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Regional ski tourism risk to climate change: An inter-comparison of Eastern Canada and US Northeast markets

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ABSTRACT

Climate change has become a business planning reality in the ski industry, with differential impacts and adaptive capacity important for intra- and inter-regional market competitiveness. Potential climate change impacts are examined at 171 ski areas in Ontario, Québec and the US Northeast using the SkiSim2 model with regional parameterizations of snowmaking capacity. With advanced snowmaking, mid-century season length losses are limited to 12–13% under a low emission pathway (RCP 4.5), increasing to 15–22% under high emissions (RCP 8.5). By late-century, low and high emission pathways diverge creating very different futures for the ski industry. Season length and skiable terrain losses increase only marginally in the low emission pathway, while transformational impacts occur under a high emission pathway, with only 29 ski areas in Québec and high-elevation areas of the US Northeast able to maintain a 100-day season and open regularly for the economically important Christmas-New Year holiday. A low emission future, where current national pledges to Paris Climate Agreement are achieved, is crucial to preserve the Eastern North America ski tourism marketplace. The results are compared with previous studies that have neglected the adaptive capacity of snowmaking and substantially overestimated the impact of mid-century and lower emission climate change scenarios.

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climate change; ski tourism; competitiveness; snowmaking; adaptation; sustainable tourism

Introduction

The multi-billion dollar North American ski tourism market is considered a mature market (Hagenstad, Burakowski, & Hill, 2018; Vanat, 2018), characterized by relatively stable annual skier visits that have ranged between 50.9 to 60.5 million in the US over the 1997–1998 and 2017–2018 seasons (National Ski Area Association [NSAA], 2019) and 17.2–20.7 million in Canada over the 2004–2005 and 2017–2018 seasons (Canadian Ski Council [CSC] 2015, 2019). Future development of the North American ski industry is strongly influenced by demographic and leisure trends, as well as the state of the economy (Research & Markets, 2017). Increasingly, the impacts of climate change are also being considered by industry stakeholders as an important driver of future competitiveness and viability (Knowles, 2019; Scott, Gössling, & Hall, 2012; Hagenstad et al., 2018). The demand for foresight on how climate change will alter the competitiveness of individual ski areas and destinations is growing as investors and financial regulators

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increasingly require climate risk disclosure (e.g., European Bank for Reconstruction and Development [EBRD] 2018), real-estate markets respond to the new realities of ski tourism in a warmer world (e.g., Savills World Research, 2018), and some leading destination communities begin to develop climate change response plans (e.g., Resort Municipality of Whistler [RMW], 2016).

Steiger, Scott, Abegg, Pons, and Aall (2019) comprehensive review of the climate change and ski tourism literature found consensus that projections of decreased and more variable natural snow, increased snowmaking requirements, and reduced periods suitable for snowmaking, would result in shortened and more variable ski seasons in regional markets worldwide. The implications for the profitability of ski areas/resorts and the climatic competitiveness of ski tourism destinations around the globe remain uncertain, in part because of two important limitations of the extant literature. The first is the limited ability to compare the intra- (within a region e.g., Ontario) and inter-market (across multiple regions e.g., Eastern North America) vulnerability of individual ski areas/destinations because of the lack of consistent methods to assess future ski seasons under similar climate futures (common scenarios). The second is the methodological limitations of many studies that Scott et al. (2012) and Abegg and Steiger (2017) argue result in misinformation on the climate change risk of many ski areas. These limitations include (for a detailed discussion see Steiger et al., 2019): 1) inappropriate temporal (e.g., monthly mean temperature for modeling snow) and spatial resolution of climate data (e.g., altitudinal lines of snow reliability that are assumed to be representative for a large region) used to represent individual ski areas or broad ski tourism regions; 2) impact indicators that are not relevant to ski industry performance (e.g., snowcover days or snow water equivalent on Apr 1); and 3) the omission of snowmaking, which is a widespread and expanding climate adaptation strategy. Over the last decade, the ski industry has been particularly critical of research that does not account for snowmaking, correctly arguing that such studies do not represent their current operating reality (as the vast majority of ski areas in all regional markets have some snowmaking capacity) or their adaptive capacity to cope with additional climate change in the future (see Scott, McBoyle, & Mills, 2003; Steiger & Mayer, 2008; Wolfsegger, Gössling, & Scott, 2008 for early discussions of ski industry perspectives on climate change research). Indeed, more than a decade ago in a climate change special issue of *Journal of Sustainable Tourism*, Scott, McBoyle, Minogue, and Mills (2006) reassessment of the potential impact of projected climate change on the ski industry at six locations in eastern North America, emphasized that previous studies (Harrison, Kinnaird, McBoyle, Quinlan, & Wall, 1986; McBoyle, Wall, Harrison, & Quinlan, 1986) had vastly overestimated the potential climate change impact and that this mis-representation posed a business and destination reputation risk.

This paper addresses the aforementioned limitations by applying a common set of climate change scenarios (Coupled Model Inter-comparison Project 5 [CMIP-5] ensemble with Representative Concentration Pathways [RCP] 4.5 and 8.5 emission pathways for mid- [2050s] and late-century [2080s]) to the SkiSim2 ski season simulation model (Steiger, 2010) with a standardized parameterization of snowmaking capacity and industry performance indicators for all 171 ski areas operating across the Ontario and Québec (Canada), and the Northeast (US) regional ski markets. In addition, a number of advancements have been made over previous assessments in the region (Scott et al., 2006, Scott, Dawson, & Jones, 2008) aiming at a more realistic representation of ski area operations and potential impacts: more detailed snowmaking practices (e.g., base-layer, improvement and emergency snowmaking); a better altitudinal representation of ski areas (i.e., critical altitude); a new performance indicator which considers the system capacity in terms of skiable terrain; impact analysis based on season segments allows to consider differential impacts of lost skiable days in different season segments owing to high seasonality of demand; and considering the variability of ski seasons. The study provides ski industry and destination community stakeholders a common information base to consider intra- and inter-regional market differences in climate risk and competitiveness that is germane to climate change adaptation strategies.

A second objective is to compare these results with recent studies that do not directly model snowmaking capacity to demonstrate the implications for mis-representing future climate change risk when existing adaptive capacity is not accounted for, a problem that persists with new contributions to the literature in these regional markets (e.g., Wobus et al., 2017; Chin, Byun, Hamlet, & Cherkauer, 2018).

Eastern North American ski markets

The study includes 171 ski areas located in the Ontario, Québec and Northeastern US markets. The US Northeast ski region is defined by the NSAA to include the states of Connecticut, Maine, Massachusetts, New Hampshire, New York, Rhode Island, and Vermont. Table 1 summarizes the characteristics of these three ski markets in terms of skier visits and economic value.

The US Northeast ski region has represented approximately 21–24% of the US market over the last decade, with annual skier visits ranging between 11.8 and 14.3 million between 2004–2005 and 2017–2018 (NSAA, 2019). The large majority of ski areas and skier visits (over 75%) are concentrated in the states of Vermont, New Hampshire and New York. The estimated economic contribution of ski tourism in Vermont and New York alone exceeds USD1.2 billion (Hagenstad et al., 2018). The first documented application of machine-made snow at a ski area was in 1949 at Mohawk Mountain, Connecticut (Ericksen, 1980). The use of snowmaking technology is widespread in the Northeast ski region, with more than 73% of all skiable terrain equipped with snowmaking since the 2000-01 season, and recent terrain coverage estimated at over 80% (NSAA 2019). Compared to other major ski tourism markets in the European Alps (Steiger & Abegg, 2018) or Scandinavia (Scott, Steiger, Dannevig, & Aall, 2019a), the diffusion of snowmaking started earlier and terrain coverage is still higher in the Northeast region.

The provinces of Québec and Ontario represent approximately 54% of the Canadian ski market (by skier visits) (CSC, 2019). Skier visits in these eastern Canadian markets have been relatively stable over the last decade (2004–2005 to 2017–2018 seasons: Québec 75–82 operating ski areas and 5.18–7.16 million skier visits; Ontario 61–65 operating ski areas and 2.36–3.59 million skier visits). The estimated combined annual economic contribution of ski tourism in these two provinces is over USD900 million (Table 1). Although the same industry reported data on percentage of skiable terrain covered with snowmaking is not available for these markets, based on the self-reported ski area characteristics (OnTheSnow, 2019) all ski areas have snowmaking capacity, with average terrain coverage in Québec similar to the Northeastern US region and even higher in Ontario (typically 90% or more).

Table 1. Characteristics of the major eastern North American ski markets.

Region	2019 population (millions)	Skier visits (millions)	Skier visits per capita	Ski resorts	Economic size (million US$)
Québec	8.39[2]	5.73[4]	0.68	75[7]	$777[6]
Ontario	14.19[2]	3.24[4]	0.23	61[7]	$140[7]
US Northeast[1]	34.65[3]	11.59[5]	0.33	135[5]	>$1200[8] (VT and NY only)

[1]The National Ski Areas Association's (NSAA) Northeast ski region is comprised of the following states: Connecticut, Maine, Massachusetts, New Hampshire, New York, Rhode Island, Vermont.
[2]Statistics Canada (2019).
[3]US Census Bureau (2019).
[4]Average of 2013–14 to 2017–2018 ski season (CSC, 2019).
[5]Average of 2013–14 to 2017–2018 ski seasons (NSAA, 2019).
[6]Archambault (2015).
[7]CSC (2019).
[8]Hagenstad et al. (2018).

With the long history and extensive use of snowmaking in these ski markets it is important to emphasize that to neglect this adaptive capacity would misrepresent the current sensitivity to climate variability as well as any future climate change risk. This was an important concern expressed by the ski industry to one of the authors 20 years ago.

The earliest studies on the potential impact of climate change on the ski industry began in the Ontario market in the mid-1980s (Harrison et al., 1986; McBoyle et al., 1986) and were soon followed by similar studies in Québec (Lamothe & Periard Consultants, 1988; McBoyle & Wall, 2005). These studies were not able to account for snowmaking capacity that was rapidly expanding in the 1980s and 1990s and projected massive reductions in average ski season length. Under the warmest climate change scenarios, average ski season losses were projected to be as high as 100% in Ontario and 87-100% in Québec as early as the 2050s. The ski industry in these provinces rejected these conclusions when they appeared in the media, because they did not represent their current operating realities. A second generation of studies that accounted for snowmaking, projected much lower ski season losses at a limited sample of ski areas under the warmest scenarios: Ontario (46% [Scott et al., 2003]) and Québec (34% [Scott et al., 2006]). While the climate change scenarios used by these studies differed, the scenarios captured a comparable range of uncertainty of projected warming and change in winter precipitation.

The very different magnitude of impact projected by studies that only consider natural snow and studies that incorporated snowmaking make it clear that the impact on season length was severely overestimated when only natural snow resources were accounted for. Unfortunately, the omission of snowmaking as an adaptation strategy persists in recent studies in this region (e.g., Chin et al., 2018) and in other cases proxies for potential snowmaking opportunities are used, which may not accurately represent the snowmaking operational capacities in this region (e.g., Wobus et al., [2017] assume 450 hours of snowmaking is needed for ski terrain to become operational, while some ski areas in these regional markets state they only need approximately 72 hours). The results of this analysis will be compared to the above noted studies that do not physically incorporate snowmaking and to observed ski seasons (as reported by ski areas to the NSAA), including recent record warm winters (2001/2, 2011/2, 2015/6) that represent analogues for ski seasons under warmer conditions projected for the 2050s.

Methods

Baseline climate data and climate change scenarios

Baseline climate data (1981–2010) including daily temperature (maximum, minimum and mean) and precipitation (rain and snowfall) was obtained from the Meteorological Service of Canada (2017) and the National Oceanic and Atmospheric Administration (NOAA, 2018). Where available, daily snow depth was also obtained to train the natural snow module in the SkiSim model. The selection criteria for climate stations were (1) data record from 1980 to 2010 with as few data gaps as possible and (2) close proximity to one or more of the 171 downhill ski areas included in the study. The final climatological dataset consisted of 84 stations. Minor data gaps were filled through interpolated data from nearby climate stations (in all cases less than 5% of daily observations for temperature and precipitation over the baseline record). The density of climate stations in rural/mountain regions is a challenge in all ski regions of the world. In this study the minimum distance between the climate station and ski area was 200 m, the median was 10 km, and the maximum was 77 km.

Climate change scenarios from the World Climate Research Programme's CMIP-5, which were developed for the IPCC Fifth Assessment Report (IPCC, 2013), were utilized to represent the range of possible climate futures in the study area. To represent the range of uncertainties regarding climate responses to future GHG emission pathways, climate change vulnerability studies have increasingly used ensemble projections from multiple climate models rather than an individual or small number of selected climate responses from individual climate models (Hawkins & Sutton, 2009; Environment Canada, 2017). Outputs from 29 CMIP5 models were used to develop ensemble projections for two GHG emission scenarios: RCP 4.5 and 8.5. Recent analyses have indicated that the likelihood of achieving the rapid and deep emission reduction pathway of the RCP 2.6 scenario to be relatively low (e.g., United Nations Environment, 2018; Raftery, Zimmer, Frierson, Startz, & Liu, 2017 estimate a 5% probability). RCP 4.5 was selected as the lower emission scenario that approximates the achievement of current country emission reduction pledges to the Paris Climate Agreement. RCP 8.5 represents a high emissions trajectory or business-as-usual scenario.

Monthly temperature and precipitation ensemble climate change scenarios from the CMIP5 models for mid- (2040–2069) and late-century (2070–2099) were downscaled to daily resolution at the 84 climate station locations using the Long Ashton Research Station (LARS) stochastic weather generator (Semenov & Stratonovitch, 2010). LARS was selected for this study because it has been found to simulate precipitation statistics in Eastern North America better than other weather generators (Qian, Gameda, Hayhoe, De Jong, & Bootsma, 2004). While late-century scenarios are generally not considered relevant to tourism or business planning time horizons, they are included to explore the long-range future of winter sports that are important to the regional identity (Scott, McBoyle, & Minogue, 2007) and many rural/small town economies in the study area.

Ski season simulation model

The SkiSim 1.0 model was originally developed and validated in the Ontario ski market place (Scott et al., 2003), which includes: (1) a physical snow model of the natural snow pack, (2) a snowmaking production module, and (3) industry-based ski operations decision rules. Steiger (2010) further modified the model (SkiSim 2.0) for application in the European Alps by refining snowmaking rules to better represent varying operational decisions over the ski season and to produce outputs across the entire ski area elevation range of a ski area (in 100 m intervals). Several applications of the SkiSim2.0 model have followed in Austria, Italy, Germany, Switzerland, China, Norway and provincial/state markets in the US and Canada (e.g., Fang, Steiger, & Scott, 2019; Dawson & Scott, 2013; Scott, Steiger, Rutty et al. 2019c; Steiger, 2012; Steiger & Abegg, 2013; Steiger & Stötter, 2013). It has also been applied to large scale assessments in the European Alps (e.g., Steiger & Abegg, 2018) and globally for all Winter Olympic Games locations (Scott, Steiger, Rutty, & Johnson, 2015, Scott, Steiger, Rutty, & Fang, 2019b). Additional methodological details on the physical snow model and other components of the SkiSim model can be found in Scott et al. (2003) and Steiger (2010).

1. *The physically based model of the natural snow pack* is calibrated with observed daily snow depth data over a 30-year observation period (1981-2010 baseline) from the closest climate station to the ski area. Two important snow model parameters are calibrated for each weather station. The first is snowfall temperature (or precipitation typing), where a lower value defines the temperature threshold for 100% snow and an upper value defines the threshold for 100% rain. In between these two values, the snow-rain ratio is linearly interpolated. Snowfall measurements are used for this model calibration to compare observed versus modelled cumulative snowfall per season. The second parameter is the degree-day factor defining the amount of snow water equivalent that is melted per 1 °C using mean daily temperature. This parameter increases sinusoidally between Dec 21st and June 21st. This calibration step is evaluated with a multi-year analysis of days with snow cover (snow depth threshold of 1 cm) per season. After these snow model calibration steps, SkiSim can be used to simulate the ski season and needs for snowmaking to

achieve specified operational snow depth requirements (≥ 30cm). As ski groomers prepare and smooth the snow surface of the slopes in the study area, a snowpack density after grooming of 400 kg/m^3 is assumed (Fauve, Rhyner, & Schneebeli, 2002). Daily precipitation and temperature data from weather stations were used to simulate the natural snowpack. For 146 ski areas the base elevation was used for analysis, while for another 25 ski areas the critical altitude was used. Critical altitude is where the ski lift system allows partial ski operations in the upper (more snow reliable) section of ski areas that have a substantial vertical drop, for example a gondola mid-station, or separate upper mountain lifts. Generalized lapse rates for temperature (0.65°/100m) and precipitation (3%/100m) were used to adjust the altitudinal difference between the climate station and the analysed altitude in the ski area.

2. *The decision rules and capacities for the snowmaking production module* are derived from consultations with ski area managers and snowmaking crews in the study area (also including those from Rutty et al., 2017 and Scott et al., 2003). Snowmaking activity is represented in the model in two ways: a) an early season dense base layer (40cm) to provide a durable foundation for ski operations, and b) improvement snowmaking to respond to mid-season melts and repair high traffic areas to enable continuous ski operations until the planned season end (usually in late-March to early April in the study area) (Steiger & Mayer, 2008). With the exception of 'emergency snowmaking' during warm temperatures (-2 °C or warmer) in the two weeks preceding the Christmas-New Year holiday period, ski area managers in this region generally avoid snow production above the -5 °C temperature threshold, as efficiency declines rapidly in these conditions and costs increase substantially. As ski areas focus strongly on ensuring a sufficient snow base during this economically important time period (Steiger & Mayer, 2008), the model only activates this 'emergency snowmaking' decision rule between Dec 15 and Jan 5. Data on the varied snowmaking capacity at the 171 ski areas in the study area is not available. Based on data available in the Ontario market (derived from daily snow conditions reports produced by the Ontario Ski Resorts Association [OSRA] - see Rutty et al., 2017) ski areas can typically make 5-10cm/day over their skiable terrain. For this analysis, the upper range of advanced snowmaking (10cm/day) was utilized to represent the current capacity of many ski areas and the capacity others could be upgraded to with additional investment in snowmaking. The SkiSim model records the amount of snowmaking produced (both daily and seasonal requirements) throughout the industry defined snowmaking period (between 22 November and 30 March). Snow will be produced in the model if current combined natural and machine-made snow depth is insufficient to guarantee ski operations until 31 March. Potential snowmaking hours per day are calculated by linearly interpolating minimum and maximum temperature to simulate the daily variation of temperature.
3. *Ski area operational rules* were originally derived for the study area by Scott et al. (2003) using 20 years of daily ski operations data from Ontario ski areas and consultations with ski industry stakeholders. These were subsequently refined using consultations for studies in Québec (Scott et al., 2007) and the US Northeast (Dawson & Scott, 2013). Ski areas were recorded as closed if snow depth was less than 30 cm during the prescribed operating season (15 Nov to 30 April). To estimate changes in the system capacity of all ski areas in the study area to collectively accommodate current and future ski tourism demand, the 'terrain-days' indicator developed by Scott, Steiger, Rutty et al. (2019c) was calculated by summing the number of days skiable terrain (in acres) was operational at each ski area. These operating rules are largely consistent with SkiSim applications in other regional markets to enable inter-market comparisons (e.g., Scott, Steiger, Dannevig & Aall, 2019a; Steiger & Abegg, 2013; Steiger & Stötter, 2013).

Table 2. Average ski season length (by state/province).

Province/State	**Baseline** (Days)	2050s		2080s	
		RCP 4.5	RCP 8.5	RCP 4.5	RCP 8.5
Québec	137	121 (−12%)	116 (−15%)	119 (−13%)	106 (−22%)
Ontario	117	102 (−12%)	93 (−21%)	96 (−18%)	46 (−60%)
US Northeast Region	121	104 (−13%)	94 (−22%)	98 (−18%)	67 (−45%)
New Hampshire	125	112 (−10%)	106 (−15%)	108 (−13%)	80 (−36%)
Maine	127	112 (−12%)	107 (−16%)	109 (−14%)	86 (−32%)
Connecticut	110	89 (−19%)	73 (−34%)	81 (−27%)	15 (−87%)
Massachusetts	111	93 (−16%)	82 (−26%)	87 (−22%)	38 (−66%)
New York	118	100 (−15%)	85 (−28%)	91 (−23%)	55 (−54%)
Vermont	127	115 (−9%)	111 (−13%)	113 (−11%)	96 (−24%)
Rhode Island	70	10 (−86%)	2 (−97%)	3 (−96%)	0 (−100%)

Results

The model results consistently project a trend toward shorter ski seasons and increases in snowmaking requirements throughout Québec, Ontario and US Northeast under both low and high emission scenarios (Table 2). Detailed results for each of the ski operations performance indicators (ski season length and season segments, skiable terrain [acre/days], snowmaking requirements, economic sustainability) are compared below for the three markets.

Changes in ski season length and season segments

The average baseline season length in the three market regions ranged from 137 days in Québec to 117 days in Ontario, with the US Northeast regional average at 121 days, and ski areas in the State of Rhode Island having the shortest average at 70 days (Table 2). Figure 1 provides further spatial detail of the changes in average season length at the 171 ski areas in the study area, with the longest seasons concentrated in Québec and higher elevations of New York, Vermont, New Hampshire and Maine.

In the 2050s, projected changes in the length of the ski season remain relatively modest under the low emission RCP 4.5 scenario, yet all three regions are projected to lose more than 10% of the ski season (Table 2). In high emission RCP 8.5 scenario, differential impacts become more visible, particularly at the state level where Vermont and New Hampshire ski areas only lose 9% and 10% respectively, but Connecticut (-34%) and Rhode Island (-97%) face much greater season losses by mid-century.

In the 2080s, average season length reductions remain moderate under the low emission scenario (RCP 4.5), ranging from -13% in Québec to -18% in Ontario and the US Northeast region. Figure 1 visibly illustrates that the late century high emission scenario (RCP 8.5) represents a very different and challenging future for the ski industry in much of the study area. Average season reductions of -60% in Ontario reduce operating season well below what is generally considered economically sustainable levels (see *ski area economic viability* section). While the average season length reduction in the US Northeast is −45%, there is a notable dichotomy between the impact in Vermont (−24%), Maine and New Hampshire (−36% and −32% respectively), and all other states where seasons are reduced by 54–100% (Table 2). Ski areas in Québec and the high elevation regions of Vermont, New York, New Hampshire and Maine are the most resilient to longer term, higher magnitude climate change (see the remaining green ski area in Figure 1).

In addition, the notable increase in variability of ski season length is highly salient to the future financial sustainability of ski areas. Under all scenarios the standard deviation of season length (days) increased in all three regions, but substantially more in Ontario (baseline = 6.6, 2050s = 9.6 to 13.2 [RCP 4.5 and 8.5], 2080s = 13.1 to 19.8 [RCP 4.5 and 8.5]) and the US

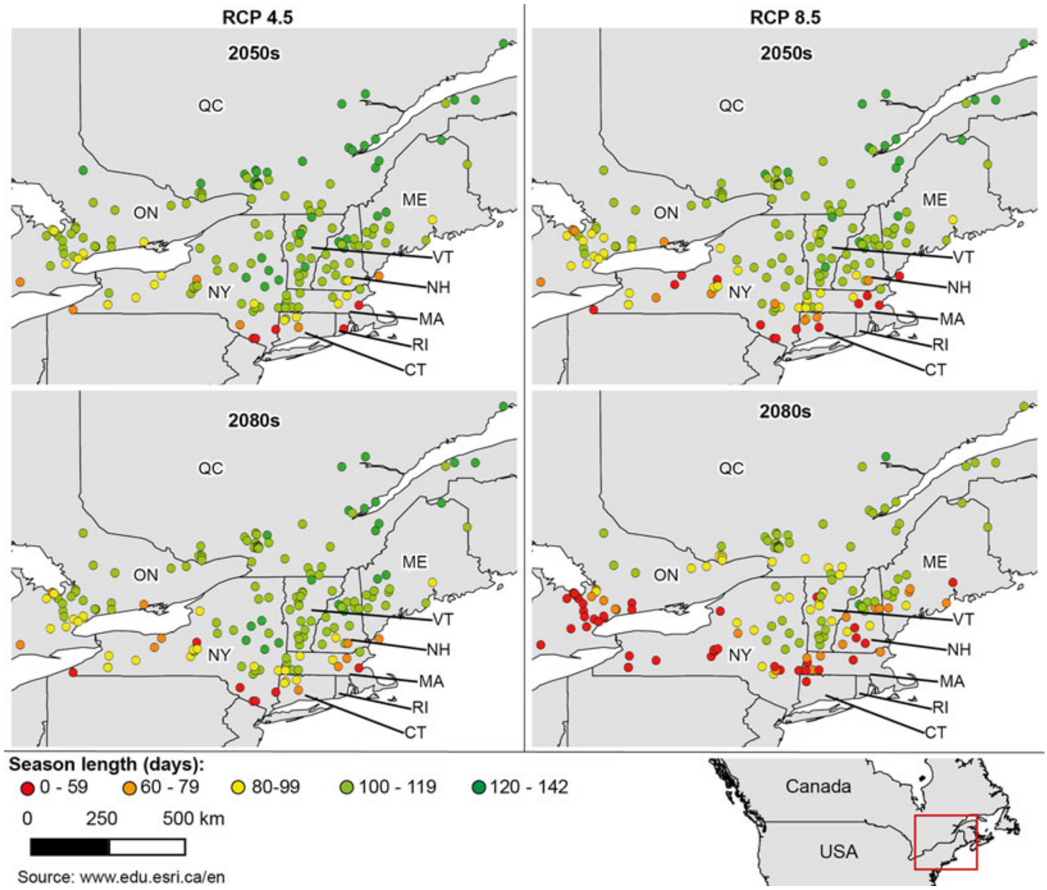

Figure 1. Projected season length (days) at 171 individual ski areas.

Northeast (baseline = 6.5, 2050s = 8.7 to 10.6 [RCP 4.5 and 8.5], 2080s = 10.4 to 14.1 [RCP 4.5 and 8.5]). The minimum season length (days), which can severely challenge the viability of ski areas especially if they occur sequentially, declined substantially in Ontario (baseline = 102, 2050s = 75 to 56 [RCP 4.5 and 8.5], 2080s = 56 to 12 [RCP 4.5 and 8.5]) and the US Northeast (baseline = 106, 2050s = 84 to 69 [RCP 4.5 and 8.5], 2080s = 73 to 33 [RCP 4.5 and 8.5]) and to a lesser extent in Québec (baseline = 126, 2050s = 106 to 100 [RCP 4.5 and 8.5], 2080s = 104 to 89 [RCP 4.5 and 8.5]). This increase in variability points to the limits of snowmaking as a technological adaptation will be exceeded at many ski areas under warmer scenarios and revenue diversification and other management adaptations (e.g., SME vs ski conglomerate business model) will also need to be considered.

Some segments of the ski season are much more important in terms of skier visits and associated revenues. To assess whether key economic periods are at risk and to better understand the potential economic impact of climate change on ski tourism, changes in the average operational days in the five season segments are presented in Figure 2, including 'early' (EARLY) 1 November–19 December, 'Christmas–New Year holiday' (XMAS) 20 December–4 January, 'mid-season' (MID) 5 January–28 February, 'school holiday' (HOL) 1 March–20 March, and 'late season' (LATE) 21 March-30 April.

Across the three regional markets most of the lost ski days occur in the 'early' and 'late' season segments, while the 'mid-season' and 'school holiday' segments are more resilient to warming conditions, due to greater snowmaking potential in January. As indicated, Québec has the smallest losses of operational days (Figure 2a), with its MID and HOL segments remaining

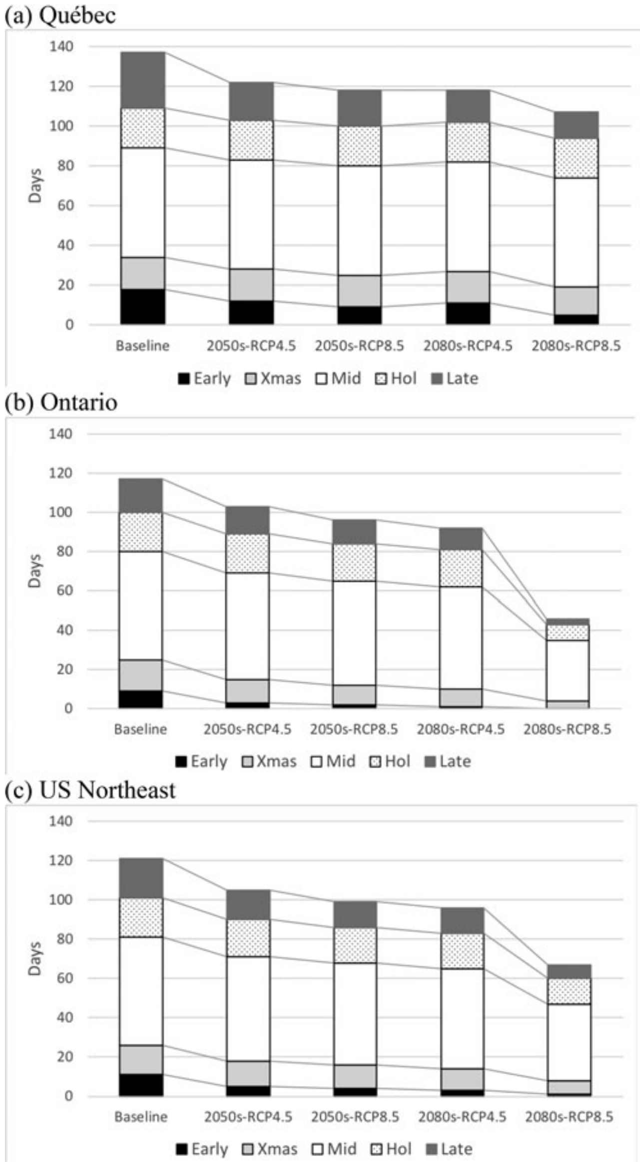

Figure 2. Ski season segments (operational days).

unchanged in the mid- and late-century scenarios. The XMAS segment remains intact in the mid-century and low emission 2080s scenario as well.

The MID and HOL segments in Ontario remain largely unchanged as well in mid-century, but the XMAS segment is reduced substantially under the high-emission scenario. Its EARLY segment, which is only half of Québec's in the baseline, is also substantially reduced by mid-century (-66 to -78%). In late century, the low and high emission scenarios represent two very different futures for the Ontario market, with the MID and HOL segments largely intact and moderate losses to the XMAS and LATE segments. The high emission future in contrast eliminates the EARLY and most of the XMAS and LATE segments, while also reducing the MID and HOL segments almost in half.

The northeastern US region as a whole follows a similar pattern of season segment losses as Ontario. The higher elevation ski areas in the States of Vermont, New Hampshire, New York and

Table 3. Annual skiable terrain (by state/province).

Province/State	Baseline (acre-days)	2050s RCP 4.5	2050s RCP 8.5	2080s RCP 4.5	2080s RCP 8.5
Québec	173,110	−3%	−4%	−4%	−7%
Ontario	71,682	−6%	−14%	−10%	−57%
US Northeast Region	633,413	−4%	−7%	−6%	−24%
New Hampshire	104,763	−2%	−4%	−3%	−15%
Maine	122,099	−4%	−5%	−4%	−8%
Connecticut	9,909	−9%	−21%	−15%	−80%
Massachusetts	43,361	−6%	−12%	−10%	−49%
New York	161,384	−6%	−14%	−12%	−47%
Vermont	191,073	−2%	−3%	−3%	−11%
Rhode Island	823	−85%	−97%	−96%	−100%

Maine are more similar to Québec, with more resilient MID and HOL segments, and longer and more resilient XMAS and LATE segments.

Changes in skiable terrain

'Terrain-days' is a ski industry performance indicator introduced by Scott, Steiger, Rutty et al. (2019c) to represent the skiable area in operation each day at the regional market scale. Ski areas vary considerably in size and the closure of a number of smaller ski areas may have very limited impact on marketplace level supply, while the closure of only a few very large ski areas would impact system capacity greatly (including crowding and wait times that diminish visitor experience). Annual terrain-days represent the cumulative acres of skiable terrain operational over the course of the ski season.

Skiable terrain-days losses in the three regional markets are projected to remain relatively modest in mid-century, at approximately 3-4% in Québec, 6-14% in Ontario and 4-7% in US Northeast (Table 3, low and high emission scenario respectively). In contrast, by the 2080s the different emission pathways create fundamentally different supply futures for these ski tourism markets. Under the low emission pathway, average system capacity losses remain at 10% or less across all three regions (Table 3). Current levels of skier visits would be very difficult to maintain with a 57% loss of annual skiable terrain in Ontario under the high emission scenario (RCP 8.5). System capacity losses of 24% in the US Northeast may not unduly alter visitor experience if the number of skier visits declines 10-15% as it has in recent record warm winters (i.e., climate change analogues) (see Dawson, Scott, & McBoyle, 2009; Rutty et al., 2017). Like season length, much of the terrain in higher elevation, higher capacity ski areas of Vermont, New Hampshire, and Maine is retained. A decline of only 7% in annual skiable terrain in Québec would have marginal impact.

It is important to note that losses in system wide capacity of skiable terrain are much less than losses in ski days. In the three regional markets and under low and high emission scenarios for the 2050s, terrain-day losses are only about half to one-third of season length losses. This is because season length losses are often much less in larger and higher elevation ski areas, so that less terrain capacity is lost. Regional losses in average season length is a somewhat misleading indicator of system vulnerability because it can be more highly influenced by losses in small and low capacity ski areas.

Projected changes in snowmaking requirements

Under the baseline conditions the US Northeast region produces the most machine-made snow (81 cm), however, that average is heavily influenced by the much higher use of snowmaking by

Table 4. Required snow production (cm) to maintain a continuous ski season from December 15 to March 31 (by state/province).

		2050s		2080s	
Province/State	**Baseline** (cm)	RCP 4.5	RCP 8.5	RCP 4.5	RCP 8.5
Québec	31	+73%	+136%	+107%	+377%
Ontario	63	+179%	+256%	+229%	+545%
US Northeast	81	+88%	+144%	+125%	+308%
New Hampshire	58	+88%	+133%	+121%	+296%
Maine	55	+80%	+127%	+116%	+304%
Connecticut	133	+68%	+99%	+91%	+207%
Massachusetts	111	+87%	+125%	+114%	+261%
New York	98	+93%	+165%	+132%	+297%
Vermont	42	+94%	+153%	+140%	+412%
Rhode Island	335	+64%	+88%	+82%	+164%

ski areas in Rhode Island, Connecticut and Massachusetts (Table 4). Ontario (63 cm) and Québec (31 cm) currently have a lower reliance on snowmaking.

Additional snowmaking will be required to minimize ski season length and terrain losses across all three regional markets and under all climate change scenarios. The projected amount of additional machine-made snow required to maintain a continuous ski season from December 15 to March 31 is identified for each regional and scenario in Table 4. In mid-century, the smallest increase in snowmaking occurs in Québec (+73-136%). Increases are largest in Ontario (+179-256%) meaning Ontario ski areas will need to produce approximately as much as the US Northeast. Snowmaking requirements continue to rise in the late-century, particularly under the high emission scenario (RCP 8.5) where average snowmaking production will increase between 308% and 545% in these three regions. The relative increase in some States (Rhode Island, Connecticut, Massachusetts) is less than in Ontario, Québec, or high elevation states like Vermont, in part because these states were already producing much more snow and because conditions become so warm that there are fewer opportunities to make snow (i.e., some ski areas reach operational capacity limits). These additional snowmaking requirements have important implications for operational costs and the sustainability of snowmaking as a climate adaptation, both in terms of limits to adaptation and energy/water requirements.

Ski area economic viability

Assessing the longer term economic viability of an individual ski area is complex and influenced by many factors, including business model (public vs private, small-medium sized enterprise [SME] vs conglomerate, primarily ski business vs four season resort, revenue diversification, real estate development/management), proximity to source market(s), demographics and other demand influences on primary market(s), transportation access, destination reputation, climatic resources and snowmaking capacity, infrastructure age/efficiency, and operating cost-revenue structure (Falk, 2009; Falk & Steiger, 2019, Gonseth, 2013). Most of this business information is proprietary and unavailable to researchers.

This analysis focuses only on the potential impact of changing climatic conditions on economic viability and adopts two indicators that have been used in the literature to estimate pressure on skier visits and potential revenues: (1) season length of 100 days or more (Abegg, 1996) and (2) being operational during the high visitation Christmas-New Year holiday period (Scott et al., 2007). Both indicators need to be reached in 70% of all years. It is acknowledged that changes in these indicators will impact individual ski areas differently (e.g., an SME with limited cash reserves/access to capital may be put out of business by a series of poor seasons, while a ski area that is part of a multi-property conglomerate can buffer poor seasons and access capital to diversify revenues), and this remains an important area of future research as ownership

Table 5. Percentage of ski areas meeting indicators of economic viability.*

		2050s		2080s	
Region	**Baseline** (Current)	RCP 4.5	RCP 8.5	RCP 4.5	RCP 8.5
Québec	100%	100%	90%	100%	46%
Ontario	94%	15%	6%	15%	0%
US Northeast	83%	45%	30%	38%	11%
New Hampshire	94%	56%	31%	38%	6%
Maine	100%	57%	50%	57%	29%
Connecticut	25%	0%	0%	0%	0%
Massachusetts	73%	0%	0%	0%	0%
New York	77%	37%	26%	29%	11%
Vermont	100%	88%	50%	81%	13%
Rhode Island	0%	0%	0%	0%	0%

*Indicators of economic viability: (1) 100-day or longer season length and (2) operational during the Christmas-New Year holiday period, both with a probability $\geq$ 70%.

structure and other operational data becomes available. Increased snowmaking requirements discussed in section 4.3 will also impact operating costs, but is not included here because data on differential snowmaking system efficiency and proportion of operating costs in the three regions is not available.

Currently, not all ski areas achieve the economic indicators (Table 5), with only 94% in Ontario and 83% in the US Northeast meeting both criteria. These two markets have a number of small ski areas operating at climatic margins (even with snowmaking) and some have ceased operations in the last 10 years (CSC, 2019; NSAA, 2019). This trend is likely to accelerate as observed regional warming continues (see Hamilton et al., 2003).

Warmer winters projected by mid-century will accelerate the financial challenges for ski areas in the three regional markets. Ski areas in Québec are the most climate resilient, with 100% able to achieve the economic indicators under low emissions and 90% in high emission scenarios. In the US Northeast region, the number of ski areas achieving the indicators is reduced almost in half under the low emission scenario (to 45%) and to nearly one-third (to 30%) under the high emission scenario. The Ontario market and some individual US States see very large declines in the number of ski areas able to maintain both indicators, particularly under the high emission scenario (Ontario 6% and Connecticut, Massachusetts, and Rhode Island 0%). In total only 66 of the 171 ski areas (35 in Québec, 26 in the US Northeast, and 2 in Ontario) are able to achieve both economic indicators under the high emission scenario (RCP 8.5), indicating the potential for substantial losses of operating ski areas and a transformation of these markets as early as mid-century.

In the longer 2080 timeframe, this dual future for the ski industry in Eastern North America is further highlighted. A low emission future (RCP 4.5) would see all of Québec's ski industry and portions of the US Northeast (38%) and Ontario (15%) markets able to achieve the economic indicators. While this would transform the competitiveness and viability of individual ski areas within and among these three markets, it is a much more desirable future than a high emission scenario. Under the high emission (RCP 8.5) scenario the proportion of ski areas able to maintain the economic indicators declines much further to 46% in Québec, 11% in the US Northeast, and 0% in Ontario. Under such a long-term scenario, operating ski areas would contract to Québec (18), Maine (4), Vermont (2), New York (4), and New Hampshire (1) only.

Discussion

The results of this market wide analysis on climate change impacts in the Eastern North American ski industry (171 ski areas) are broadly consistent with the early analysis of a limited number of ski areas (6) by Scott et al. (2006) with respect to changes in average season length and snowmaking requirements. Compared to the early analysis (Scott et al., 2006), SkiSim 2.0

model better simulates observed season length and provides much greater insight into the geography of ski tourism climate change risk and the differential implications for intra- and inter-regional competitiveness and adaptation needs.

Comparisons with other recent studies in the region are also highly salient for advancing understanding of climate change risk for ski tourism and providing decision-relevant information for stakeholders. As indicated, the use of snowmaking technology has long been widespread throughout Eastern North American ski markets and a key finding of Scott et al. (2006) was that studies that did not include snowmaking had underestimated current ski season length and vastly overestimated the impact of climate change. Despite this, contemporary research (Chin et al., 2018; Wobus et al., 2017) continues to examine climate risk in this region without directly modeling snowmaking adaptive capacity. Analysis of the ski season length for the US Northeast reported in the annual 'end of season' report by the NSAA finds the average season between 1980 and 2010 was 119.2 days. SkiSim 2.0 modeled a ski season length of 121 days over this same baseline period (within 2% of the reported average season). By comparison Wobus et al. (2017) produced a baseline season in the same region of 92 days (only 77% of the reported average).

As the studies project future season length, the disparity broadens. In the 2050s, the average ski season length in this study are double those of Wobus et al. (2017). In the late century under high emission scenarios, this study projects an average ski season length that is eight times longer than Wobus et al. (2017). Comparing modeled ski seasons during recent record warm winters (analogues for normal future climate conditions) provides further insight. In the US Northeast region, the 2001-2, 2011-12 and 2015-16 seasons are record warm winters that were respectively 3.5˚C, 3.2˚C and 2.8˚C above the region's 1981-10 baseline temperatures. Despite these anomalously warm conditions, the average reported season length in these winters was 112 days. The SkiSim model slightly overestimates the climate impact, with the average ski season reduced to 104 days in the 2050s under the lower emission (RCP 4.5) scenario (Table 2), while Wobus et al. (2017) project much greater losses, with the average season reduced to 50 days (RCP 4.5).

Chin et al. (2018) also does not incorporate snowmaking in their study of the New York and Midwest ski markets. While Chin et al. (2018) calculate days suitable for snowmaking, they do not include machine-made snow in their model of snow depth. As such, Chin et al. (2018) estimate a baseline season of only 68 days (a 43% underestimation of the reported season length in New York) versus the 119-day season in this study (a 1% underestimation). Looking forward, Chin et al. (2018) conclude no New York ski areas will remain operationally viable in a high emission (RCP 8.5) scenario in the 2080s. Our study similarly projects major reductions in the average ski season (−54%, Table 2) under such an emissions scenario, but that 11% of ski areas (located in eastern New York) would still be able to achieve both indicators of economic viability (Table 5).

Despite the contraction of eastern North America's ski season length and economically viable ski areas projected in this study, this comparison suggests that some previous projections in the literature have highly over-estimated the climate risk to the ski industry through mid-century and perhaps even late-century if a low emissions future consistent with the Paris Agreement can be achieved. This finding is critical for adaptation decisions by the ski industry, destination communities, and institutional and real estate investors.

Although this study represents the most comprehensive assessment of climate change impacts on the skiing industry in North America, several limitations need to be considered: we used an air temperature of -5 °C as threshold for snowmaking (and -2 °C for emergency snowmaking). Snowmaking is also dependent on humidity and wind. A further advancement would be to also consider these two factors, although then the challenge is how to downscale air humidity and wind speed/direction to the local scale. Another limitation are our standardized lapse rates for temperature and precipitation. These can differ between locations and are in some cases also not linear as assumed in this study. To overcome this assumption, high altitude weather stations are required to calculate lapse rates that better represent local climate conditions near ski areas. Unfortunately, high elevation stations are rare and never so widely available to allow this approach for a regional market wide study like this.

Conclusions

Several important advances over previous research in the study area were made and the improved SkiSim 2.0 model (versus SkiSim 1.0 in Scott et al., 2006) was found to better simulate observed season length in all three regional markets. The comparative analysis of 171 ski areas across Ontario, Québec, and US Northeast provided the first marketplace wide climate risk assessment and the implications for intra- and inter-regional competitiveness. Valuable new insights into the influence of latitude, elevation, and proximity to lake effect snow of the Great Lakes on differential climate change impact reveal which ski destinations are at risk and which could gain market share as competition declines. The inclusion of new ski industry performance indicators also provided new insight. The projected reduction of skiable terrain days indicated that the use of ski season length as a sole indicator may overestimate the impact on system capacity because it treats all ski areas as equal. Terrain days better accounts for the relative impact of climate change on ski areas of different sizes and capacity, and in this region reflects the greater climate resilience of large and high elevation/latitude ski areas in Québec, Vermont, New Hampshire and Maine. The analysis of the vulnerability of ski season segments also provides new insight into the importance of advanced snowmaking capacity and other adaptation strategies for the higher risk Christmas-New Year holiday period.

Three central conclusions emerged. First, the results demonstrated that regardless of the climate change scenario (low or high emission), for all three regional markets the average ski seasons shorten and snowmaking needs increase even as snowmaking opportunities decline. The projected changes in average ski season length continue to follow the observed trends in the US Northeast, where the NSAA (2019) reported 124-day season in the 2010-17 period declined from 127 days in the 2000s. This was the first such decline since the 1980s, as additional snowmaking capacity was able to lengthen average seasons from 100 days in 1983-89 to 119 days in the 1990s.

Second, projected climate change impacts are not uniform and will alter intra- and inter-regional market competitiveness, with the effect of reinforcing the historic contraction and consolidation of the ski industry in Eastern North America. While the differential impact of climate change will cause the inevitable contraction of operating ski areas, it is important to emphasize that some climatically advantaged ski areas remained viable in late century (see Table 5; Figure 1). Both highly vulnerable and climate-resilient ski tourism destinations will need to adapt to climate change, but for very different reasons.

Third, Ski area operators and communities in the most vulnerable areas (see Table 5; Figure 1) need to begin to develop climate change adaptation strategies to diversify tourism and the local economy to cope with business and livelihood losses from the ski industry. All ski area operators also need to consider how to minimize the higher operational costs related to additional snowmaking measures, while at the same time improving and diversifying revenues and maintaining visitor experience. While it may at first seem counter-intuitive, the adaptation needed in the most climate-resilient ski tourism destinations will be to invest in further lift and other service capacity (e.g., parking, hospitality, retail) to be able to accommodate market share transfer from ski areas that cannot open during a season or that close.

Finally, it was also clear that global mitigation policy over the next 20 years, and the resultant GHG emission pathways, will be a decisive determinant of the future of ski tourism in this region and likely across global ski markets. There are two fundamentally different futures for the ski industry in Eastern North America. In a lower emission pathway (RCP 4.5) that is consistent with the country pledges made to the Paris Climate Agreement through their Nationally Determined

Contributions, losses in system capacity (terrain-days) can be limited to less than 10% (Table 3) and 81 of the 171 ski areas are able to achieve the two economic indicators through late-century (Table 5). While a contraction of primarily climate disadvantaged ski areas is inevitable, a low emission pathway portends the continuation of ski tourism in Eastern North America.

In sharp contrast, a high emission scenario (RCP 8.5) would disrupt parts of this ski tourism market as early as mid-century, with only 6% of Ontario ski areas and 30% in the US Northeast still able to achieve the two economic indicators (Table 5). The market would be transformed in the later decades of this century with only 57 ski areas able to achieve the two economic indicators (46 in Québec and 11 throughout the US Northeast). Aggressive climate mitigation policy consistent with the targets set by the Paris Climate Agreement is in the best interest of the ski industry in Eastern North America to reduce projected high emission related impacts, and thus the industry should be a strong advocate for global climate action and policy. In the light of the intensifying discussion of climate change mitigation and the required transformation of economies and lifestyles to a low carbon society, including tourism (Scott, Hall, & Gössling, 2016), ski area operators are advised to engage in mitigation policies and community level actions not only to prevent adverse impacts on their business but also to stress that the industry has recognized its responsibility to act. That has not been the case in Canada and remains tempered in the US as well (Knowles, 2019), where the winter sports athletes led organization – Protect Our Winters – has been much more visible in its advocacy to state, federal, and business leaders.

Two important research directions are needed to better assess the risk climate change poses to the ski industry in eastern North America. There remains a need to consider the synchronous adaptations to the impacts of climate change by ski area operators and ski tourists, in order to assess the integrated effects of these responses for the spatial and temporal distribution of skier visits across the evolving regional marketplace of competitive destinations. Studies of recent record warm winters in the study area (Dawson et al., 2009; Rutty et al., 2017) have demonstrated that skier demand is thus far resilient to climate change analogue conditions. Demand-side climate risk remains uncertain including skiers, particularly younger market segments, willingness to travel longer distances to visit ski areas that remain operational, if participation rates in skiing will decline if nearby entry level ski areas are lost, or the role of snow in urban source markets as motivation for ski tourists. A second important area of research is the sustainability of snowmaking as a climate change adaptation strategy that is central to limiting the impact of future climate change. The major increases of snow production, ranging from 74-257% in the 2050s to 110-548% in the 2080s, represents both an important increase in operating costs and a sustainability challenge for ski areas in the study area. Although water use for snowmaking is largely non-consumptive (an estimated 80-90% returns to the same watershed as spring melt), where ski areas access natural water bodies for snowmaking, these large increases in water demand could cause conflicts with other stakeholders or restricted usage may be insufficient if not managed carefully. Snowmaking has been questioned as maladaptation (Hopkins, 2014; De Jong, 2015; Aall, Hall, & Groven, 2016) because it could contribute additional GHG emissions. Scott and Steiger (2020) have suggested that if additional snowmaking, powered by electricity which can be low/no carbon in regions with a low carbon electricity grid (like hydro-power dominated Québec), keeps a large number of tourists closer to home and prevents tourists from increased driving or flying to alternative distant destinations, snowmaking may result in lower GHG emissions across the tourism system. Empirical analyses of these two positions are an important knowledge gap, as is the investigation of other industry specific innovations and adaptation strategies including all-weather snowmakers and snow-farming. Climate change has become a reality of business planning as ski destination communities (e.g., RMW, 2016), ski tourism companies (e.g., NSAA, 2019), and ski tourism investors (e.g., Savills World Research, 2018) incorporate the implications of changing climate and emission reduction targets for the competitiveness of companies and development projects. Over the past several years the authors have been contacted by increasingly diverse decision-makers (e.g., ski area owners, ski destination communities, grooming and snowmaking equipment companies, insurance companies, institutional investors and pension fund managers, and real estate buyers and developers) for information and expert advice on the implications of climate change for individual ski areas and regional ski tourism markets. The demand for foresight on climate risk in the ski industry will only increase in the years ahead as the financial sector increasingly formalizes disclosure requirements on climate and carbon risk. The Financial Stability Board of the G20 countries established a Task Force on Climate-related Financial Disclosures which developed guidelines for companies to disclose their physical climate risks and opportunities now and under scenarios of future climate change (EBRD, 2018). While the disclosure of physical climate risk is currently only recommended, it is likely to be required by major stock markets in the early 2020s. At that time all publicly traded ski companies or ski resorts owned by publicly traded companies will need to assess and disclose their physical climate risk. Presumably banks and investors will then require the same information from all other ski companies and related destination development projects.

Despite the clear evidence provided over a decade ago by Scott et al. (2006) that not accounting for the current adaptive capacity provided by snowmaking misrepresented the current and future climate risk to the ski industry in Eastern North America, several studies in the peer reviewed literature continue to omit snowmaking in their projections of climate change risk. The resulting media coverage is dangerous for the industry because decision-makers are influenced by this misinformation (Mayer & Job, 2014; Scott et al., 2012, Scott & Steiger, 2013). A wide gap exists between the climate change risk perception of the ski industry and what is commonly portrayed in the media (Abegg, Kolb, Sprengel, & Hoffmann, 2008; Abegg & Steiger 2017; Hopkins, 2014; Knowles, 2019; Morrison & Pickering, 2013; Trawöger, 2014; Wolfsegger et al., 2008), with some in the ski industry have labeled 'scaremongering'.

This misinformation hinders industry engagement in climate adaptation and serves as a barrier to collaboration with the research community when there is an imperative for decision-relevant information in the ski industry, ski destinations and the tourism sector broadly. As the World Travel and Tourism Council (WTTC) (2015a, p. 5) concluded, "The next 20 years will be characterized by our sector fully integrating climate change and related issues into business strategy, supporting the global transition to a low carbon economy, strengthening resilience at a local level against climate risks … ." The tourism research community has an important role to provide science-based climate change risk and adaptation planning information to the above-mentioned range of ski tourism stakeholders. New research that does not reflect the current operational realities of ski areas, let alone future adaptive capacities, and cannot reasonably simulate current ski seasons should not be acceptable. Our credibility with these stakeholders to influence the future development of ski tourism demands this.

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