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Climate Change and Ski Tourism Sustainability: An Integrated Model of the Adaptive Dynamics between Ski Area Operations and Skier Demand

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Abstract: Climate change is an evolving business reality influencing the sustainability of ski tourism worldwide. A new integrated model of the co-evolution of supply (27 ski areas) and demand-side (skier behaviour) climate change adaptation in the ski tourism market of Ontario, Canada is presented. Ski area operations are modeled under a high-emission 2050s scenario, with skier responses to altered operations informed by a survey of 2429 skiers. These market adaptive dynamics reveal new insights into differential climate risk, capturing patterns not apparent when considering only operational conditions of ski resorts. A decoupling of ski season length and skier visitation was found at four ski areas, where, despite average season length losses, visitation increased as a result of reduced competition. Simulated skier visit losses were smaller than reductions in season length, contributing to an increase in crowding. Growing the market of skiers was also identified as a critical adaptation strategy that could offset skier visit losses from shortened seasons. Climate change challenges the future sustainability of ski areas in this market in several ways: profitability of ski areas with substantially shorter seasons, increased snowmaking costs, crowding impacts on visitor experience, and potential overtourism at the few most climate resilient destinations.

Keywords: climate risk; ski industry; sustainable tourism; adaptive dynamics; tourism demand

1. Introduction

Established tourism business models and livelihood strategies are challenged by climate change, which in turn may impede sustainable tourism development in regions with greater climate change risk or high dependency on climate-dependent tourism markets. The multi-billion-dollar global ski industry is a particularly climate-sensitive tourism market that has received considerable attention in the research literature [1,2], the media (see [3] for a critical review), and tourism organizations [4–6]. Climate change is an evolving business reality for the ski industry, with recent trends toward shorter and more variable ski seasons and emerging climate risk disclosure requirements. Recent record warm winters in major ski tourism regions around the world have illustrated differential climate risk among ski areas and destinations. Industry reports on annual ski season length in the United States (US) and other international markets indicate average ski seasons were reduced in the 2010s for the first time in 40 years [7–9]. Future climate risk has also received increasing attention from the financial markets and institutional investors (e.g., [10–12]). Although much of the ski industry remains hesitant to publicly engage in climate action, emerging pressures for climate and carbon risk reporting [13,14] mean that publicly traded ski resort conglomerates (e.g., Vail Resorts and Alterra Mountain Company in the US) will need accurate climate risk assessments to meet disclosure requirements likely before 2025. Independent ski resorts seeking loans or investments are likely face similar requirements soon after [15].

Climate change risk of the ski industry has been examined by over 120 studies in 27 countries [2]. This geographically and methodologically diverse literature has consistently projected decreased reliability of natural snow cover, shortened and more variable ski seasons, increased snowmaking requirements, contraction in the number of operating ski areas, altered ski tourism demand affecting revenues and employment, and declining real-estate values of vacation properties. The timing and severity of these impacts depends on the rate of climate change and the adaptive responses of both tourists (i.e., demand) and decision makers in the ski tourism industry and destination communities (i.e., supply), as well as the resulting shifts in intra- and intermarket competitiveness [2,8].

An important limitation of this literature is that the interactions between evolving supply-side (i.e., shorter and more variable ski seasons, with declining number of operating ski areas) and demand-side responses (i.e., ski tourist adaptation behaviours) have not been assessed to determine the consequences for regional ski tourism markets and individual destinations [2,8]. For example, the ski season in the US Northeast region is projected to shorten by 22% in a mid-century (2050s) high-emission scenario (RCP 8.5) [7] and by 18% in Austria under the same scenario [16]. Surveys with skiers in these two markets show a large share of respondents stating they would ski less often (39% in Austria, 34% in the US Northeast) revealing a high potential for climate-induced reduction in demand [17,18]. However, past anomalously warm winter seasons that are representative of average seasons in a mid-century high-emission scenario have shown smaller impacts on skier visits than suggested by season length projections and skier surveys. During two record warm winters in these two markets, skier visits in the US Northeast declined by 11.6% in the 2001–2002 season, while in Austria, the 2006–2007 season resulted in 11% less skier visits [19,20].

There are two factors that could explain the gap between observed and projected demand response to changing climate. First, season length changes do not lead to a proportionate decline of skier visits, as demand is characterized by high seasonality [21]. For example, ski operation days are initially lost at the more sensitive beginning and end of the season when demand is substantially lower than in core winter periods (e.g., Christmas, school holidays in February). Second, the stated response of skiers to snow deficiency cannot be directly translated to precise estimates of reduced demand, as only the proportion of respondents that would ski less often (or not ski at all) is estimated, but how many fewer days they would ski is not. In the above example, if the approximately one-third of skiers who indicated they would ski less in these two markets would ski 25% less often, then net impact on total skier visits would be a 9% decline.

The differences between supply-side modeling (i.e., season length projections), demand-side stated behavior (i.e., surveys) and observed ski market responses to anomalously warm conditions (i.e., analogues) stress the need for integrated climate risk assessments that examine the dynamics between synchronous supply-side operations and demand-side tourist behavioral adaptation. The objective of this study is to address this gap by coupling the SkiSim2.0 ski operations model (developed by [22,23] with a spatially dynamic tourist behaviour agent-based model (ABM) (based on [24,25]) to model the internal dynamics of skier visits within a regional ski tourism market (Ontario, Canada) under variable climate conditions and an evolving landscape of competitive destinations [26].

The integrated model was developed to simulate how the regional ski market in the Canadian Province of Ontario could evolve in response to changes in supply (season length, ski area closures) and demand (number of active skiers/participants, population, substitution behaviour patterns). This study area was selected because: (1) the limited size (27 ski areas, with average of 3.01 million skier visits between 2007–2008 and 2018–2019) and relatively closed nature of this market make it suitable to development and testing of the new coupled model; (2) the important economic contribution to small and rural economies in the province (represents 31% of the total Canadian ski and snowboard market); (3) high relevance to contemporary decision making in the ski industry and municipal and provincial governments, because this market has lost ski areas and experienced challenging climatic conditions over the last decade; and (4) working relationships critical to the success of the project (including data access) had been established with Ontario Ministry of Tourism, Ontario Ministry of Natural Resources, and Ontario Snow Resorts Association.

2. Materials and Methods

This research takes a novel approach to modeling climate risk of ski tourism by combining multiple data inputs into an integrated geospatial model: (1) "SkiSim2.0", a ski area operations model that utilizes daily climate inputs to simulate snow conditions (with natural and machine-made snow) and the operational status of ski areas (i.e., open/closed); (2) an empirical skier survey with stated behavioral responses of skiers to closed ski areas (i.e., spatial, temporal, activity substitution); (3) ski area characteristics, including ski resort snowmaking and lift capacity used to consider the impacts of increased visitation on resort crowding; and (4) ski industry performance data to define the number of available skiers (agents) and seasonality of demand (e.g., season segments, annual visits). Each of the components of the integrated model and the data sources included in Figure 1 are further described below.

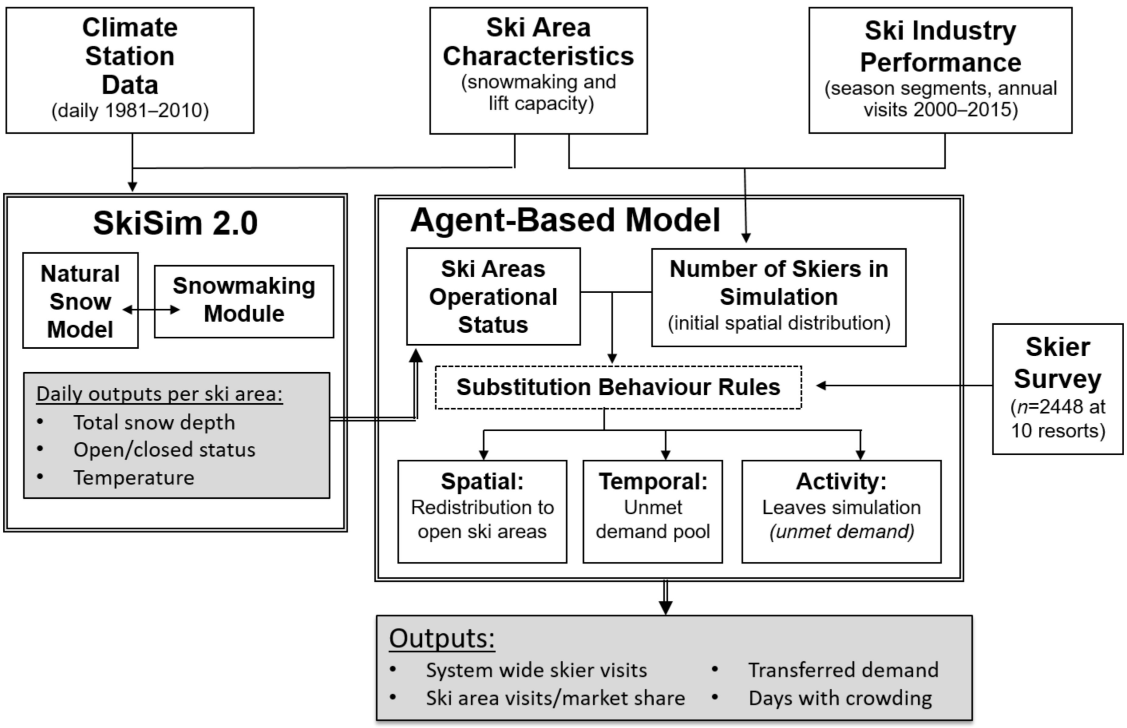

Figure 1. Integrated Ski Operations—Skier Visitation Model.

2.1. Ski Area Operations Model (SkiSim2.0)

SkiSim was developed to overcome a major limitation of climate change impact studies in the winter tourism sector-the omission of snowmaking that has been an integral weather management strategy in several regional markets for 30 years. Originally developed and applied in the Ontario ski market [22], SkiSim has since been further developed [23] and applied in several regional ski markets including part of Canada [22,26,27], China [28], European Alps [16,23,29,30], Scandinavia [31], the United States [7,32,33]; and worldwide at Olympic Winter Games sites [34].

SkiSim2.0 uses daily weather data to simulate natural and machine-made snow, based on snowmaking capacity and operational decision rules. The decision rules applied in this study have been derived from consultations with ski area managers and snowmaking crews in the study region [26]. To validate the modelled seasons length under different snowmaking capacities, the SkiSim2.0 output was compared to the daily snow conditions at each resort, as reported by the Ontario Ski Resorts Association [OSRA]) (see [35]). The most accurate season length simulation from SkiSim2.0 was then used to represent current snowmaking capacity at each ski area (ranging from 5 to 10 cm/day). The model was also run with advanced snowmaking capacity at each ski area, where the highest capacity of any ski area in the study area became the standard for all 27 ski areas.

Daily weather data from 13 climate stations within the study area were obtained from the Meteorological Service of Canada [36] and used to simulate snow conditions at the 27 ski areas in this regional market (Figure 2). To represent the range of possible climate futures in the study region, climate change scenarios from the IPCC Fifth Assessment Report [37] were used. Only scenarios from global climate modelling groups that participate in the World Climate Research Programme's Coupled Model Inter-comparison Project Phase 5 (CMIP5) were considered for this analysis. The climate change ensemble scenarios were obtained from the Environment and Climate Change Canada [38] climate and scenarios portal, which provides the projections of 29 individual Global Climate Models (GCMs) as well as an ensemble scenario. For this analysis, a current emissions trajectory or high-emission scenario (RCP 8.5) was utilized for the mid-century time period (2040–2069). A high-emission scenario was utilized to explore the potential impact of new warm extreme winters that this regional market has not yet experienced, and the capacity of current and improved snowmaking to cope with these new conditions. To produce daily temperature and precipitation data for each location, monthly temperature and precipitation ensemble scenarios were downscaled to the 13 individual climate station locations using the Long Ashton Research Station (LARS) stochastic weather generator [39,40]. Further details on the SkiSim2.0 model and its application on the Ontario ski market place can be found in [26].

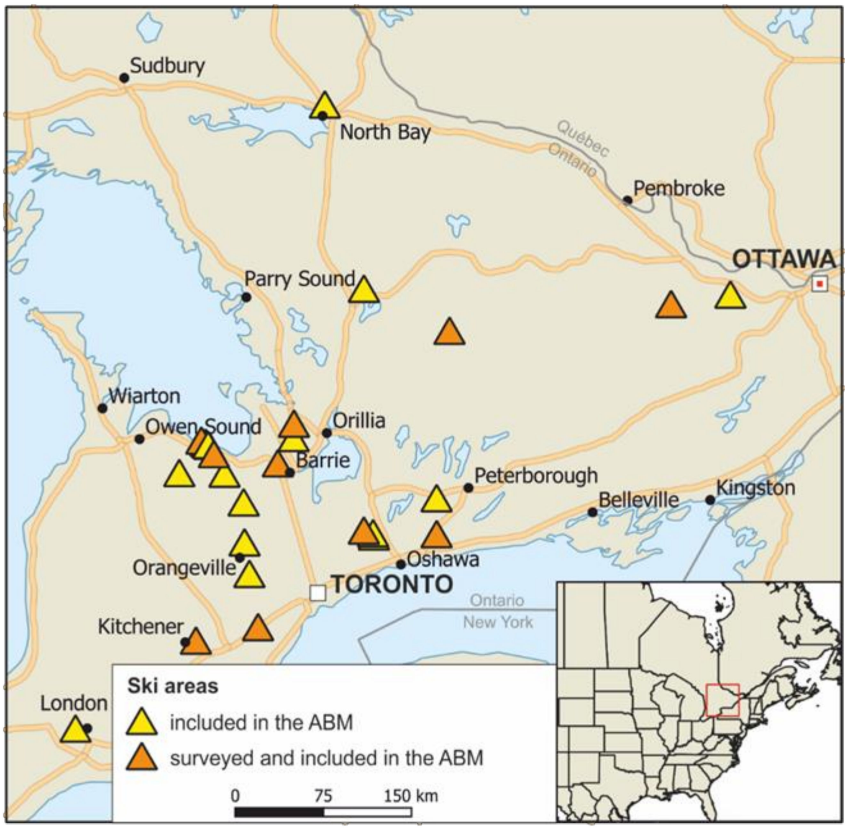

Figure 2. Locations of the 27 Modelled Ski Areas in the Ontario Market.

The primary coupling between the SkiSim2.0 and ABM modules in the integrated model (Figure 1) is the input of the daily operational status of each of the 27 ski areas in the simulation (i.e., the transfer of a daily open/closed value, based on a minimum snow depth threshold of 30 cm for ski operations and daily temperature conditions).

2.2. Skier Survey and Market Demand Projections

A survey of skiers and snowboarders (here after "skiers") ($n = 2429$) was conducted in the 2013–2014 winter season in 10 selected ski resorts, which included one private resort, the two largest resorts in the market, and seven medium-to-small-sized resorts (as defined by OSRA). The aim of the survey was to identify behavioral responses of skiers to (temporary or permanently) closed ski areas in the Ontario ski market [41,42]. Descriptive statistics of the behavioural response (i.e., share of respondents selecting each adaptation behavior) and their alternative ski resort choice (when applicable) was used to generate behavioral rules for the agents in the ABM. Specifically, survey results on substitution behavior, preferred alternate ski resorts (e.g., if primary/preferred ski resort is closed), and temperature preferences were used to inform agent decisions in the ABM. Three substitution behaviors were distinguished in the survey: (1) temporal substitution (i.e., postponing the ski trip within the current ski season); (2) spatial substitution (i.e., traveling to a different ski resort); and (3) activity substitution (i.e., forego the ski trip and participate in non-skiing activity). To account for a range of temporal closures, respondents selected their preferred substitution type if the ski resort was "closed today", "closed until mid-January" and "closed permanently" [41]. In the case of spatial substitution, respondents were asked to choose their most likely alternate ski resort from a list of the 27 Ontario ski resorts in the study area or in the neighbouring provinces and US states (Quebec, Michigan, New York). To determine the acceptable travel distance to an alternate ski resort (i.e., spatial substitution) a matrix of respondents' home location (first three digits of postal code) and the location of their preferred resort was generated using ArcGIS Geographic Information System software. A network analysis was conducted using the Ontario road network to calculate not only the distance, but approximate driving time from origin to destination for each respondent. This matrix defines the pool of potential alternative ski areas based on respondent's travel distance. For additional detailed results from the skier survey, please refer to [41,42].

A limitation of many climate risk assessments of socio-economic systems has been the application of changed climate conditions (30, 50, 80 years in the future) to unchanged socio-economic systems (e.g., [43,44]). This is a visible limitation of climate risk assessments of the ski industry (e.g., [45]) and both [46,47] have discussed its importance for estimating climate change impacts on skier visits in European markets. To compare climate change related impacts on skier visits with potential changes in ski demand, two different ski market development trends based on scenarios developed for the Canadian Ski Council (CSC) were utilized [48]. In the "trend" scenario, demographic (population growth and ageing) and skiing participation rates are projected to result in a 3% decline of skiing demand by the early 2030s (from the 2014–2015 season baseline). The CSC "market intervention" scenario projects market growth of 148% over the same time frame. Considering the maturity of this ski tourism market and relatively stable national ski participation rate over the last two decades (ranging from 8.5% in 2002–2003 to 5.8% in 2015–2016) [49], the highly optimistic market intervention scenario was not included in the analysis. Instead, a "mid-point" scenario that assumes a still very successful market intervention strategy to increase demand by 59% with marketing campaigns to attract new skiers and support novices, especially from families and those with little background in snow-based leisure activities [50].

2.3. ABM Module

An ABM approach provides a framework for creating simulations that can represent heterogeneous characteristics of tourism actors, such as individual decision making of skiers in response to daily snow and weather conditions and available ski area destination options. The ABM approach has been used to examine supply-demand dynamics in diverse tourism systems, including travel, lodging and leisure patterns [25,51–57]. A main advantage of the ABM approach is that individual tourist decision making, and characteristics can be modeled through a sequence of "if–then" decisions. This type of modelling approach supports the development of different scenarios (e.g., [58]) that can be used to experiment with a variety of structural characteristics of the ski tourism system, such as the loss of specific ski resorts or projected growth/decline in skier numbers resulting from population growth or market development strategies.

To link snowpack variability and ski area operations with potential changes in ski visitation patterns at the regional market scale, Pons et al. [24,25] developed a geo-referenced ABM using behavioural rules to simulate the adaptation of skiers to projected changes in snow conditions under climate change. The ABM structure [24] was adapted for this study, with skier visit data and skier surveys (Section 2.2) used to define the behavior rules within the ABM. This adapted ABM was used to simulate skier response to current climate variability (for the 1981–2010 period), represented by a climatologically average ski season, a record warm season (which also represents an analogue for an average winter in the 2050s under projected climate change), and the coldest season in the last 25 years. For mid-century ski seasons under climate change (RCP 8.5 scenario), seasons representing the coldest, warmest, and an average season within the 30-year period (2040–2069) were used in the ABM simulation.

The functioning of the ABM module is described following a skier agent as it moves through a series of step-by-step decisions in the modelled landscape of ski resorts in Ontario (see Figure 3). The simulation is initiated by generating the number of agents based on the number of skier visits in the climatically average year, provided by the OSRA annual end-of-season reports [59]. Due to unavailable resort-specific skier visit data, the reported skier visits per OSRA's size classification were allocated to the resort-level proportionate to lift capacity in each size category [42]. Seasonality of skier visits was implemented by different weights for weekdays (0.3), weekends (1) and the holiday season (1.5) based on OSRA data.

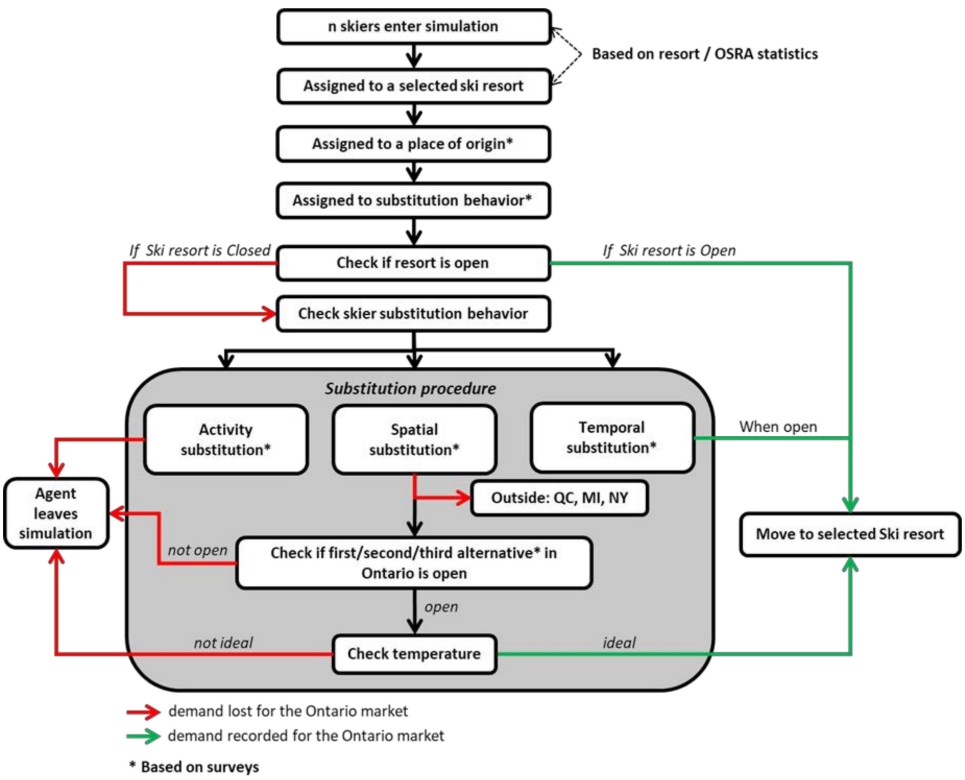

Figure 3. Skier agent decision making flowchart.

For each skier agent and time step in the simulation (i.e., one day of the skiing season), the model checks whether the allocated ski resort is open. If the resort is open, the temperature at the base station of the ski resort is then checked to confirm it is within an acceptable range. Using secondary data from [60], the ABM includes a 5% reduction in skier visitation if temperatures are colder than −15 °C, a 10% reduction if temperature is less than −20 °C, and a 15% reduction when temperatures are less than −25 °C. Similarly, unusually warm weather results in a 15% reduction in visitation when temperatures exceed +15 °C. If temperatures are between −15 and +15 °C, all skier visits without thermal reductions are recorded for that day and ski area.

Conversely, if the ski resort is identified by the SkiSim2.0 module as closed, then the substitution behavior sub-model is enacted. This sub-model places skier agents into one of three types of substitution patterns: (1) spatial (check for open ski resorts elsewhere in Ontario or in nearby regional markets), (2) temporal (delay skiing for another day in the season at the same ski area), and (3) activity (removed from simulation). The percentage of skier agents engaging in any one of these substitution behavior rules are based on the responses from the skier survey (Section 2.2). The potentially differing behavior in the earlier and later season segments was included by using mid-January as a breakpoint. On simulated days before mid-January, the substitution behaviour pattern is 7% activity, 48% temporal and 45% spatial, while after mid-January it is 3% activity, 36% temporal and 61% spatial substitution [41]. Spatial substitutions include other ski areas within an established acceptable travel distance (identified in the survey), including alternative destinations outside of the Ontario market (Quebec, New York, Michigan). Should a skier agent select spatial substitution, open status and temperature thresholds of a list of alternative ski areas that are within acceptable travel distance from place of origin is checked. Skier agents performing temporal substitution delay their skiing for when their chosen resort may be open later in the season.

The ABM also compares the maximum skier capacity of each ski area (based on hourly lift capacity obtained for each ski area) with simulated visitation numbers, and records overcrowding when resulting waiting time at lifts would exceed 15 min. It is important to note that overcrowding is only used as an indicator of visitor experience on peak demand days and does not influence substitution behaviours or overall skier visits. Key outputs from the ABM module include the total number of skier visits per resort (daily and seasonally) and incidents of overcrowding (see Figure 1).

2.4. Model Performance

To test the ABM simulation performance, we compared total system-wide skier visitation generated by the model to the total visitations reported by OSRA during ski seasons that represent the range of climate variability in the study area. The 2011–2012 season was a record-warm winter (at 3.6 °C above the 30-year average), while 2013–2014 represents the coldest winter in over 20 years (at 2.8 °C below the 30-year average). The coldest winter within the 1981–2010 period was not selected because it occurred in the early 1980s when the ski marketplace was not comparable to recent seasons (i.e., the number, size, and snowmaking capacities of ski areas were very different and annual skier visits were not systematically recorded).

In each type of winter, the ABM simulates system visitation levels well, with a −6.3% difference in the climatically average season and shows very close fit with both the record warm (−2.6% difference) and cold seasons (+0.4% difference). The largest difference during climatically average winters is related to the difference in the SkiSim2.0 module and observed operational patterns of ski areas in the early and late portions of the ski season. SkiSim2.0 models ski area operational status as a binary variable (entirely open/closed), while reported conditions often reveal ski areas as partially open (some terrain and lifts are operational) (see [35]). The integrated model reallocates skier visits in the early and late months of the season on days when it simulates certain ski areas as fully operational, when in fact some are only partially operational. During the record warm season, more ski areas were closed during these marginal early and late season days, reducing this overestimate by the model. Similarly, during the cold season, most ski areas benefitted from increased snowfall and greater snowmaking opportunities, enabling greater terrain and lift capacity in the early and late season (i.e., fewer partial operating days) and reducing the difference with simulated capacity. A possible explanation for the larger bias in the warm season is that the SkiSim2.0 model does not capture extraordinary efforts of ski areas during record warm conditions, increasing snowmaking capacity on the most important ski runs by moving snow guns from less important ski slopes, making snow in more marginal (and expensive) warmer conditions, as well as partially opening skiable terrain and lifts.

While the results of the simulations are very promising, it is important to note that these results provide an indication of fit at the marketplace scale. A more detailed level of validation at the individual ski area level would be an important additional test of the model but is not possible because daily visitation data from all ski areas is not available. This proprietary visitation data, kept private by ski resorts for competitive reasons, means that the model should be considered experimental, with increasingly confident results possible if ski area resolution data should become available to researchers in the future. Nonetheless, the model provides valuable understanding of the competitive dynamics of a regional ski market and the impact of climate variability and change on ski area operations and skier behavior. The model also provides important insights into the potential implications of market evolution, including lost or new ski areas, investments in snowmaking that allow some ski areas to protect their season length more reliably, market development and demographic trends, and even tourism or environmental policies that might alter access to water for snowmaking.

3. Results

3.1. Ski Season Length

In a climatically average season (e.g., 2010–2011) in the reference period (1981–2010), the average season length across all 27 simulated ski areas was 116 days (Figure 4). The record warm season (2011–2012) resulted in a much shorter season (−35 days or −30%). Importantly, the record warm season also had a considerably higher standard deviation at the 27 ski areas (Figure 4), with the season length ranging between 49 and 92 days, compared to a climatically average season (112–119 days). This differential impact of anomalously warm conditions was expected based on observed seasons (see [35]), as climatic sensitivity and snowmaking capacity differs between the ski areas in the study area.

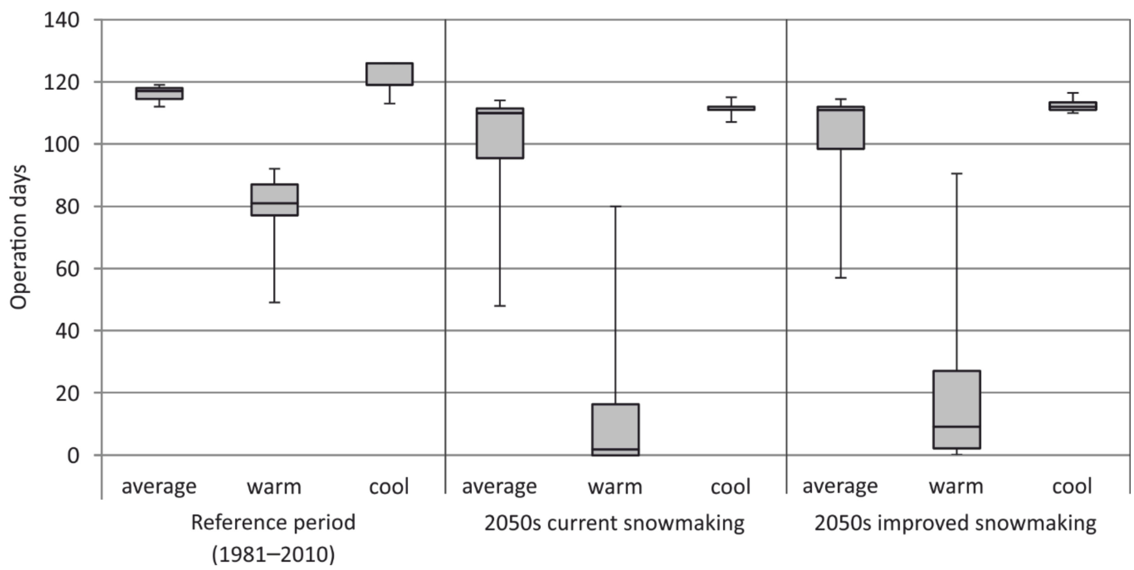

Figure 4. Modeled ski seasons (operation days).

A climatically average season in the 2050s, with current snowmaking capacity, is approximately 17 days shorter than in the reference average period and has higher variation (48–114 days) among the ski areas. This future average season is nonetheless 19 days longer than the record warm 2011–2012 season. A cool season in the 2050s is only slightly shorter than in the reference cool period (−11 days) and has limited variation across ski areas (107–115 days). A warm season in the 2050s results in a highly pronounced season shortening (−78% compared to reference warm season) and variation among the ski areas (ranging from 0–80 days). While five ski areas still have seasons of 70 days or longer, the remaining ski areas have less than 30 days.

With improved snowmaking capacity in the 2050s, losses in a climatically average season are slightly less (−11%), but variation remains high (57–118 days). The results underscore that while some ski areas are limited by climatic conditions and not their snowmaking capacity, others have an opportunity to intensify snowmaking to allow them to better maintain season length under future warmer conditions. Importantly, increased snowmaking capacity reaches the limits of its effectiveness in the warm seasons of the 2050s, where even with advanced snowmaking, only five ski areas are able to maintain a season longer than 70 days, one ski area has 50 days, and the remainder of the Ontario ski market has 30 days or less.

3.2. *Skier Demand, Utilization and Crowding*

The impact of the altered ski season length and operational status of individual ski areas in the study area on annual market-wide skier visits is substantially affected by the market development scenarios. Under the trend scenario in market development (−3% relative to 2014–2015 season) and current snowmaking capacity, simulated skier visits in the 2050s shows moderate reductions in the climatically average (−10.9%) and cool season (−8.7%) (Table 1). Notably, the simulated demand losses are considerably lower than simulated season length losses (Table 1), which is consistent with observations during anomalously warm winters in this marketplace (see [35]). In the warm 2050 season, skier visits decline markedly by 77.5%, demonstrating the combined threat of market stagnation and climate change for the future of this ski tourism market. Investment in improved snowmaking across all ski areas is able to slightly reduce losses in skier visits (Table 1) but cannot offset the severe losses in the warm winters of the future. This finding illustrates the limits of technical adaptation through snowmaking in this market and it remains uncertain whether this investment would be economic for all 27 ski areas.

Table 1. Modeled Skier Visits Under Climate Change and Market Development Scenarios.

2050s Climate Change Scenario (RCP 8.5)	Market Development Scenario			
	Trend Scenario (−3%)		Midpoint Scenario (+59%)	
	Current Snowmaking	Improved Snowmaking	Current Snowmaking	Improved Snowmaking
Average winter	−10.9%	−10.4%	+46.0%	+46.9%
Warm winter	−77.5%	−70.0%	−63.1%	−50.9%
Cool winter	−8.7%	−8.5%	+49.8%	+50.0%

In the mid-point scenario, where the ski industry has been highly successful in market development (+59% relative to 2014–2015 season) by attracting new skiers among Ontario's growing and increasingly diverse population and/or increasing annual number of skiing days, the impact of shortened ski seasons in the average winters of the 2050s is mitigated. In climatically average winters of mid-century, annual skier visits are 46% higher with current snowmaking capacity. The increased demand in the mid-point market development scenario is not able to prevent the massive losses in skier visits the warm seasons of the future (−63.1%), as too many ski areas are closed for much of the ski season and supply capacity is much reduced at the regional market scale.

In addition to insight into how annual skier visits may change at the regional market scale, the coupled model provides novel insight into the spatial redistribution of demand as climate sensitive ski areas are not operational for longer periods of the season or are potentially closed. Information on potential market share gains by ski areas with climatic advantages and/or higher adaptive capacity is very important for business and destination level adaptation. In a climatically average season in the 2050s, three (four with improved snowmaking) ski areas attract more skiers than in the 1981–2010 reference period, with an average increase of 10.5% (current snowmaking) and 8.4% (improved snowmaking). Reduced competition from some closed ski areas for part of the season leads to a transfer of demand to these ski areas preferred by the skiers surveyed. In a warm season in the 2050s, when most ski areas struggle to open, two of the most climate resilient ski areas are projected to receive an increase of 11.1% (current snowmaking) and 17% (improved snowmaking) skier visits compared to a warm season in the 1981–2010 reference period. The projected increase in demand at both resorts occur despite being open far fewer days, highlighting that there are business opportunities even where there is climate risk and an overall decline in skier visits at a regional market level.

A potential effect of fewer opportunities to ski (e.g., shorter ski seasons, resort closures) is a higher concentration of skiers. From a business perspective, concentration could be positive, as ski lift capacity is better utilized, enhancing the profitability of ski areas. However, from a customer perspective, higher levels of skier concentration may be perceived as crowding (e.g., busier slopes, longer lift lineups, congested parking lots and retail shops). To further investigate the potential for crowding that could degrade the visitor experience, the utilization rate as a percentage of annual capacity (where annual capacity = ski operation day * daily lift capacity in persons/h) was calculated for the reference period and future scenarios. The average market-wide utilization rate (across all 27 ski areas) ranged between 10–13% in the reference period (average vs. warm season), with a broader range between 4–24% among individual ski areas (Table 2). The utilization rate remains similar in 2050s average seasons; however, it increases substantially in warm seasons to 18–19% (up to 36% at some individual ski areas) in the trend scenario and 29–31% (up to 59% at some individual ski areas) in the mid-point scenario (Table 2).

Table 2. Utilization rate (%) of market-wide annual lift capacity.

2050s Climate Change Scenario (RCP 8.5)	1981–2010 Current Snowmaking	Market Development Scenario			
		Trend Scenario (−3%)		Midpoint Scenario (+59%)	
		Current Snowmaking	Improved Snowmaking	Current Snowmaking	Improved Snowmaking
Average winter	9.7	10.2	9.9	16.7	16.3
Warm winter	13.0	19.1	17.7	31.4	29.0
Cool winter	9.0	9.3	9.2	15.2	15.0

At a seasonal utilization rate of 25% at an individual ski area, a skier would wait an average of 15 min for every lift ride. This 15 min threshold was used to define a "crowding day" in the model. Averaged across all 27 ski areas, 5% (cool season) to 11% (warm season) of operating days exceeded the crowding threshold in the reference period (Table 3).

Table 3. Share of crowding days to total operation days.

2050s Climate Change Scenario (RCP 8.5)	1981–2010 Current Snowmaking	Market Development Scenario			
		Trend Scenario (−3%)		Midpoint Scenario (+59%)	
		Current Snowmaking	Improved Snowmaking	Current Snowmaking	Improved Snowmaking
Average winter	7%	5%	5%	17%	17%
Warm winter	11%	23%	18%	50%	46%
Cool winter	5%	4%	4%	15%	15%

In the 2050s, the proportion of crowded days increases in the warm seasons to 23–50% (trend and mid-point scenario, respectively), whereas in the future average and cool seasons, crowding days remain relatively stable. This implies substantial challenges with overcrowding in future warm seasons when the number of ski areas and skiable terrain/lifts in operation (i.e., marketplace scale supply) are substantially diminished. Importantly, analysis of the incidence of crowding at the ski area level (Figure 5) shows that a high proportion (61% with current snowmaking; 57% with improved snowmaking) of the crowding days occurs at resorts with very short ski seasons (≤50 days). These ski areas account for 46%/54% (current/improved snowmaking) of simulated demand, indicating a high potential for additionally redistributed skiers if these ski areas were to close permanently. It remains unclear whether ski area managers/owners will continue to operate a ski area for only a few weeks in a season, but financially the season start-up and closure costs make operating for such a short season highly doubtful. With the likelihood that more vulnerable ski resorts would remain closed during these future warm seasons, or close permanently, crowding days at the more climate resilient ski areas (i.e., remain in operation) would be higher than the model indicates, as skiers would be further concentrated as market supply contracts. The potential closure of more vulnerable ski areas identified with industry stakeholders and tourism officials is an additional scenario the coupled model could explore, but that analysis is beyond the scope of this paper.

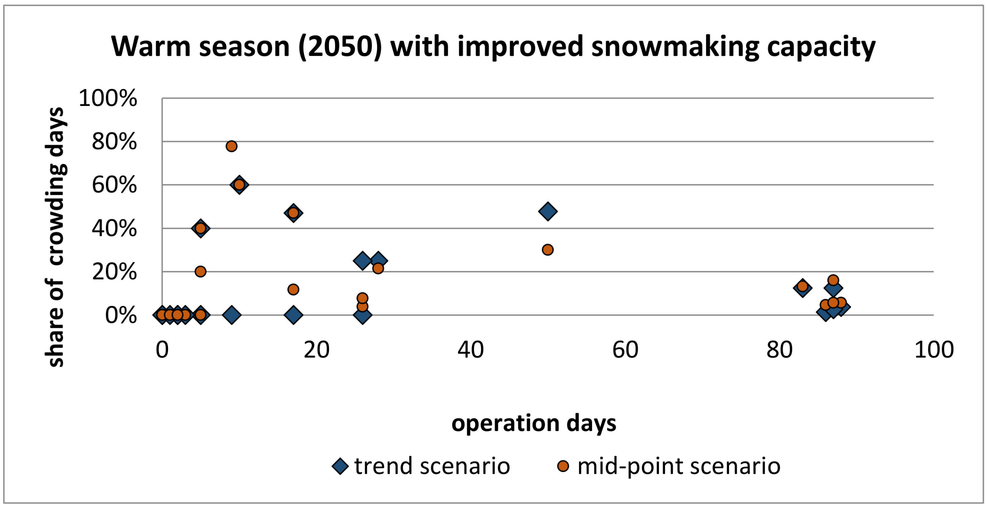

Figure 5. Share of crowding days in relation to operation days.

4. Discussion

The new integrated model linking climate-induced changes in the operations of individual ski areas (operating days, snowmaking requirements) with the adaptive behaviour of skiers (spatial, temporal, or activity substitution) was designed to explore the interactions of adaptation dynamics at a regional ski tourism market scale and provide novel insights into differential climate risk and possible climate change adaptation strategies. As an integrated tourism system, inter-resort competition and ski tourist decision making play a key role in the impacts of climate variability and change, and this analysis was able to reveal patterns that are not apparent when considering only the operational conditions of ski resorts as isolated entities.

Consistent with previous studies in this and nearby regional ski markets (see [7]), climate change resulting from a high-emission scenario reduced the average ski season length in the 2050s and snowmaking requirements to limit season losses increase at all ski areas in cool and average seasons. Many of the ski areas would be able to cope with future average winter conditions through current or improved snowmaking (if it were affordable). However, future warm winters exceed the adaptive capacity of even advanced snowmaking at most of the ski areas in this study area. Snowmaking declined in future warm seasons at most ski areas because they physically cannot make sufficient snow to be operational, resulting in devastating impacts on ski season length (−78% across the 27 ski areas), with only three ski areas (those further north and further away from the moderating effect of the Great Lakes) able to maintain ski seasons of approximately 80 days. The distribution and sequence (i.e., consecutive warm winters that could bankrupt smaller ski area businesses) of future extremely warm seasons will be critical to the evolution of this ski tourism market, emphasizing the importance of better understanding extremes within climate change projections. As is evident in previous record warm seasons, compared to ski demand, supply-side operations are more sensitive to unseasonably warm conditions [35]. The financial implications of frequent or successive extreme warm winter seasons is an important area for future inquiry, including the need to explore the probability of warm winters moving forward.

Four other novel findings from the integrated model are notable. First, the analysis revealed that improving the snowmaking capacity at all 27 ski areas (i.e., increasing all ski areas from their current capacity to the advanced capacity of leaders in the region) was not a highly effective adaptation strategy. Market-wide skier visits were not substantially higher (see Table 1) when all ski areas possessed advanced snowmaking. Therefore, any public-private partnerships to increase snowmaking capacity should strategically focus on investment at the most climate resilient and highest capacity (lifts and terrain) ski areas that are closest to large population centres.

Second, market development (i.e., strategies to increase skiing participation and annual skier visits) was found to be an important adaptation strategy that was capable of offsetting losses from shorter average seasons under climate change. This potential adaptation strategy is rarely discussed in the literature, in part because it is currently difficult to accomplish in mature markets, but this may change as the baby boomer generation stops skiing and the industry focuses on younger generations that will dominate the market [61]. A potential shift toward domestic tourism following the covid-19 pandemic [62] and as a response to reduce tourism related greenhouse gas emissions, may favour a revival of ski tourism market development in this region and others. Ensuring ski operations are decarbonized will be an important factor in taking advantage of potential opportunities in the transition to a low carbon economy [63]. The impact of climate change on future skier visits was found to be greater than the impact of market trends, but the combined impact of climate change and declining trend in skiing participation was very detrimental to a sustainable future for this ski tourism market. The range of climate and market development scenarios revealed substantially different outcomes, and hopefully inspire ski industry and tourism officials to pursue policies that support the low emission and high market development pathways.

Third and most importantly, the integrated model provided new insight into differential climate risk among ski areas within this regional market and the potential for increased demand transfers to other regional markets as well. The operational success of some ski areas was not exclusively dependent on climatic conditions, but rather on their ability to capitalize on transferred skiers from other resorts. The adaptive dynamics reveal opportunity for some ski areas where the transfer of skier visits from more vulnerable competitors was concentrated. A decoupling of ski season length and skier visitation was found at 3–4 ski areas, where, despite average season length losses in the 2050s, visitation market share increased through the loss of competitors. Transfer of demand from more vulnerable to more climate resilient ski areas, and the capacity of those ski areas to accommodate this transferred demand and provide quality visitor experience, are crucial adaptations that needs to be better understood if the profitability and continued operation of many ski areas is to be accurately projected. The findings further indicate that assumptions in the literature [58,64–66], and the media that climate change shortened ski seasons will result in reduced skier visits is not likely to be accurate for all destinations.

Fourth, as a result of the increased transfer of skier visits to more climate resilient ski areas, more frequent and more intense crowding at these ski areas is a highly likely scenario, with a higher concentration of skiers in a shorter ski season at fewer open ski resorts. While seemingly counter intuitive in an era of accelerating climate change, an important recommendation from this study is that the more climate resilient ski areas in this regional market should invest in capacity (e.g., lifts, parking, transportation, hospitality and retail) to accommodate transferred demand, as these additional revenues will be essential to offset the financially damaging extreme warm seasons in the decades ahead. Other potential supply-side responses to crowding include price increases and limiting access to skier volumes that current capacities can handle, thereby limiting overtourism impacts at destinations. Collectively, these adaptation strategies raise important questions for ski operation management. Is it financially feasible to invest in higher infrastructure and service capacities if these capacities are used on fewer days due to shortening seasons (i.e., capacities are mainly needed for peak days when demand is exceptionally high)? How would price increases affect demand in the short term and influence the image of this sport and skiing culture (e.g., participation rate) in the long term? How might guests perceive access limits and how does that effect the trip planning behavior of skiers? Additional research with the ski industry and government tourism authorities is needed to further explore the effectiveness of these and other adaptation strategies to increase the sustainability of ski tourism in a warmer world.

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