

# Potential impact of climate change on the risk of windthrow in eastern Canada's forests

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**Abstract** Climate change is likely to affect windthrow risks at northern latitudes by potentially changing high wind probabilities and soil frost duration. Here, we evaluated the effect of climate change on windthrow risk in eastern Canada's balsam fir (*Abies balsamea* [L.] Mill.) forests using a methodology that accounted for changes in both wind speed and soil frost duration. We used wind speed and soil temperature projections at the regional scale from the CRCM5 regional climate model (RCM) driven by the CanESM2 global climate model (GCM) under two representative concentration pathways (RCP4.5, RCP8.5), for a baseline (1976–2005) and two future periods (2041–2070, 2071–2100). A hybrid mechanistic model (ForestGALES) that considers species resistance to uprooting and wind speed distribution was used to calculate windthrow risk. An increased risk of windthrow (3 to 30%) was predicted for the future mainly due to an increased duration of unfrozen soil conditions (by up to 2 to 3 months by the end of the twenty-first century under RCP8.5). In contrast, wind speed did not vary markedly with a changing climate. Strong regional variations in wind speeds translated into regional differences in windthrow risk, with the easternmost region (Atlantic provinces) having the strongest winds and the highest windthrow risk. Because of the inherent uncertainties associated with climate change projections, especially regarding wind climate, further research is required to assess windthrow risk from the optimum combination of RCM/GCM ensemble simulations.

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## 1 Introduction

Wind is a major disturbance agent in forests (Mitchell 2013). Wind damage, or windthrow, occurs when the force applied by the wind overcomes the anchorage of a tree or the strength of its stem, resulting in uprooting or stem breakage (Mitchell and Ruel 2015). Windthrow ranges in severity from small-scale disturbances affecting one or a few trees to large-scale, catastrophic disturbances occurring over extensive areas (Girard et al. 2014). In eastern Canada, stand-replacing windthrows are rather infrequent (Bouchard et al. 2008). Yet some common stand types, notably in managed balsam fir stands, are much more vulnerable to windthrow than others. As such, windthrow can play an important role in eastern Canada's forest dynamics (Waldron et al. 2013) and can have major economic consequences, especially in managed forests (Gardiner et al. 2013).

The probability of windthrow varies as a function of tree-, stand- and site-level characteristics (Waldron et al. 2013), as well as with the local and regional wind climate. It is therefore expected that climatic changes will influence windthrow risks in the future (Blennow et al. 2010a; Moore and Watt 2015). However, there is a high degree of uncertainty regarding the possible changes in wind climate and storminess (Hanson and Goodess 2004), especially at the regional scale where severe winds are affected by small-scale phenomena or processes (IPCC 2012). Global scale projections of wind regimes often predict both increases and decreases in wind speed depending on the region studied and the model used (McInnes et al. 2011). For extratropical areas, however, a higher frequency of extreme wind speed and more severe storms are expected (Gastineau and Soden 2009). For Canada, Cheng et al. (2014) reported an increase in wind gust frequency for later this century. Based on an ensemble of GCMs (global climate models), Colle et al. (2015) revealed that most models project a steady decrease in the number of extratropical cyclones by the mid- to late twenty-first century over the western Atlantic (including the coastlines of eastern Canada) but an increase in more intense cyclones with potentially more damaging winds.

Besides wind speed, changes in soil freezing dynamics could also influence the risk of windthrow (Peltola et al. 1999). Unfrozen soil conditions can reduce tree anchorage, and if such conditions become more frequent in the future under global warming conditions, trees could become more vulnerable to uprooting at specific times of the year (e.g., in early spring and late autumn), when winds tend to be stronger (Gregow et al. 2011). Although soil thermal dynamics are complex (e.g., the interaction with the insulating effect of snow), an increase in the duration of unfrozen soil conditions is generally expected to occur over the course of the twenty-first century (Venäläinen et al. 2001; Kellomäki et al. 2010).

This study's main objective was to assess the effect of a changing climate on the risk of windthrow in eastern Canada's boreal forests by considering changes in both wind speed and soil frost simulated at the regional scale (instead of using coarse scale GCM runs) using outputs from the fifth generation of the Canadian Regional Climate Model (CRCM5) (Martynov et al. 2013; Hernández-Díaz et al. 2013; Laprise et al. 2013; Šeparovic et al. 2013). A secondary objective was to identify regions that are more at risk of windthrow in eastern Canada. We focused on balsam fir (*Abies balsamea* [L.] Mill.), a commercially important species that is dominant over large portions of the study area and highly vulnerable to windthrow (Frank 1990; Ruel 2000). We focused on tree uprooting because previous studies reported it as more frequent than stem breakage in eastern Canadian boreal forests (Ruel 1989; Achim et al. 2005; Cimon-Morin et al. 2010).

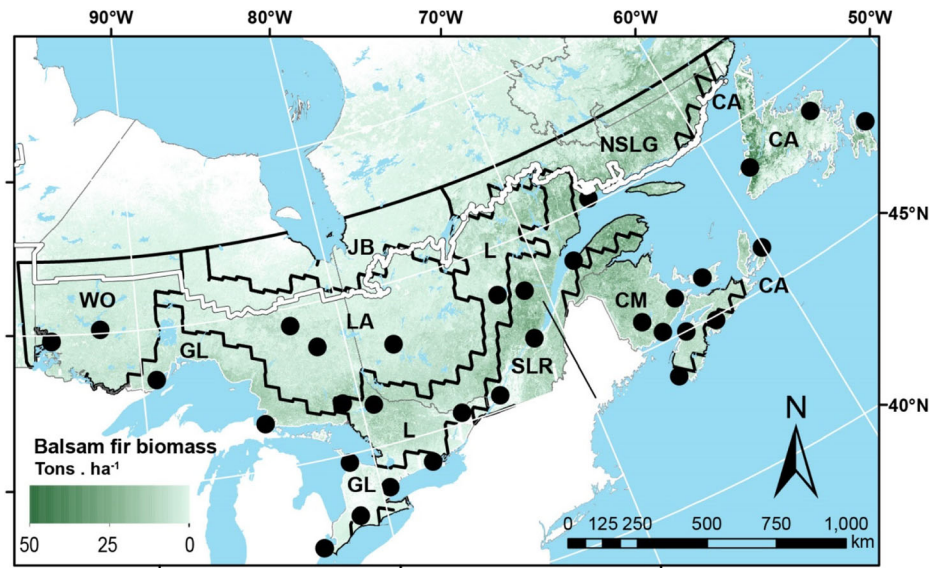
## 2 Methods

### 2.1 Study area

The study area extends from Ontario to Newfoundland in eastern Canada (Fig. 1). The climate of the easternmost part of the study area is influenced by periodic incursions of relatively moist and cool airflows from the Atlantic Ocean. Most of the remaining area is under a continental climate, characterized by cold winters and warm summers with annual precipitation typically lower than 1000 mm on average but with a net increase from west (continental) to east (coast) areas. Unfrozen soil conditions generally last between mid-March/late April throughout late December with longer durations being reached along the Atlantic coast as well as in southernmost Ontario. Balsam fir is widely distributed throughout the study area with a higher biomass in western Newfoundland and eastern Quebec (Fig. 1). Topography is generally smooth with low- to mid-altitude rolling hills except within the St. Lawrence lowlands where it is generally flat.

### 2.2 Historical and projected wind speeds

The CanESM2 GCM (resolution of  $\sim 300$  km) (Arora et al. 2011) provided time-dependent boundary conditions for climate simulations performed by the CRCM5. CRCM5 provided outputs at a finer spatial resolution of  $\sim 50$  km on a rotated polar grid (733 grid points over our study area). Preliminary analyses showed a reasonable fit between regional reanalysis products (i.e., NARR; Mesinger et al. 2006) and CRCM5-simulated median wind speed (*Online*



**Fig. 1** Map of the study area. The *black dots* represent the 32 weather stations from which wind speed data were obtained, and the homogeneous wind regime zones are delineated in *black*. Balsam fir biomass ( $\text{tons ha}^{-1}$ ) as estimated from MODIS remote sensing imagery (Beaudoin et al. 2014) is also shown as for the northern limit of managed forest in eastern Canada (*white thick line*). CA Coastal Atlantic ( $n = 52$ ), CM Continental Maritimes ( $n = 55$ ), GL Great Lakes ( $n = 59$ ), JB James Bay ( $n = 54$ ), L Laurentians ( $n = 91$ ), LA Lake Abitibi ( $n = 161$ ), NSLG North St. Lawrence Gulf ( $n = 57$ ), SLR St. Lawrence River ( $n = 71$ ), WO Western Ontario ( $n = 78$ )

*Resource 2*); however, CRCM5 extreme wind speed were rather underestimated when compared to NARR and selected Environment Canada weather stations in most homogeneous wind regime zones so windthrow estimates might be conservative.

Three time periods were investigated: a baseline (1976–2005) and two future time periods (2041–2070, 2071–2100), under two different Representative Concentration Pathways (RCPs, van Vuuren et al. 2011) climate scenarios: (1) RCP4.5, which is characterized by a stabilization of the radiative forcing at  $4.5 \text{ W m}^{-2}$  after 2100 that is made possible by the implementation of technologies reducing greenhouse gas emissions (Thomson et al. 2011); and (2) RCP8.5, which is characterized by a rising radiative forcing reaching  $8.5 \text{ W m}^{-2}$  by 2100, resulting from a “business as usual” scenario that does not include any specific climate mitigation target (Riahi et al. 2011). In our study area, the corresponding temperature increases<sup>1</sup> are  $\sim 3 \text{ }^\circ\text{C}$  (RCP4.5) and  $5\text{--}7 \text{ }^\circ\text{C}$  (RCP8.5) for the May–October period (relative to the baseline period).

### 2.3 Period of unfrozen soil conditions

Because tree root anchorage is affected by whether the soil is frozen or not, windthrow risk was evaluated by considering the wind speed prevailing during the period of the year when soils are unfrozen. We first determined the start and end dates of unfrozen soil conditions from CRCM5 soil temperature projections. The duration of unfrozen conditions was determined for each grid point, climatic period, and RCP. In the CRCM5, soil temperature is simulated using the Canadian land surface scheme model (CLASS 3.5) of Environment Canada (Verseghy 2011). Soil temperature is simulated at several depths, but in this study, we focused on 10–30 cm because most of the main roots occur in that zone (Strong and LaRoi 1983). Selecting soil depths at least 10 cm below the surface also allowed us to base our analyses on soil temperatures that were less affected by high-frequency variations in air temperature and potentially less subject to bias in simulated surface conditions. The period of unfrozen soil for each grid point was determined using the complement of the estimated number of days with frozen soil conditions between the months of July to June of next year. The start [end] date of the frozen soil period was determined by the first [last] day of five consecutive days with mean daily soil temperatures below [above]  $0 \text{ }^\circ\text{C}$ . In the case where the freezing threshold is not met within these 12 consecutive months, the unfrozen soil period is extended into the following year (or years) until the frozen soil condition is satisfied. Median onset and end of the unfrozen soil period at the zone level were estimated from cell-level data.

### 2.4 Windthrow risk assessment

Windthrow risk was assessed with ForestGALES 2.5, a hybrid mechanistic model that considers the mechanic action of the wind according to empirical relationships (Forestry Commission 2015). It considers both stem breakage and uprooting, but we focused on uprooting because of its more frequent occurrence compared to stem breakage in eastern Canadian boreal forests (Ruel 1989; Achim et al. 2005; Cimon-Morin et al. 2010).

First, ForestGALES calculates the resistance to uprooting using a relationship between stem mass and critical turning moment determined from tree pulling studies. This critical turning moment is then converted into a critical wind speed (CWS; the threshold wind speed above which windthrow is expected to occur) based on the extreme wind loading on the mean tree

<sup>1</sup> From ensemble mean values of all CMIP5 GCMs.

calculated from the aerodynamic properties of the stand (a function of tree height, spacing, and crown characteristics). Balsam fir parameters were obtained from Achim et al. (2005) and Ruel et al. (2000), and stand characteristics corresponded to yield table data for 75-year-old balsam fir stands growing on the most productive sites (Boudoux 1978) (height = 19.2 m, diameter at breast height (DBH) = 17.8 cm, tree spacing = 2.7 m). These represent the oldest stand in the yield table, considering that it would be the most susceptible to be impacted by climate change. Although balsam fir is generally harvested at a younger age (around 60), many balsam fir stands reach or exceed that age given the extensive management taking place in eastern Canada. The intent here was to simulate a realistic stand that would likely be susceptible to wind damage. Choosing site conditions present in the central part of the simulation domain ensures that it remains realistic. Soil type (freely draining mineral soil) and rooting depth (>80 cm) corresponded to those of winching study sites (Achim et al. 2005) and offer no restriction for balsam fir rooting. Simulations were conducted for well-acclimated trees, far from forest edges.

ForestGALES then calculates the probability of exceeding the CWS given the wind speed probability distribution of the sites. More details on ForestGALES can be found in Gardiner et al. (2000). A two-parameter Weibull function was used to describe the wind speed probability distribution (during the unfrozen soil period of the year; see Eq. 1), with parameters evaluated using maximum likelihood estimation (Smith 1985).

$$f(v|a, k) = \left(\frac{k}{a}\right) \left(\frac{v}{a}\right)^{k-1} e^{-\left(\frac{v}{a}\right)^k} \quad (1)$$

where  $v$  is wind speed,  $k$  the shape parameter, and  $a$  the scale parameter.

The estimation of wind speed probability distribution was done for each grid point, climatic period, and RCP for the windthrow season determined from soil temperature simulations. Estimated windthrow return intervals are thus function of changes in wind distribution and unfrozen soil period on standardized balsam fir stands and as such, do not consider any potential tree architecture acclimation of these stand types to changes in wind speed distribution.

ForestGALES provides an estimate of the return interval, which is the inverse of the annual exceedance probability (Forestry Commission 2015). A consequence of this approach is that the unfrozen soil periods vary per grid point and year. In other words, for certain grid points and years, a longer (or shorter) period of wind data was considered to fit the Weibull distributions. As a consequence, a weighting factor of 87,840/h was applied<sup>2</sup> where  $h$  is the number of 3-h time steps (frequency of archived fields used from the CRCM5 outputs) with unfrozen soil and 87,840 represents the total number of time steps in a 30-year period (i.e., 366 days/year  $\times$  30 years  $\times$  8 time steps/day). The purpose of this weighting factor was therefore to account for the variation in sample size used for distribution fitting and to return estimated probabilities of windthrow occurrence under a standardized temporal reference.

## 2.5 Homogeneous wind regime zones

Windthrow results were summarized by homogeneous wind regime (HWR) zones, i.e., where wind regime defined as average and extreme wind speeds is rather similar. These zones were delineated using dynamically spatially constrained agglomerative clustering and partitioning

<sup>2</sup> Because the return interval is the inverse of the probability of windthrow, we used the inverse of  $h/87840$ .

algorithms developed by Guo (2008) that aimed to connect spatially joined cells into distinct regions having maximum internal similarity according to wind regime attributes. Clustering analyses were based on CRCM5 grid points from which Thiessen polygons (hereafter “cells”) were delineated. We built a connectivity graph linking cells in a queen-type fashion. Then, cells were clustered with spatial contiguity constraints according to the Ward’s hierarchical clustering method. We considered two variables in clustering analyses, i.e., the  $a$  and  $k$  parameters of the Weibull distribution (see Eq. 1) fitting wind speed frequency distribution during the windthrow season within each CRCM5 cell for the historical period (1976–2005). Both attributes were scaled (standardized) to have a 0 mean and 1 standard deviation prior to zonation analyses. Zones (hereafter HWR) were dynamically determined through an agglomerative algorithm using all edges between clusters, i.e., all links between cells pertaining to different candidate clusters (Guo 2008). Using a heuristic, the tree was partitioned to optimize the delineation of spatially contiguous regions with minimum sum-of-squared deviations (SSD). Minimal zone size was set to 50 CRCM5 cells. The tree was then partitioned successively from two to ten zones. For each solution, 1000 cross-validations were performed using the *mvpart* v1.4.0 package in R 3.2.4 (R Core development Team 2016). The “best” partition, i.e., the most parsimonious solution, was selected as the one showing the smallest coefficient of variation of error (Segal and Xiao 2011). Zonation solutions were computed using REDCAP v2.0.1 (Guo 2011).

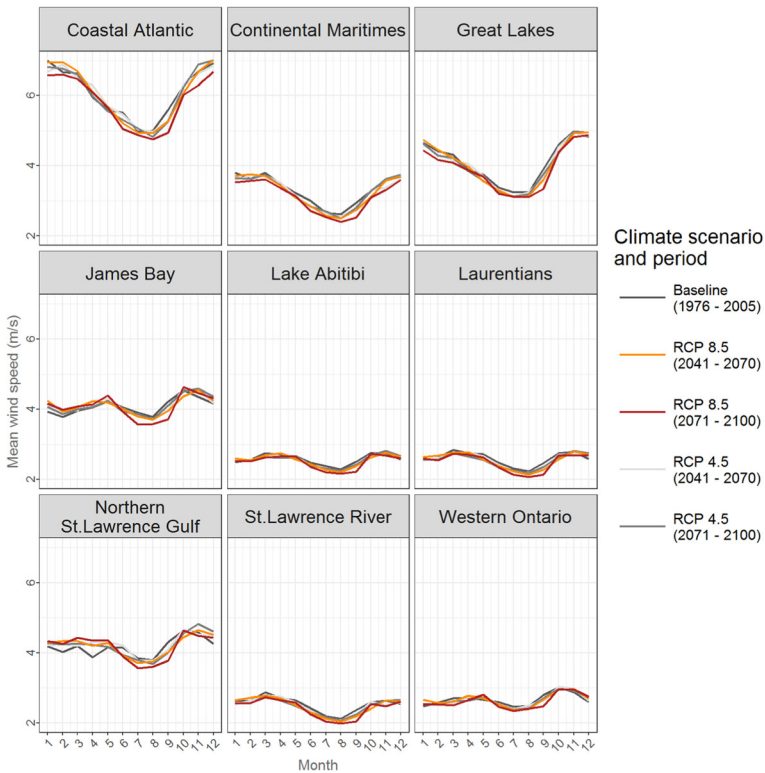
### 3 Results

#### 3.1 Wind climate

Nine homogeneous wind regime zones were identified using the spatially constrained clustering (Fig. 1). Spatial heterogeneity in the CRCM5 wind speed distribution was largely explained by the zonation for the historical period (adj.  $R^2 = 0.767$ ) as well as for future periods under the two RCPs scenario (adj.  $R^2$  between 0.612 and 0.627). There was generally an east to west gradient in wind speed with the Coastal Atlantic zone generally having the strongest winds and Western Ontario the weakest winds. In addition, winds were generally stronger in zones close to large water bodies such as the Great Lakes, the James Bay, and Northern St. Lawrence Gulf zones (Figs. 2 and 3). Seasonal patterns of variation in wind speed occurred but differed in shape or magnitude depending on the zone. In general, wind speed was lower during summer and higher from autumn to spring. In zones close to the Atlantic Ocean (Coastal Atlantic and Northern St. Lawrence Gulf) as well as in the Great Lakes zone, extreme wind speed was markedly higher during winter months, corresponding to the period of the year with the most frequent and the most intense synoptic-scale extratropical cyclones over this area. Wind speed varied little between climatic periods and RCPs in all zones. Extreme wind speed decreased very slightly from the baseline to the 2071–2100 period under RCP8.5, especially in late summer and early autumn.

#### 3.2 Duration of unfrozen soil period

Under baseline conditions, the duration of the unfrozen soil period varied between regions, being longer in the southernmost and easternmost zones (Great Lakes, Coastal Atlantic, and Continental Maritimes) while being shortest in the Northern St. Lawrence Gulf zone (Fig. 4).



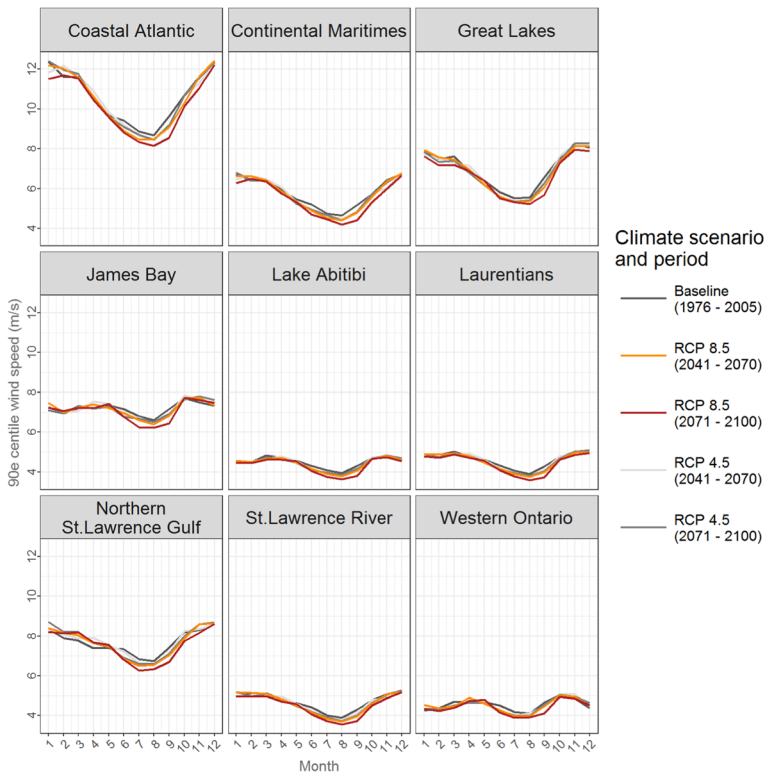
**Fig. 2** Monthly variations in median wind speed by zone for a baseline and two future periods under two RCPs

The duration of the unfrozen soil period also varied among climatic periods and RCPs. The lengthening of the unfrozen soil period was the greatest for the 2071–2100 period under RCP8.5, and the magnitude of the increase was the greatest in northernmost zones (James Bay, Lake Abitibi, and Northern St. Lawrence Gulf zones), reaching more than 90 days relative to the baseline period. This corresponds to the area where the higher warming will appear among all regions from fall to spring periods, especially by the end of the twenty-first century.

### 3.3 Windthrow risk

The CWS for uprooting as estimated from ForestGALES was  $17.8 \text{ m s}^{-1}$ , for the most vulnerable balsam fir stand (*Online Resource 3*). The frequency distribution of windthrow return intervals varied among regions, climatic periods, RCPs, and types of windthrow season (Fig. 5). The Coastal Atlantic zone had the shortest return intervals of all regions as the winds there were stronger than elsewhere for both the historical and future periods under the two forcing scenarios (Figs. 3 and 4).

Generally, windthrow return intervals decreased with the higher forcing scenarios (i.e., RCP8.5) at the end of the twenty-first century. Except for Coastal Atlantic, decrease in mean windthrow return intervals would range from 3 to 24% under RCP 4.5 whereas they would range from 8 to 30% under RCP 8.5 by 2071–2100. In Continental Maritimes, Laurentians and St. Lawrence River zones, most of these decreases would be the result of a very swift decline in areas experiencing very long (>200 years) windthrow return intervals. Largest decreases in



**Fig. 3** Same as Fig. 3 but for the 90th percentile wind speed

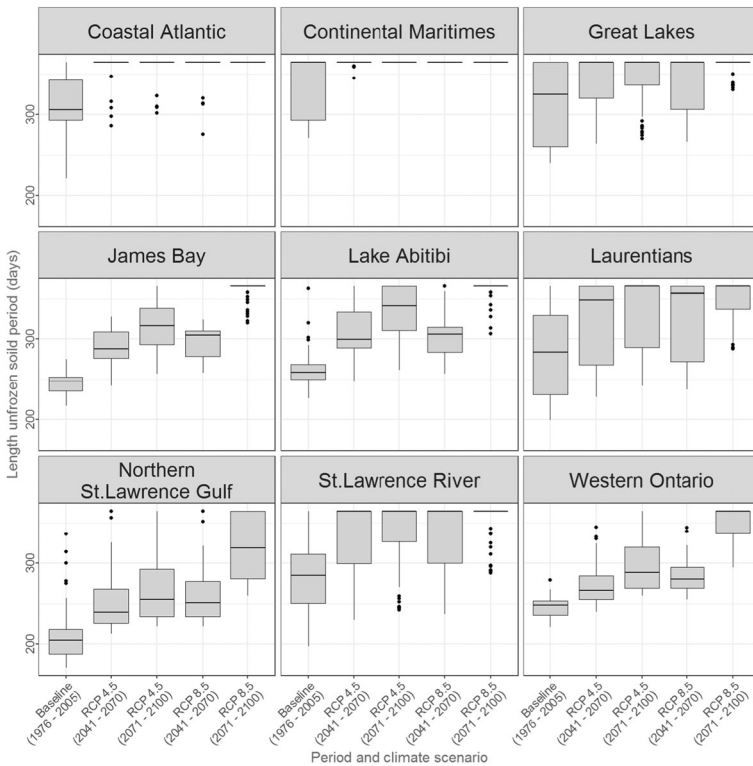
windthrow return interval would occur in zones located in the central part of the study area (Lake Abitibi, Laurentians, and St. Lawrence HWR zones, Fig. 5). In the James Bay and Western Ontario, the decrease would mainly occur under RCP 8.5 between 2071 and 2100 whereas Continental Maritimes, Laurentians, and St. Lawrence zones would experience important decreases as soon as in 2041–2070 under milder forcing (RCP 4.5). In these two latter HWR zones, rather short (<50 years) windthrow return intervals would greatly increase especially under RCP 8.5 between 2071 and 2100 (Fig. 5). Elsewhere, the mean windthrow return interval would be rather stable (Great Lakes, Northern St. Lawrence Gulf zones) or slightly increase (Coastal Atlantic zone) with higher anthropogenic climate forcing.

## 4 Discussion

### 4.1 Effect of wind and soil frost patterns on windthrow risk

We assessed the effect of climate change on windthrow risk in eastern Canada's forests using a methodology that accounted for changes in both wind speed and soil freezing conditions. Including changes in soil frost duration had a major impact on the calculated windthrow risk. Had we not taken that factor into account, we would potentially have concluded that the windthrow risk remained stable or slightly decreased with a changing climate. Indeed, such a conclusion would result from the near absence of change or the decrease in wind speed



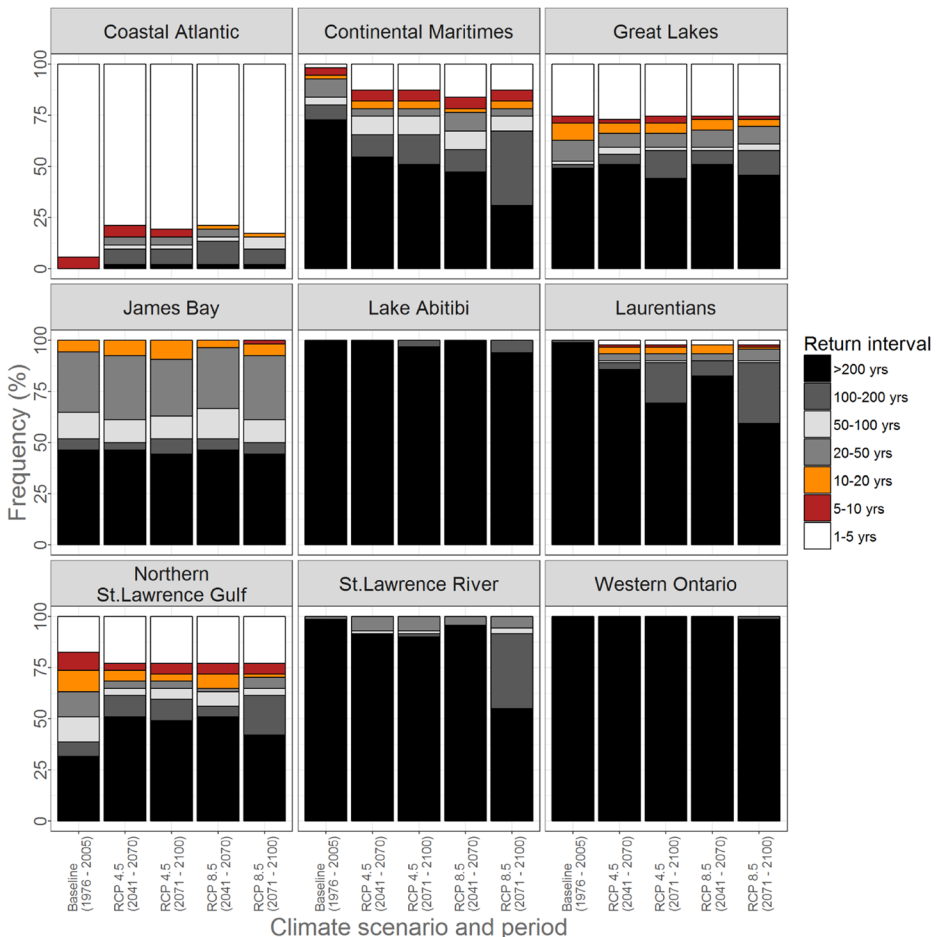


**Fig. 4** Box plot representing the duration of the unfrozen soil period by zone, climatic scenario, and period

predicted under a changing climate for our study area (Figs. 3 and 4). The latter results are in line with recent studies suggesting a slight decrease in storm frequency over eastern North America from both GCMs (Colle et al. 2015) and a previous version of the Canadian RCM (Long et al. 2009).

However, when changes in soil freezing conditions (2 to 3 months longer by 2100 under RCP8.5) were taken into account, an increased risk of windthrow was predicted. The mean windthrow return intervals projected for the end of this century decreased by 3 to 30% compared with the baseline. Despite no clear change in future wind speed, our results suggest an increased windthrow risk under a changing climate, due to a lengthening of the “windthrow prone period” which, in the future, included months (end of fall/early winter) with stronger winds (Fig. 4). While most climate models project a decrease in storminess in the western Atlantic for the second half of the twenty-first century, a potential increase in more intense cyclones was reported by Colle et al. (2015). Such phenomenon could exacerbate the occurrence of strong winds prevailing during the cold season (November to April), which could increase the probability of uprooting if trees are more vulnerable to uprooting due to unfrozen soils.

A few other studies have considered the effect of changes in the duration of unfrozen soil conditions on the risk of windthrow and have obtained results that agree with ours. For instance, Peltola et al. (1999) predicted an increase (1 to 2 months) in the duration of unfrozen soil conditions in Finland and concluded that the risk of windthrow would increase due to reduced tree anchorage at the windiest times of the year. Gregow et al. (2011) concluded that



**Fig. 5** Relative frequency of windthrow return intervals for each homogeneous wind regime zone. Return intervals were calculated for a baseline and two future periods under two RCPs

windthrow risk would increase under higher level climate forcing scenario (SRES A1B), despite only slight projected changes in wind speed. They showed that the increased risk was due to the near disappearance of soil frost from late autumn to early spring in southern and central Finland, thereby reducing root anchorage and making trees more liable to windthrow.

#### 4.2 Regional differences in wind climate and windthrow risk

The HWR zones identified in this study based on wind speed distribution (Fig. 1) show similarities with the wind gust regions of Cheng et al. (2014). The easternmost zones (e.g., Coastal Atlantic, Northern St. Lawrence Gulf) and the Great Lakes zone had the strongest winds and a distinctive seasonal pattern with high wind speed in winter (Figs. 3 and 4), i.e., during a time of the year when the frequency and intensity of cyclone tracks is especially high (Plante et al. 2015). High wind speed during the winter in the Atlantic region was reported by Wan et al. (2010), who also found a positive trend in wind speed over the recent years (1953–2006) for spring and autumn, but with no systematic trend or slightly negative trends in the

90th and 99th percentiles of maximum annual wind speed (in general occurring in winter) over the Gulf of St. Lawrence area over the recent 1979–2004 period (Hundecha et al. 2008). In agreement with its distinctive wind regime, these zones, especially Coastal Atlantic, consistently had the shortest windthrow return intervals and the highest proportion of grid points with very short (1–5 years) return intervals (Fig. 5), indicating that these regions are those where windthrow risks are the highest and should deserve further attention. The high mean and extreme wind speeds estimated for the Great Lakes, James Bay, and the Northern St. Lawrence Gulf particularly in the fall season can partially explain the higher windthrow risks of those HWR zones. These windthrow risks will be exacerbated in the future under the corresponding extension of the unfrozen soil periods, especially over the Great Lakes area where the mean return interval of uprooting is relatively low and the James Bay, Laurentians, and the St. Lawrence river and Gulf where the increase in unfrozen conditions over the future will be particularly marked. For all areas located near water masses, the increase in the windthrow risk will be particularly severe with a clearer and stronger signal than elsewhere. Furthermore, these areas will be also subject to decrease in sea-ice or lake-ice extent and duration under future warming conditions. This factor could also exacerbate the risks of localized intense wind events during synoptic storm systems, as strong wind speed events are often observed in the Maritimes or Great Lakes region in winter and early spring when there is a higher temperature gradient between land and ice free ocean/lake area (favorable to the enhancing of low-level cyclogenesis; e.g., Gachon et al., 2003).

### 4.3 Balsam fir stands susceptibility to windthrow

We evaluated variations in windthrow risk across a wide area using a CWS value corresponding to a single type of stand. We believe this approach was useful to highlight large-scale regional variations in windthrow risk, which was the objective of our study. However, in reality, local variations in terrain and in stand characteristics would modulate the general trends obtained from RCM projections (Blennow and Olofsson 2008). The CWS value for uprooting that was calculated for the balsam fir stand type under study, and used for windthrow risk assessment, is within the range of values reported for the same species in comparable stands (Achim et al. 2005). Such a CWS value corresponds to a stand type that is relatively vulnerable to windthrow.<sup>3</sup> Using a CWS associated with a vulnerable stand type allowed us to better capture variations in windthrow risk (among regions, climatic periods, and RCPs).

To evaluate the impact of climate change on windthrow risk in balsam fir stands, we used stand characteristics from available yield tables and kept them constant across climatic periods and scenarios. However, it is likely that climate change will affect tree growth so that these stand characteristics may not be observed at the same stand age in the future (Pretzsch et al. 2014). A few studies about windthrow risk under a changing climate did incorporate the effect of climate on forest productivity and predicted an increased vulnerability to windthrow resulting in part from increased forest growth in the future (Blennow et al. 2010a, b; Moore and Watt 2015). However, variations in forest productivity are the results of complex interactions and, for Canada, it is not clear yet whether climate change will result in increased productivity of boreal forests (Price et al. 2013). In this study, keeping stand conditions comparable across periods and scenarios allowed us to get a clearer understanding of the effect of changes in abiotic factors

<sup>3</sup> See *Online Resource 3* in which CWS values are reported for a range of balsam fir stands varying in their characteristics and vulnerability to windthrow.

(wind speed and soil frost) on the future vulnerability of forests to windthrow. However, windthrow risk projections that would account for climatic impacts on forest productivity would eventually be useful to obtain for eastern Canadian boreal forests.

#### 4.4 Limitations

Although the future frequency of high wind speed and variations in soil frost conditions were used to project future windthrow in eastern Canadian forest, other climatic variables that were not included in our models may play a significant role. Among others, the projected increase in the frequency of extreme rainfall events and/or in rainfall intensity per wet days (Eum et al. 2014), notably during periods with high wind regimes coupled with intense extratropical events occurring regularly over the east coast from fall to spring seasons (Colle et al. 2015), may further increase windthrow risk (Kamimura et al. 2012). Also, projections of soil freezing conditions vary greatly in their conclusions depending on the factors that are taken into account in the soil thermal simulations and depending on regional climatic conditions. This is not surprising since soil freezing dynamics are complex and involve many interacting factors (Helama et al. 2011; Jungqvist et al. 2014). For instance, the presence (and depth) of a snow cover influences thermal exchanges between air and soil (Zhang 2005; Henry 2013). Therefore, variations in spatial and temporal patterns of snow cover that could result from climate change would interact with projected air temperature to affect patterns of soil freezing. CRCM5-simulated extreme wind speeds were rather underestimated when compared to NARR (except for Coastal Atlantic) for the baseline period suggesting that our estimations of windthrow return intervals might be conservative (*Online Resource 2*). Although this was out of the scope of the present study, this highlights the fact that future wind regime conditions should be explored with more than one single (RCM) model, i.e., using ensembles of model simulations for studying the range of plausible climate responses to one or several given forcing scenarios (IPCC 2012).

#### 5 Conclusion

This study evaluated the windthrow risk in eastern Canada's boreal forests under a changing climate using a modeling approach that considered both changes in wind speed and soil frost duration. An increased risk of windthrow was predicted for the future, mainly due to the lengthening of the period with unfrozen soil conditions. Identifying the regions that are more at risk of windthrow is important to adequately plan forest management in the long term (Heinonen et al. 2009). However, because of the inherent uncertainties associated with climate change projections, further study would be required to assess windthrow risk from the optimum combination of RCM/GCM ensemble simulations (Eum et al. 2014). This would help provide more robust climate information since synoptic-scale storm events (which are responsible for the observed wind regimes) vary greatly among GCMs, especially on the east coast of North America (Colle et al. 2015). Preliminary works using different CRCM5 simulations driven by various GCMs revealed that the coastal Atlantic area is subject to substantial variability among various runs concerning both the occurrence and the intensity of extratropical storm tracks in winter. The risk of storm damages in the Atlantic forest area will also benefit from dedicated work on the potential changes in the tracks of tropical cyclones and their transition to extratropical systems, over this area during the fall season.

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