16.7	16.7	28.4	20.3
14897	Marathon	Tmin	−28.6	−32.8	−29.6	−29.4	−28.1	−27.7
		Tmean	−6.8	−8.4	−7.9	−7.3	−6.4	−6.3
		Tmax	12.1	10.4	12.0	11.2	11.5	11.7
		Snow	76.2	87.4	80.2	59.4	86.6	85.5
		Rain	18.8	15.0	14.2	14.6	27.4	20.2
14839	Milwaukee	Tmin	−30.7	−33.0	−30.9	−30.8	−28.8	−27.9
		Tmean	−8.3	−8.9	−8.7	−8.0	−7.0	−7.3
		Tmax	11.7	9.3	10.9	9.6	10.7	11.1
		Snow	104.9	104.9	103.5	88.0	125.6	97.5
		Rain	33.6	23.5	28.9	17.7	16.3	13.7
477113	Oneida	Tmin	−23.7	−26.7	−24.3	−24.7	−21.3	−21.7
		Tmean	−5.1	−6.4	−6.5	−5.6	−4.7	−3.9
		Tmax	11.5	11.9	10.7	10.6	10.6	12.9
		Snow	77.9	94.4	97.9	78.5	73.6	95.7
		Rain	38.3	29.2	30.9	22.5	34.4	47.3
478349	Superior	Tmin	−31.4	−34.5	−34.1	−33.4	−31.9	−30.3
		Tmean	−8.2	−9.0	−9.5	−9.0	−7.8	−7.9
		Tmax	11.4	10.7	12.4	13.0	13.8	13.7
		Snow	100.2	122.2	57.8	23.2	110.5	114.4
		Rain	20.2	21.9	13.6	6.9	16.1	11.0

[a] Mean calculated from 1948 to 1960.

past disturbance effects on the merchantable wood volume (cubic meters per hectare) within a stand, which may have affected how much area was harvested.

We used annual harvest amount as the response variable in models with residuals of winter conditions from ARIMA models as independent variables. We used mixed-effects models to account for fixed effects of year and the soil condition variables, and a random effect for each county and state forest. We structured the random effect such that each county and state forest had a unique intercept, but not unique slope. We used Akaike's information criterion (AIC) to rank models and Akaike weights (w_i) to determine which model associating harvest with winter conditions had the strongest support (Burnham and Anderson, 2002). We fitted all models with the lmer function in the lme4 package for the R language and environment for statistical analyses (version 2.15.2) (R Core Development Team, 2012).

2.3. Contextual impacts of changing winter conditions on forestry operations

This research was developed through a participatory approach to examine climate change impacts on forest management and operations. The need for research on frozen ground conditions was identified through a focus group and three initial interviews with scientists and managers from the Wisconsin Department of Natural Resources (DNR) and United States Forest Service in 2011. The focus group was conducted in northern Wisconsin with state and federal forest scientists and managers, including specialists in hydrology, forest pests, operations, and forest planning. We also gathered feedback to hone our research design from the Wisconsin Initiative on Climate Change Impacts (WICCI) Forestry Working Group.

We further relied on purposive sampling of key informants to understand the importance of frozen ground conditions for forest management and operations. Between 2011 and 2012, we conducted additional interviews with foresters ($n = 5$), public land administrators and policymakers ($n = 4$), highway administrators ($n = 3$), and a forest industry representative ($n = 1$). We asked respondents how forestry operations are affected by weather and frozen ground conditions, whether they have observed changes in weather and frozen ground, and if so, how those changes have impacted forest management, operations, and logger livelihoods. We attended the 2012 Wisconsin County Forest Association meeting to solicit responses to our initial results. After our presentation, we asked county foresters to complete a short questionnaire that asked: This past winter was unusually warm. Did this impact timber management in your county? We received responses from 15 of the approximately 60 county foresters in attendance. These comments were considered as additional forest manager perspectives and not as a representative cross-section of forest managers.

We analyzed interview responses in Dedoose software version 4.5.95 (Los Angeles, CA: SocioCultural Research Consultants, LLC). We examined transcripts and comments for perspectives on the role of frozen ground in forest operations; restrictions that require frozen ground for harvest; ecological impacts from harvesting on wet, unfrozen soil; transportation impacts from driving on unfrozen roads; and impacts on logger livelihoods and timber supply. We examined both majority and minority perspectives. We also examined public forest timber contracts and state policies that restricted forest operations on unfrozen ground. Themes from interviews are provided as Supplementary material, Appendix 2.

3. Results and discussion

3.1. Changes in winter conditions, 1948–2012

We documented spatial and temporal variability in air temperature, total snowfall, and total winter rainfall (Table 2), and in all metrics of winter conditions in the focal counties, with the greatest number of trends in Douglas (11 of 25 metrics), Marathon (9 of 25 metrics), Milwaukee (8 of 25 metrics), and Eau Claire (7 of 25 metrics) counties (Table 3; Supplementary material, Appendix 3). Among metrics of winter conditions, trends in frozen ground duration (8 of 8 counties), frozen ground season (7 of 8 counties), and minimum soil temperature (7 of 8 counties) occurred with greater frequency than trends in snow season (1 of 8 counties), snow duration (2 of 8 counties), and start of snow (1 of 8 counties). Collectively, the winter condition metrics indicated that frozen ground seasons in Wisconsin have decreased in length with fewer frozen ground days within the season. The primary factors associated with fewer frozen ground days were increases in minimum and mean soil temperatures, and an earlier end to the frozen ground season.

We observed substantial reductions in the length of the frozen ground season (start of frozen ground to end of frozen ground) and the total number of frozen ground days per season for all counties in our study (Fig. 2, Table 3). For example, Milwaukee County in southeastern Wisconsin had the greatest decrease in frozen ground season length (slope −0.58 days per year; a reduction of 36.8 days since 1948) but also had the slowest decrease in total number of frozen ground days (slope −0.11 days per year; a reduction of 6.8 days since 1948) among all counties. In contrast, Douglas County in northwestern Wisconsin had a modest decrease in frozen ground season (slope −0.35 days per year; a reduction of 22.3 days since 1948) but the fastest decrease in total number of frozen ground days among all counties (slope −0.47 days per year; a reduction of 30.3 days since 1948).

The trend toward shorter frozen ground seasons resulted from an earlier end of frozen ground, a higher minimum soil temperature, and a higher mean soil temperature during the frozen ground season (Table 3). Trends toward earlier end of frozen ground were strongest in Milwaukee County (Fig. 3; slope −0.343 days per year; starting 22.0 days later since 1949) and weakest in La Crosse County (slope −0.131 days per year; starting 8.4 days later since 1948). A pattern of increasing minimum soil temperature was evident for all but one county (Fig. 4). Trends for mean soil temperature ranged from 0.009 °C per year in Milwaukee County (a 0.58 °C increase in mean soil temperature since 1948) to 0.043 °C per year in Douglas County (a 2.8 °C increase in soil temperature since 1948) (Table 3; Fig. 5). We found no trends for maximum soil temperature (Fig. 4) or snow melt duration (Supplementary material, Appendix 4).

3.2. Association between forest harvest and winter conditions, 1996–2012

Standard deviation of ground thaw duration was the most strongly supported model of changes in annual harvest amount as a function of winter conditions for 10 of the 15 forest cover types, while standard deviation of snow melt duration was most strongly supported in the remaining forest cover types (Table 4). No other winter condition metrics were supported by the data for any forest cover type. Standard deviation of ground thaw duration and snow melt duration indicated more within-season variability in the duration of non-frozen conditions.

This analysis is the first to quantify an association between variability in frozen ground duration and annual harvest amount by forest cover type. Forest cover types that grow on sandy, well-drained soils or slopes, such as jack pine, had increased harvest with standard deviation of thaw duration (Fig. 6, Table 4). The increase in jack pine harvest during winters with high variability in thaw duration presumably resulted from a decrease in harvest conducted on moist, poorly drained soils or bottomlands. Indeed, moist or wet-ground forest cover types, such as black spruce, hemlock, and white spruce, had a decrease in harvest during winters with high variability in thaw duration. We assume the switch from moist or wet ground to dry ground allowed loggers to access stands, conduct harvest within stands, or transport materials following harvest. Associations with variability in frozen ground duration were not evident in all forest types. The northern hardwood forest type, which grows on mesic sites with well-drained to moderately drained loamy soils, had only a slight decrease in harvest during winters with high variability in thaw duration.

In addition to ground thaw duration, variability in snow melt duration was associated with harvest. Harvest of aspen, oaks, and white pines decreased with variability in snow melt duration, indicating that consistent snow cover was an important factor for harvest of those species (Table 4). In contrast, red pine harvest

Table 3
ARIMA model trends (SE) for winter conditions in Wisconsin, 1948–2012. Only winter conditions with ARIMA model trends included in the table.

Winter condition	Brown	Dane	Douglas	Eau Claire	La Crosse	Marathon	Milwaukee	Oneida
Frozen ground season	−0.515 (0.622)	−0.436 (0.750)	−0.348 (0.624)	−0.383 (0.572)	−0.3249 (0.794)	−0.352 (0.685)	−0.575 (1.182)	
Frozen ground duration	−0.435 (0.716)	−0.152 (0.858)	−0.4728 (0.629)	−0.359 (0.724)	−0.281 (0.704)	−0.387 (0.733)	−0.106 (0.475)	−0.171 (0.689)
Start of frozen ground				0.196 (0.754)				
End of frozen ground			−0.131 (0.469)	−0.202 (0.255)	−0.194 (0.482)		−0.343 (0.609)	
Freeze-thaw cycles		−0.076 (0.171)					−0.059 (0.101)	
Mean ground thaw duration	0.087 (0.200)	−0.001 (0.254)		0.007 (0.030)	0.024 (0.119)		−0.069 (0.388)	
SD thaw duration	0.023 (0.234)	0.038 (0.215)		−0.030 (0.045)				
Mean soil temperature	0.012 (0.021)		0.023 (0.017)			0.014 (0.044)	0.009 (0.025)	
SD soil temperature			−0.009 (0.017)					
Min. soil temperature	0.025 (0.037)	0.023 (0.036)	0.043 (0.047)	0.042 (0.038)		0.035 (0.030)	0.030 (0.043)	0.021 (0.036)
Soil temperature at first snow						0.077 (0.203)		
Snow season			−0.730 (1.150)					
Snow duration			−0.424 (1.092)				−0.322 (0.880)	
Start of snow			0.709 (1.851)					

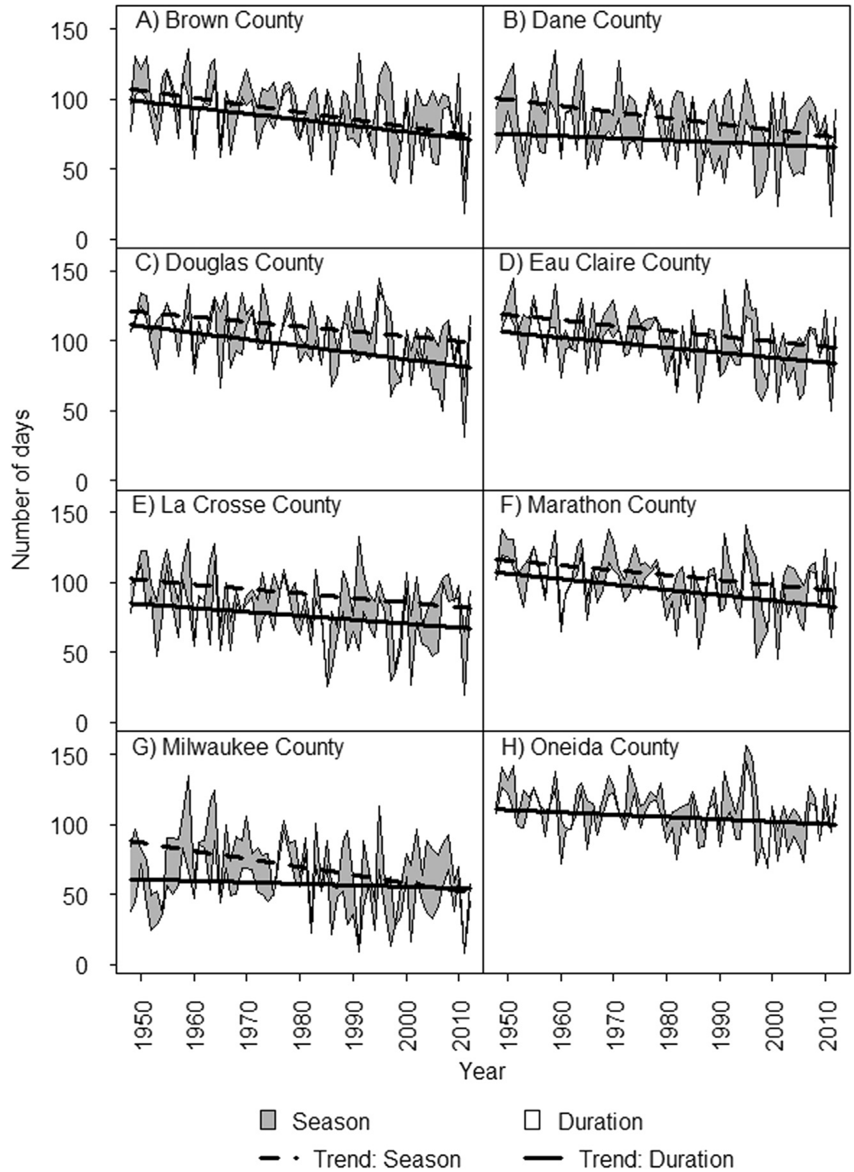

Fig. 2. Length of frozen ground season and total number of frozen ground days per season, by county, for Wisconsin, USA. Trends estimated from ARIMA models denoted with trend line.

increased with variability in snow melt duration, indicating that when snow conditions were less favorable for harvesting species that grow on moist, poorly drained soils or bottomlands, red pine may be substituted.

Our analysis offers important insights into potential effects of changing winter weather conditions on timber harvest. Other factors may also have influenced timber harvest over the study period, including changes in market demand, variance of economic development, and renewal of processing technologies or replacement of transportation facilities. Future research could incorporate these or other variables that were outside the scope of this analysis.

3.3. Contextual impacts of changing winter conditions on forestry operations

Interviews revealed how frozen ground is a mediating condition that allows lower-impact timber harvesting. Frozen ground is an important condition for harvesting forested wetlands and wet sites in loamy to clay soils. A county forester explained the importance of frozen ground duration:

> "Historically we begin frozen-season logging in December and work through March. Last winter (2011–2012) many winter-only sites were not accessible until late January due to lack of frost/frozen soil for winter roads, and spring breakup came a week early. This limited timber harvest and put strain on loggers, and if this occurs in future years it may affect the total productivity of the county forest."

Common logging contract language for public land harvests on wet sites rests on assumptions of average, historic frozen ground conditions, requiring that "equipment use will be restricted to frozen ground conditions due to wet soil conditions. General operational period will most likely be December through March. No cutting can be done during the months of April, May, and June" (Wisconsin DNR, 2012). Typical logging contracts allow two years to complete a harvest and remove equipment. In some cases

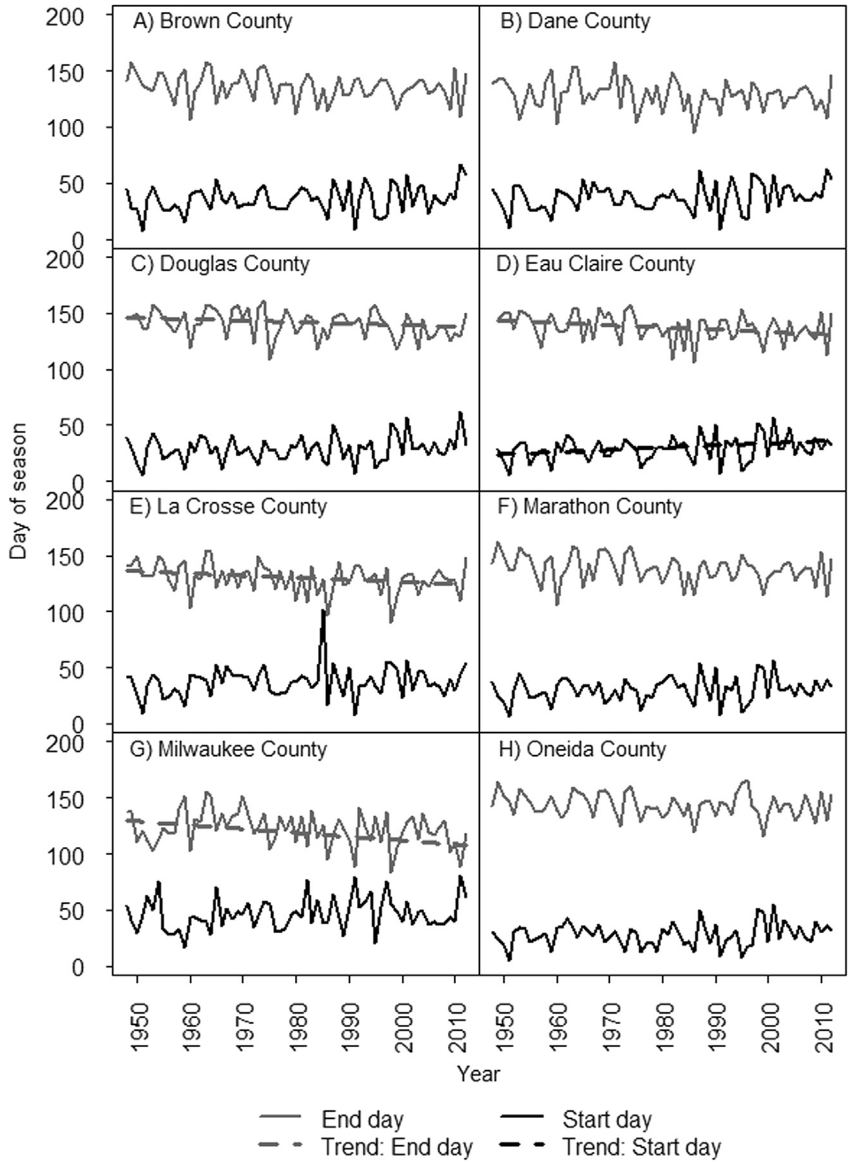

Fig. 3. Start and end of frozen ground by county for Wisconsin, USA. Trends estimated from ARIMA models denoted with trend line.

loggers have been unable to complete harvests during the contract period due to lack of frozen ground.

Property managers can potentially adapt to warm winters by shifting the timing of harvest. In contrast to the seven county foresters who experienced impacts, three county foresters reported little effect of the warm 2011–2012 winter, since low snowfall and subsequent summer drought facilitated harvests. Several foresters reported that years with early spring breakup also have earlier forest health restriction periods for invasive diseases such as oak wilt and annosum root rot that infect oak and pine stands. Since summer harvest may increase the spread of these diseases, managers may be constrained in their ability to shift from winter harvest to 'summer dry' harvest. Conflicts with recreational uses such as hunting and snowmobiling also impact the timing of winter harvests.

Several foresters reported increased rutting due to harvests on unfrozen ground, and suspected that rutting is happening without DNR knowledge. Foresters noted more rutting with shorter frozen ground duration and when major snowfall events occurred before the ground had frozen. One forester described significant tradeoffs between rutting and livelihoods, along with pressure to supply wood to mills. Conditions that cause rutting are increasing; at the same time there is more monitoring and sanctioning of rutting. In Wisconsin, the Sustainable Forestry Initiative (SFI) and Forest Stewardship Council (FSC) certifiers asked the DNR to quantify excessive soil rutting or disturbance, which was then defined by DNR policy and state land timber sale contracts as more than 6 inches deep and 100 feet long for riparian management zones or secondary skid trails. Forest certification auditors review rutting and can require mitigation for excessive rutting. Several interviewees expressed frustration that certification has increased oversight of rutting and impeded logging operations, implying that certification does impact forest management and guard against increased soil disturbance in years with variable frozen ground conditions.

While forest managers adapt by shifting harvests through time to summer dry conditions, loggers must find work throughout the year by shifting their harvests in space. Loggers often hold multiple contracts per year and thus have some flexibility in determining where and when to harvest. However, season-specific decreases in

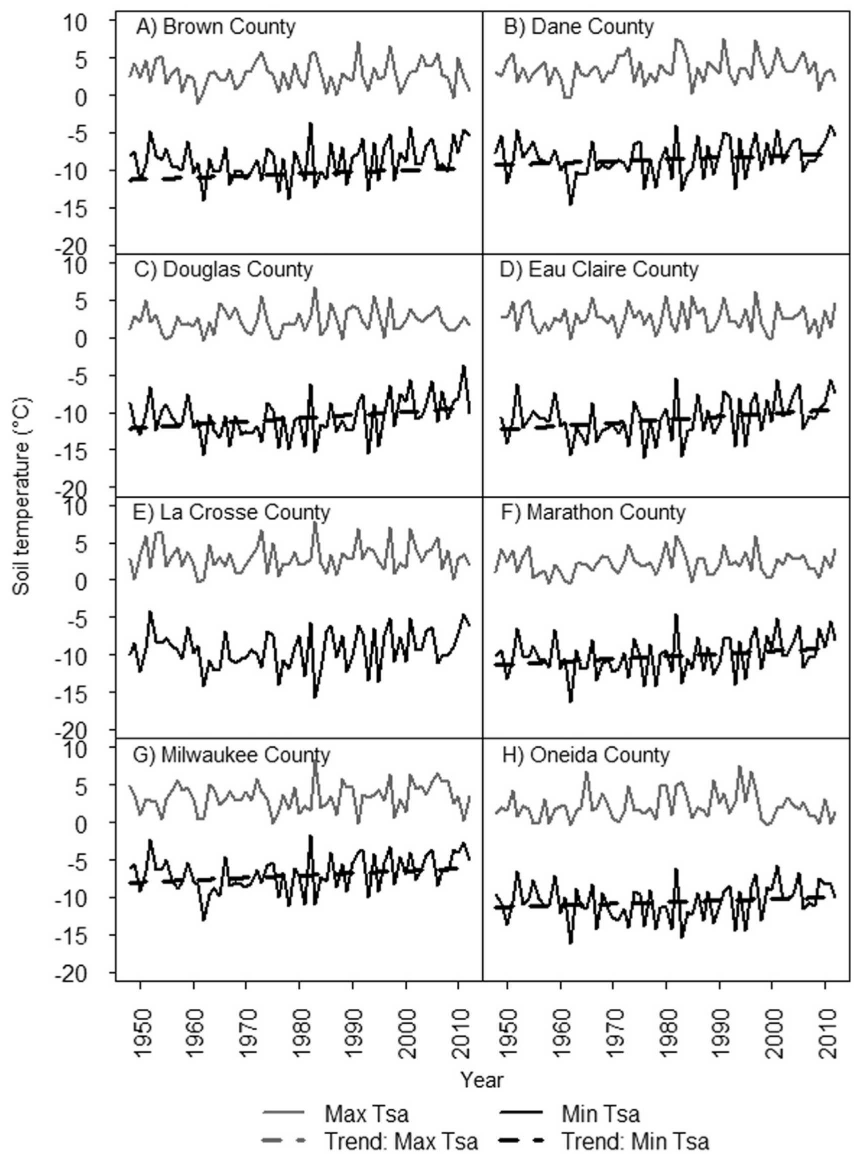

Fig. 4. Minimum and maximum soil temperature (°C) by county for Wisconsin, USA. Trends estimated from ARIMA models denoted with trend line.

harvest opportunity, combined with increased expenses, have increased loggers' livelihood vulnerability. One forest industry representative explained:

> “When I started in the business … some guys were able to find work during the spring break up on sandier ground, but the typical logger … would shut down and not do anything for the month or two months that the spring break up would last for. Nowadays, with the cost of equipment, and just the cost of insurance on that equipment alone, you're looking for work almost 12 months out of the year.”

Some key informants suggested that loggers have responded to changing winter conditions primarily by harvesting on sandy soils during the spring break-up period, such as participating in the “northwest migration” to jack pine and other sandy sites in northwest Wisconsin, despite the increased bidding prices. Loggers have also adapted by operating on marginally frozen soil and roads or “over-weighting” during transport to mills. Hauling timber on public roads has important implications for town, county, and state infrastructure expenses. Conflicts between industry and local governments have become more intensive, and some towns have reduced truck road weights due to the cost of maintaining road infrastructure (Taschler, 2010). Interviewees mentioned options for future adaptations including expanding contract lengths, providing flexibility for accomplishing practices required by tax programs on private land, or accepting that some forested wetlands will not be harvested.

Interviews revealed how frozen ground enables harvest and also facilitates compromise between economic and environmental forest management goals. In addition to timber production, forest management goals include supporting and regulating services that maintain forest health, wildlife habitat, and water quality to ensure the long-term stability and sustainability of forest benefits and services (de Groot et al., 2002). Interviews elicited the multiple and contested uses for forests, in which adaptations to enhance one goal have externalities that increase the vulnerability of other goals (Hallegatte, 2009). Managers identified multiple stressors on each goal of forest management, and the interaction of climate with other drivers of change. Our findings suggest that climate change

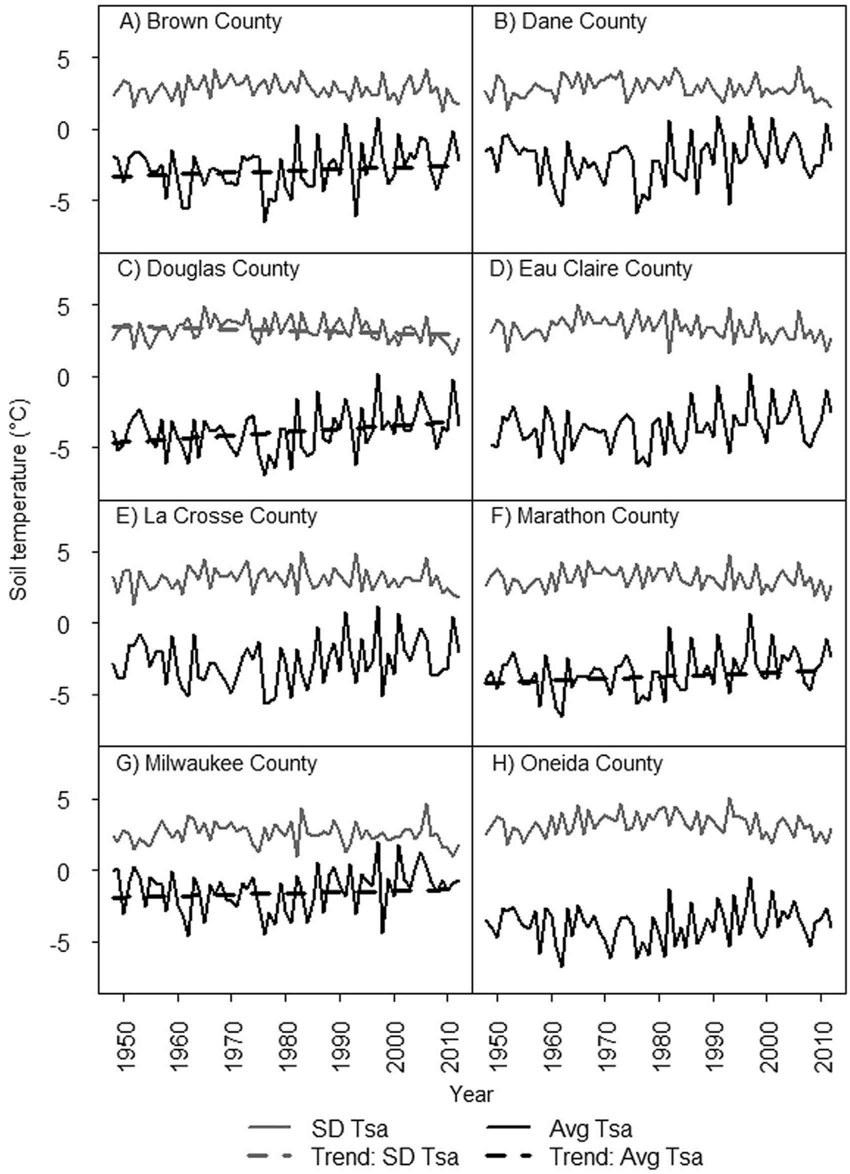

Fig. 5. Mean and standard deviation of soil temperature (*T*sa; °C) by county for Wisconsin, USA. Trends estimated from ARIMA models denoted with trend line.

may alter the balance among multiple-use objectives of public forest management.

4. Conclusions

Meteorological records for the period 1948 to 2012 indicated that winters in Wisconsin had shorter duration of frozen ground, with fewer frozen ground days within the season and warmer soil temperatures. Timber managers have responded to declining duration and increasing variability in winter conditions by increasing harvest on dry, sandy soils or slopes, and decreasing harvest on moist, poorly drained soils or bottomlands.

The impact of climate change on forest operations is altering the ability of land managers to rely on frozen ground to mediate the environmental impacts of winter harvest activities. This demonstrates the interactions between climate effects on provisioning, supporting, and regulating services. Climate change is likely to alter the balance of compatibility among public land uses. Private lands without management plans or certification may be most vulnerable

Table 4
Winter conditions associated with annual harvest size (ha) in Wisconsin from 1996 to 2012.

Cover type	Model	Estimate	SE	*t* Value	w_i[a]
Aspen	SD snow melt duration	−2.009	1.736	−1.157	1.00
Birch	SD ground thaw duration	−0.362	0.870	−0.416	1.00
Black spruce	SD ground thaw duration	−0.125	0.146	−0.857	1.00
Fir-spruce	SD ground thaw duration	0.624	0.363	1.720	1.00
Hemlock	SD ground thaw duration	−0.198	0.317	−0.626	1.00
Jack pine	SD ground thaw duration	1.351	1.516	0.891	1.00
Northern hardwoods	SD ground thaw duration	1.061	2.242	0.473	1.00
Oaks	SD snow melt duration	−1.587	0.957	−1.659	1.00
Red maple	SD ground thaw duration	0.090	0.897	0.100	1.00
Red pine	SD snow melt duration	0.041	0.957	0.043	1.00
Scrub oak	SD ground thaw duration	0.171	2.090	0.082	1.00
Swamp hardwoods	SD ground thaw duration	0.175	0.224	0.779	1.00
Tamarack	SD snow melt duration	−0.011	0.020	−0.556	1.00
White pine	SD snow melt duration	−0.339	0.308	−1.101	1.00
White spruce	SD ground thaw duration	−0.068	0.139	−0.489	1.00

[a] Weights of evidence.

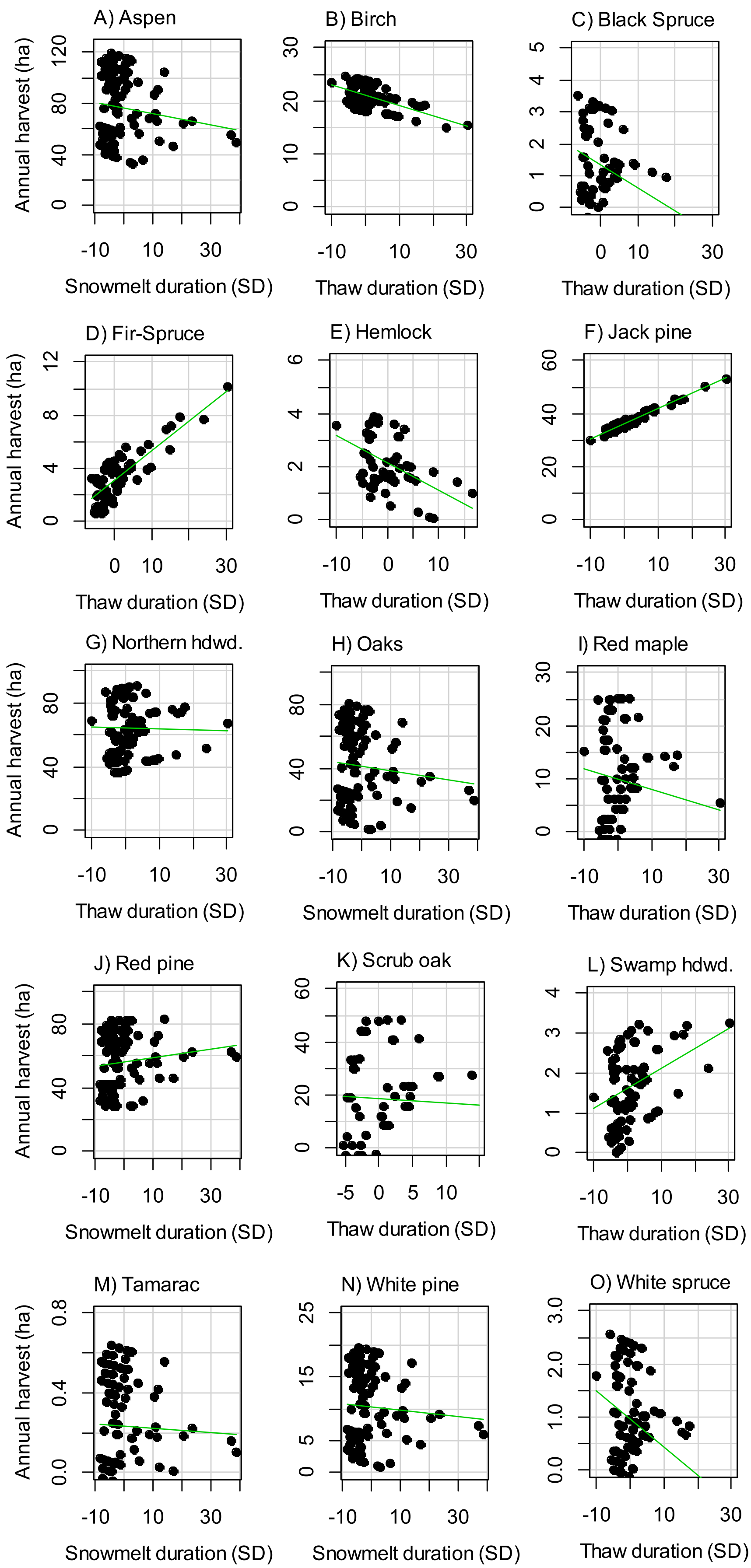

Fig. 6. Fitted values of annual harvest size (no random effects), by forest cover type, plotted against residuals of winter conditions for Wisconsin, USA, from 1996 to 2012.

to increased impacts from rutting on moist sites and unsustainable harvest of dry soil types such as jack pine. More research is needed to examine how climate change impacts on forest management and operations might have cascading effects on ecosystems and livelihoods.

Changing winter conditions are one of many factors impacting loggers and forest operations. High and increasing operational costs pressured loggers to harvest year-round, yet thaws in winter and concerns for diseases in summer reduced adaptation options to increase harvest amounts or shift harvest to alternate times of the year. Spatial and temporal variability are significant challenges for maintaining sustainable forest production and will likely continue to pose problems under future climate conditions.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found in the online version, at http://dx.doi.org/10.1016/j.jenvman.2014.10.010.

References

Alig, R.J., Adams, D.M., McCarl, B.A., 2002. Projecting impacts of global climate change on the US forest and agriculture sectors and carbon budgets. For. Ecol. Manage. 169, 3–14.
Ayers, M.P., Lombardero, M.J., 2000. Assessing the consequences of global change for forest disturbance from herbivores and pathogens. Sci. Total Environ. 262, 263–286.
Box, G.E.P., Jenkins, G.M., 1976. Time Series Analysis: Forecasting and Control. Holden-Day, San Francisco.
Burnham, K.P., Anderson, D.R., 2002. Model Selection and Inference: a Practical Information Theoretic Approach, second ed. Springer-Verlag, New York.
Chapin III, F.S., Lovecraft, A.L., Zavaleta, E.S., Nelson, J., Robards, M.D., et al., 2006. Policy strategies to address sustainability of Alaskan boreal forests in response to a directionally changing climate. Proc. Natl. Acad. Sci. U.S.A. 103, 16637–16643.
Chapin III, F.S., McGuire, A.D., Randerson, J., Pielke Sr., R., Baldocchi, D., et al., 2000. Arctic and boreal ecosystems of western North America as components of the climate system. Glob. Change Biol. 6, 211–223.
Corns, I.G.W., 1988. Compaction by forestry equipment and effects on coniferous seedling growth on four soils in the Alberta Foothills. Canadian J. For. Resour. 18, 75–84.
Dale, V.H., Joyce, L.A., McNulty, S., Neilson, R.P., Ayres, M.P., et al., 2001. Climate change and forest disturbances. BioScience 51, 723–734.
de Groot, R.S., Wilson, M.A., Boumans, R.M.J., 2002. A typology for the classification, description and valuation of ecosystem functions, goods and services. Ecol. Econ. 41, 393–408.
Dukes, J.S., Pontius, J., Orwig, D., Garnas, J.R., Rodgers, V.L., et al., 2009. Responses of insect pests, pathogens, and invasive plant species to climate change in the forests of northeastern North America: what can we predict? Can. J. For. Resour. 39, 231–248.
Foley, J.A., Asner, G.P., Costa, M.H., Coe, M.T., DeFries, R., et al., 2007. Amazonia revealed: forest degradation and loss of ecosystem goods and services in the Amazon Basin. Front. Ecol. Environ. 5, 25–32.
Food and Agriculture Organization, 2010. Global Forest Resources Assessment 2010: Main Report. FAO Forestry Paper Series 163. Food and Agriculture Organization of the United Nations, Rome.
Gauthier, S., Bernier, P., Burton, P.J., Edwards, J., Isaac, K., et al., 2014. Climate change vulnerability and adaptation in the managed Canadian boreal forest. Environ. Rev. 22, 256–285.
Grigal, D.F., 2000. Effects of extensive forest management on soil productivity. For. Ecol. Manage. 138, 169–187.
Groffman, P.M., Driscoll, C.T., Fahey, T.J., Hardy, J.P., Fitzhugh, R.D., Tierney, G.L., 2001. Colder soils in a warmer world: a snow manipulation study in a northern hardwood forest ecosystem. Biogeochemistry 56, 135–150.
Groffman, P.M., Hardy, J.P., Fashu-Kanu, S., Driscoll, C.T., Cleavitt, N.L., Fahey, T.J., Fisk, M.C., 2011. Snow depth, soil freezing and nitrogen cycling in a northern hardwood forest landscape. Biogeochemistry 102, 223–238.
Hallegatte, S., 2009. Strategies to adapt to an uncertain climate change. Glob. Environ. Change 19, 240–247.
Henry, H.A.L., 2008. Climate change and soil freezing dynamics: historical trends and projected changes. Clim. Change 87, 421–434.
Hyvönen, R., Ågren, G.I., Linder, S., Persson, T., Cotrufo, M.F., et al., 2007. The likely impact of elevated [CO_2], nitrogen deposition, increased temperature and management on carbon sequestration in temperate and boreal forest ecosystems: a literature review. New Phytol. 173, 463–480.
Iverson, L.R., Prasad, A.M., 1998. Predicting abundance of 80 tree species following climate change in the eastern United States. Ecol. Monogr. 68, 465–485.
Johnson, R.B., Onwuegbuzie, A.J., 2004. Mixed methods research: a paradigm whose time has come. Educ. Res. 33, 14–26.
Kucharik, C.J., Serbin, S.P., Vavrus, S., Hopkins, E.J., Motew, M.M., 2010. Patterns of climate change across Wisconsin from 1950 – 2006. Phys. Geogr. 31, 1–28.
Lindner, M., Maroschek, M., Netherer, S., Kremer, A., Barbati, A., et al., 2010. Climate change impacts, adaptive capacity, and vulnerability of European forest ecosystems. For. Ecol. Manage. 259, 698–709.
Mellander, P.-E., Lofvenius, M.O., Laudon, H., 2007. Climate change impact on snow and soil temperature in boreal Scots pine stands. Clim. Change 85, 179–193.
Meyer, J.L., Sale, M.J., Mulholland, P.J., Poff, N.L., 1999. Impacts of climate change on aquatic ecosystem functioning and health. J. Am. Water Resour. Assoc. 35, 1373–1386.
Norby, R.J., Wullschleger, D., Gunderson, C.A., Johnson, D.W., Ceulemans, R., 1999. Tree responses to rising CO2 in field experiments: implications for the future forest. Plant Cell Environ. 22, 683–714.
Ogden, A.E., Innes, J., 2007. Incorporating climate change adaptation considerations in forest management planning in the boreal forest. Int. For. Rev. 9, 713–733.
R Core Development Team, 2012. R: a Language and Environment for Statistical Computing. R Foundation for Statistical Computing, Vienna.
Saxe, H., Cannell, M.G.R., Johnsen Ø, Ryan MG., Vourlitis, G., 2001. Tree and forest functioning in response to global warming. New Phytol. 149, 369–400.
Serbin, S.P., Kucharik, C.J., 2009. Spatiotemporal mapping of temperature and precipitation for the development of a multidecadal climatic dataset for Wisconsin. J. Appl. Meteorol. Clim. 48, 742–757.
Sinha, T., Cherkauer, K.A., 2008. Time series analysis of soil freeze and thaw processes in Indiana. J. Hydrometeorol. 9, 936–950.
Sinha, T., Cherkauer, K.A., Mishra, V., 2010. Impacts of historic climate variability on seasonal soil frost in the Midwestern United States. J. Hydrometeorol. 11, 229–252.
Smit, B., Wandel, J., 2006. Adaptation, adaptive capacity and vulnerability. Glob. Environ. Change 16, 282–292.
Spittlehouse, D.L., 2005. Integrating climate change adaptation into forest management. For. Chron. 81, 691–695.
Stewart, I., 2013. Connecting physical watershed characteristics to climate sensitivity for California Mountain Streams. Clim. Change 116, 133–148.
Stewart, R.D., Lautala, P., Ogard, E., Pouryousef, H., Vartiainen, J., Siers, A., Chong, K., 2012. Improving Log Transportation with Data Based Monitoring and Analysis in Northern Wisconsin and Upper Peninsula of Michigan. Cfire 04-10. National Center for Freight & Infrastructure Research & Education, University of Wisconsin, Madison, Wisconsin.
Stone, D.M., 2002. Logging options to minimize soil disturbance in the northern lake states. North. J. Appl. For. 19, 115–121.
Taschler, J., 2010. A logjam over Wisconsin infrastructure. Milwaukee, WI: Journal Sentinel Online. http://www.jsonline.com/business/96771454.html (accessed 29.11.12.).
Tullus, A., Kupper, P., Sellin, A., Parts, L., Sõber, J., et al., 2012. Climate change at northern latitudes: rising atmospheric humidity decreases transpiration, N-uptake and growth rate of hybrid aspen. PLoS ONE 7 (8), e42648. http://dx.doi.org/10.1371/journal.pone/0042648.
van Mantgem, P.J., Stephenson, N.L., Byrne, J.C., Daniels, L.D., Franklin, J.F., et al., 2009. Widespread increase of tree mortality rates in the western United States. Science 323, 521–524.
Wisconsin, D.N.R., 2012. Flambeau River State Forest and other State Lands Sustainable Forestry Timber Sales. http://dnr.wi.gov/topic/TimberSales/documents/flambeau/2012NovBidPackage.pdf (accessed 29.11.12.).
Yvon-Durocher, G., Jones, J.I., Trimmer, M., Woodward, G., Montoya, J.M., 2010. Warming alters the metabolic balance of ecosystems. Philos. Trans. R. Soc. Lond. B Biol. Sci. 365, 2117–2126.
Zheng, D., Hunt Jr., E.R., Running, S.W., 1993. A daily soil temperature model based on air temperature and precipitation for continental applications. Clim. Res. 2, 183–191.