Developing an Agent-Based Model (ABM) to Explore the Geographic Redistribution of Snowmobilers During a Record Warm Winter

by
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A thesis
presented to the University of Waterloo
in fulfillment of the
thesis requirement for the degree of
Master of Science
in
Geography

Waterloo, Ontario, Canada, 2025

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Author's Declaration

I hereby declare that I am the sole author of this thesis. This is a true copy of the thesis, including any required final revisions, as accepted by my examiners.

I understand that my thesis may be made electronically available to the public.

Abstract

Canada's snowmobile industry is the second largest market in the world, with Ontario generating over $3 billion in economic activity and supporting over 10,000 full time jobs. Inter-annual climate variability and record warm winters have underscored the vulnerability of the industry, which is predicated on natural snowfall and low temperatures to support over 100,000 riders across the 33,000 kilometers network of trails. However, critical regional and methodological gaps limit our understanding of the vulnerability of snowmobiling to both current conditions and projected climate change, with no available research that empirically explores the dynamic relationship between supply- and demand-side responses to marginal climatic conditions. The presented research develops an agent-based model (ABM) to simulate how trail availability influences the spatial redistribution of snowmobilers across Ontario. Using the record warm 2023/2024 winter season as a climate analogue, the ABM was informed by a geospatial analysis of trail network availability (i.e., supply-side vulnerability) and the results from an online survey of snowmobilers' (n=161) (i.e., demand-side vulnerability). Results from the geospatial analysis revealed significant trail closures across the province, with 14 districts having ≤5% trail availability in December followed by an early end to the season (≤1% of trails available in March). Survey findings revealed that 90.4% reducing riding frequency in response to trail closures, but strong willingness to travel (e.g., 61.5% travelled to alternative trails outside their preferred district due to closures, averaging 239.8km for day trips and 861.1km for overnight trips). The ABM simulated the movement of 1,000 snowmobiler agents across the 16 districts, resulting in significant redistribution patterns that underscore differential climate risks, such that some districts gained market share (e.g., Districts 1 and 3) while others incurred substantial losses (e.g., Districts 11 and 6). Collectively, the results suggest the future of snowmobiling in Ontario may involve substantial geographical shifts rather than outright market collapse, with important implications for tourism planning and rural economic development in a warming world.

Keywords: Climate Change, Snowmobiling, Agent-Based Modelling, Behavioural Responses

Acknowledgements

Land Acknowledgement

I acknowledge that the University of Waterloo, to which this thesis is affiliated, is located on the traditional territory of the Attawandaron (Neutral), Anishinaabeg and Haudenosaunee peoples. The University of Waterloo is situated on the Haldimand Tract, the land promised to the Six Nations that includes six miles on each side of the Grand River.

Personal Acknowledgements

I extend my deepest gratitude to my supervisor, Dr. Michelle Rutty, whose guidance and mentorship have been invaluable throughout this journey. Your belief in my abilities and consistent support have made this achievement possible, especially during life's most challenging moments.

I sincerely thank my committee members, Dr. Grant Gunn and Dr. Derek Robinson, for their insightful feedback and challenging questions that significantly strengthened this research.

To my family and friends, thank you for your unwavering encouragement during both the challenging and rewarding moments of this process.

Finally, I appreciate all participants and collaborators whose contributions were essential to the completion of this research.

Dedication

For Daniel.

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Chapter 1
Introduction

Canada's snowmobile industry is the second largest market in the world (followed by the United States) and is an important economic contributor to many rural communities. Canadian snowmobiling supports over 41,000 full-time jobs, and generated over $9.3 billion in 2019 through direct and indirect expenditures derived through snowmobile-related businesses (e.g., service stations, accommodations, food service, retail, insurance agencies, manufacturers) (CCSO, 2020). Ontario represents the second largest market in the country, with over 34,000 kilometers of signed and groomed trails that are organized into 16 operational districts. During the 2022/2023 season, there were over 155,000 registered permits issued to snowmobilers, with snowmobile-related economic activity generating over $2.5 billion in the province, in addition to $538 million in tax revenues, as well as directly supporting nearly 10,000 full-time jobs (OFSC, 2023). The Ontario Federation of Snowmobile Clubs (OFSC) is the volunteer-led, not-for-profit association responsible for the provincial network of trails, which has made clear that the economic impacts of snowmobiling are dependent on weather (e.g., OFSC, 2014, 2019, 2023) Predicated on natural snowfall and low temperatures, Ontario's trails network is highly vulnerable to warming conditions because snowmaking, snow farming, nor artificial surfaces, can be readily adopted across such vast terrain. Climate observations underscore shorter and more variable winter seasons (Environment and Climate Change Canada (ECCC), 2019a), reducing trail availability as evidenced by the 2022/2023 season whereby southern districts experienced merely 1-4 weeks of viable conditions (down from 12+ weeks) (OFSC, 2023).

Critical regional and methodological gaps persist that limit our understanding of the vulnerability of snowmobiling to current warming conditions and projected climate change. Primary among these gaps is the failure to couple supply- and demand-side systems (Gössling & Scott, 2024; Rutty et al., 2021), with the vast majority of winter-tourism studies focusing solely on operating risks (Rutty et al., 2024; Steiger et al., 2024). While researchers have modelled snow cover change across trail networks (e.g., in the US - Wobus et al., 2017) and explored how snowmobilers respond to warm winters (e.g., shifts in permit purchases in

Ontario - Rutty et al., 2023), an integrated assessment that explores the synchronous evolution of behavioural responses to changing trail availability is notably absent. While all major winter tourism markets have faced several record warm winters over the past two decades, researchers have not seized the opportunity to empirically explore the climatic sensitivity of both the tourism industry and tourists in response to poor snow conditions (Steiger et al., 2019).The record warm 2023/2024 winter season is a critical climate analogue (i.e., record climatic conditions representative of future normal conditions) that can shed needed insight into how future climate change could alter snowmobile demand patterns in response to changing trail conditions. The geographic redistribution of snowmobilers will be a decisive factor in both the vulnerability and long-term sustainability of the snowmobile industry, with direct implications for the rural communities reliant on the significant economic contributions provided by this winter tourism market.

1.1 Research aims and objectives

Snowmobiling is reliant on natural snowfall, with inter-annual climate variability and changing climate conditions already impacting Ontario's multi-billion-dollar snowmobile industry. The research addresses key limitations in the climate change and winter tourism literature, with no known study that empirically explores the impact of record warm conditions on the availability of snowmobiling trails, nor any known study that pairs supply- and demand-side snowmobile vulnerabilities together (Rutty et al., 2023). In turn, the aim of the presented research is to assess the differential climate risk of snowmobile tourism across Ontario's 16 districts via the following three objectives:

1. Assess the impact of the record warm 2023/2024 winter season on the availability of Ontario's trail network across all 16 districts (i.e., supply-side vulnerability);
2. Design and conduct a survey to examine the preferences and behavioural responses of snowmobilers under changing climatic conditions, including how they adjust their travel plans in response to trail closures and reduced trail availability (i.e., demand-side vulnerability);

3. Develop an agent-based model (ABM) to simulate how trail availability (i.e., objective 1) influences the spatial redistribution of snowmobilers across Ontario's districts (i.e., objective 2) to evaluate the synchronous evolution of demand- and supply-side vulnerabilities.

While the power and benefits of ABMs within a tourism context have been highlighted (e.g., Nicholls et al., 2017), their application remains very limited (Baktash et al., 2023; Scott et al., 2020). The findings from this thesis will provide decision support for local economic development (e.g., shift in snowmobile demand patterns will have consequent impacts on surrounding businesses and communities), and can also inform risk assessments in other major snowmobile markets, including the USA and Europe.

1.2 Structure of thesis

The thesis is structured into six chapters. After this introduction, Chapter 2 presents a literature review covering snowmobiling, the critical role of weather and climate in the sport, and the application of ABMs in tourism and recreation studies. Chapter 3 provides a detailed methodology, including the study area, survey design and primary data collection, and ABM development process. Chapter 4 presents the trail availability, snowmobiler behaviours, and spatial movement patterns during the record warm 2023/2024 winter season. Chapter 5 discusses the implications of these findings, evaluates the model's strengths and limitations, and suggests directions for future research. The thesis concludes with Chapter 6, offering practical recommendations for policy and practice in the snowmobiling industry.

Chapter 2
Literature Review

This chapter starts by introducing the snowmobile industry, including its economic significance, followed by how weather and climate affect snowmobiling, such as physical impacts on the trail network and in turn, how it influences riders' behaviour. Finally, the use of Agent-Based Modelling (ABM) in tourism and recreation studies will be discussed, providing insights into the complexity of tourism systems and the advantages and limitations of this approach.

2.1 Snowmobiling market

Snowmobiling is an important winter activity in many countries and has grown to be a significant economic driver in many regions around the world. Given the large tracts of land required for trail networks, most snowmobiling occurs in rural locations, supporting local industries and employment (e.g., retail, accommodation, restaurants, service stations) (ISMA, 2023; CCSO, 2020). Snowmobiling benefits go beyond economic impacts to also include socio-cultural significance, promoting community engagement and sense of belonging, along with family and intergenerational benefits (i.e., a family sport) through shared experiences (e.g., 95% of snowmobilers consider snowmobiling a family activity) (ISMA, 2023). There are also known health benefits to those who participate in the sport, including physical exercise, and enhanced well-being (e.g., stress reduction, improved mental health) (Pereira et al., 2021).

2.1.1 Global market

Snowmobiles are primarily used for recreational purposes, but they also serve an important role in patrolling, aiding police and search and rescue teams, and providing transportation in remote or snow-covered areas. In response, the industry offers snowmobiles that are comfortable, easy to use, prioritizing safety and better suspension systems to guarantee a good experience for the users (Cognitive Market Research, 2024). In 2023, the global snowmobile industry generated $39.3 billion in annual revenue, with over 124,000 sleds sold worldwide (ISMA, 2023). There are more than 3000 snowmobile clubs globally, which are

groups that collaborate with government organizations to manage trails (e.g., groom, develop, map), fundraise, organize events (local to international), monitor legislation, and participate in public hearings (ISMA, 2023). There are more than four million snowmobile riders worldwide, with most engaged in 'day-trips', though overnight trips are becoming more popular (ISMA, 2023).

The greatest share of the global market is in the United States (43%), followed by Canada (39%). While there is a snowmobile market in Europe (e.g., generated $4 billion in economic activity in 2023), most of the market belongs to Scandinavian countries (e.g., 22,964 registered sleds) (ISMA, 2023). The Russian snowmobile market was substantial, with sales ranging from 5,900 to 7,300 units annually between 2020 and 2022. Following Russia's invasion of Ukraine, trade embargoes reduced sales to zero in 2023, representing a complete loss of what was previously one of the largest snowmobile markets outside North America (GMI, 2024). This drop significantly impacted global sales, with sales outside North America decreasing by 11.3% largely due to the Russian market closure. Secondly, the Asia Pacific market reached 61,620 units in 2021, with China dominating the region and projected to reach $156.6 million by 2030 (Cognitive Market Research, 2024). The region shows steady growth with a 4.0% growth rate (2023-2030), with Japan and India showing particularly strong growth rates of 4.4% and 3.7% respectively. The total Asian market size ranges from approximately $235-275 million to $663 million in 2024 (GMI, 2024). Finally, the South American snowmobile market is valued at $151 million in 2024, with Brazil and Argentina as key markets (GMI, 2024). The region shows promising growth potential with a 7.9% growth rate projection through 2030, driven by sustainable tourism initiatives and infrastructure developments (Cognitive Market Research, 2024). The market is expected to reach $230 million by 2030, though it faces challenges including regulatory constraints and limited consumer awareness.

2.1.2 North American market

In North America, snowmobiling has established itself as an important player in the winter tourism market, with 1.27 million registered snowmobilers (ISMA 2023). Table 2.1 provides a summary of the North American market, compiling data gathered by both the CCSO (2020)

and ISMA (2023), with economic values recalculated to 2019 constant Canadian dollars for comparability. Overall, the larger US market has 25 state-level snowmobile associations, with the greatest share of registered sleds in Wisconsin (228,289), Minnesota (219,460), and Michigan (167,140). While limited, available data indicates that the total economic activity in the US ranges from $68.7 million in Alaska up to $2,100 million in New Hampshire, and up to1300 jobs in Wyoming. In Canada, there are 13 provincial and territorial snowmobiles associations, with Quebec and Ontario representing 63% of the total registered sleds in the country (236,973 and 155,000, respectively). Economic activity in Canada ranges from $44.2 million in Yukon to $ 2,500 million in Ontario, supporting between 161 to 7,026 jobs (in Prince Edward Island and Alberta, respectively).

Table 2.1 Economic impact of snowmobiling by province and state in North America.

Province / State	Registered snowmobiles[1]	Total Economic Activity[2] (CDN Millions)[3]	Total Jobs[2]
Canada	618,872	$7,616	36,729
Alberta	32,000	$1,073	7,026
British Columbia	43,000	$306	1,424
Manitoba	38,267	$332	895
New Brunswick	20,338	$105	1,176
Newfoundland &	36,500	$228	1,602
Northwest Territories	7,600	$239	2,569
Nova Scotia	9,680	$111	433
Nunavut	12,950	$347	3,722
Ontario	155,000	$2,500	6,436
Prince Edward Island	2,569	$31	161
Quebec	236,973	$1,900	6,572
Saskatchewan	23,180	$395	4,240
Yukon	815	$44	473
United States (US)	1,266,981	$26,000	63,271
Alaska	69,500	$68	N/A
California	17,200	N/A	N/A
Colorado	32,000	N/A	N/A
Idaho	44,000	N/A	N/A
Illinois	15,744	N/A	N/A
Indiana	9,987	N/A	N/A
Iowa	22,740	$189	1,101

Province / State	Registered snowmobiles[1]	Total Economic Activity[2] (CDN Millions)[3]	Total Jobs[2]
Maine	83,400	N/A	N/A
Massachusetts	13,400	$98	N/A
Michigan	167,140	N/A	N/A
Minnesota	219,460	$606	N/A
Montana	28,000	N/A	N/A
Nebraska	870	N/A	N/A
New Hampshire	42,700	$2,100	N/A
New York	95,823	N/A	N/A
North Dakota	11,356	N/A	N/A
Ohio	4,050	N/A	N/A
Oregon	11,380	N/A	N/A
Pennsylvania	35,900	$338	N/A
South Dakota	9,712	$199	N/A
Utah	23,327	$98	N/A
Vermont	21,500	$1,080	N/A
Washington	22,929	$173	N/A
Wisconsin	228,189	N/A	N/A
Wyoming	36,674	$260	1,300

Source: [1]ISMA (2023), [2]CCSO (2020), [3]Constant Dollars (2019)

2.2 Importance of weather and climate for snowmobiling

Snowmobiling is inherently dependent on natural snowfall and low temperatures, which not only determine the feasibility of the sport, but also significantly influences the quality of the experience for participants (Perry et al. 2018). Studies have identified snowpack depths of 15 to 50cm as the minimum required to sled. For example, Mcboyle et al. (2007) and Scott et al. (2008) used 15cm to 30cm as the minimum snow depth requirement for snowmobiling in Northeast United States, after consulting with different stakeholders (e.g., snowmobile clubs and associations, trail maintenance crews, tourism boards, chambers of commerce). In a press release, the US Forest Service (2013) stated that the minimum depth should be 30cm for over-snow vehicles to safely travel without damaging the vehicles or terrain below, which aligns with Tercek & Rodman (2016) who identified 20cm to 50cm as the minimum depth for snowmobiling in Yellowstone National Park. The lower snowpack depths (15-20cm) are considered the minimum for smooth terrain (e.g., across fields, lakes) and lighter grooming

equipment (e.g., snowmobile-pulled drags, ultra-light trail groomers, single-blade drags), whereas the higher snow depth (30-50cm) is required for mountainous locations and heavy grooming equipment (e.g., tracked grooming tractors, multi-blade drags, and snow tillers) (Snowgroomers, 2024).

In addition to snow depth, snow type is directly influenced by temperature, with warmer temperatures reducing the quality of the snowpack for riding. For example, higher temperatures result in heavy, wet, or slushy snow, which is both slower and more hazardous to ride on as trail conditions deteriorate (i.e., melt) and expose terrain features below (e.g., rocks, stumps). Consistently warm temperatures in early winter can also delay season openings, while early spring warmth can lead to premature season closures. Warm temperatures also reduce ice thickness, creating safety concerns with respect to trails that cross water (e.g., rivers, lakes), with inconsistent freeze/thaw resulting in hidden weak spots and pressure cracks (Borts-Kuperman, 2024). In turn, temperature trends are a decisive factor in determining the start and end of the snowmobile season. Although it is possible, but not recommended, for sleds to ride in suboptimal snow conditions (i.e., below minimum snowpack depths) (Polaris, 2020), thermal comfort also becomes problematic in temperatures above freezing, which subsequently reduces participation in the sport (Rutty & Andrey, 2014).

2.2.1 Observed climate

In Ontario, average winter temperature (1986-2005) is -14.2°C, which ranges from –23.2°C in Northern Ontario to -1.2°C in Southern Ontario (York University, 2020). The maximum average temperature during the winter season is -9.5 °C while the minimum average temperature is -17.5°C (York University, 2020). Depending on the provincial region (Figure 2.1), the average number of snow days varies from 22 to 101, with snow accumulation varying from 79 - 330cm (Table 2.2). However, observed climate change indicates the province is becoming warmer and wetter, with the greatest changes occurring in the winter months (December, January, February) (Climate Risk Institute, 2023) and in the northern regions of Ontario (ECCC 2022).

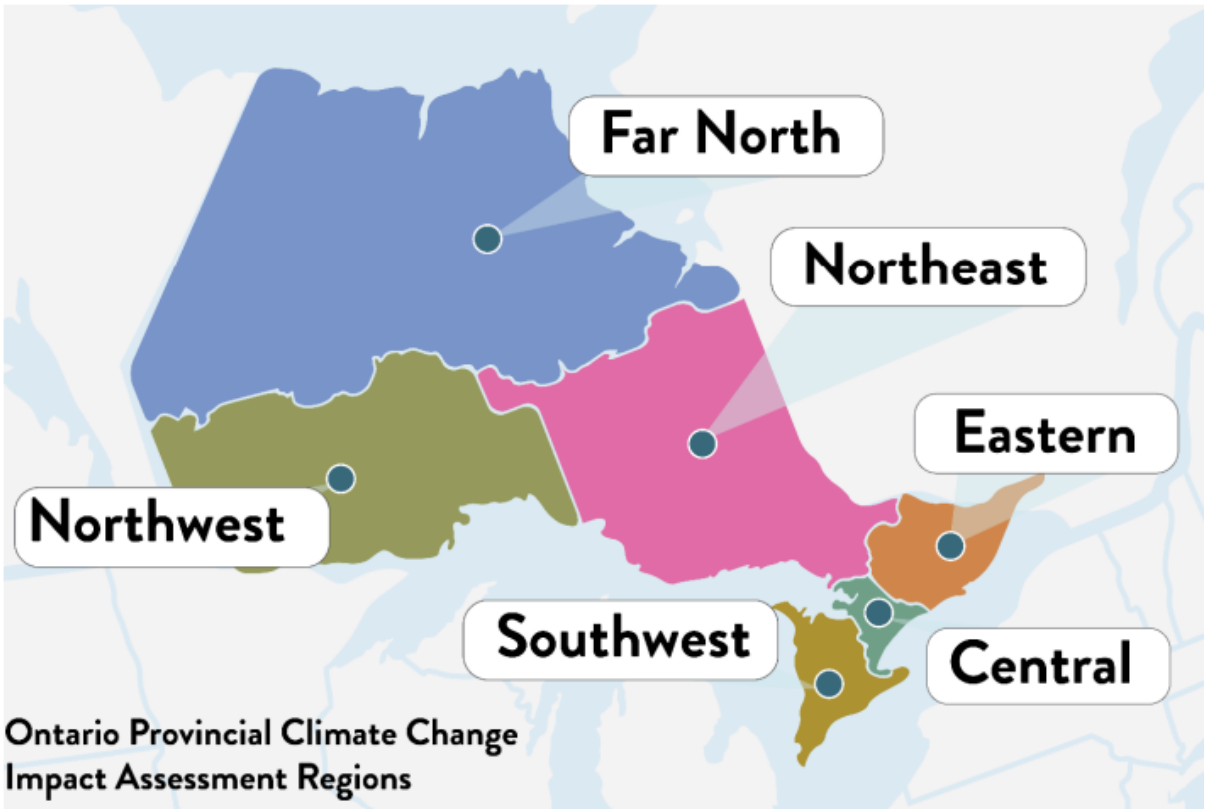


Figure 2.1 Ontario regions
Source: Ontario Ministry of the Environment, Conservation and Parks (2023)

Table 2.2 Ontario regional snowfall data

Region	Days of Snowfall	Snowfall Accumulation (cm)
Eastern	41-70	139-211
Central	24-58	98-282
Southwest	22-62	79-330
Northeast	65-101	226-320
Northwest	36-96	141-222

Source: York University (2020)

Globally, surface temperatures have increased significantly due to human activities that result in greenhouse gas (GHG) emissions, which has warmed the earth 1.1°C above pre-industrial levels as of 2011-2020 (IPCC, 2023). Most recently, 2024 was a record breaking

year, with global average temperatures reach 1.54°C (±0.13°C) above pre-industrial (WMO, 2024). Importantly, Canada has warmed at approximately double the rate of the global average, resulting in more extreme heat, less extreme cold, longer growing seasons, shorter snow and ice cover seasons, and rising sea levels (ECCC, 2019a; Natural Resources Canada, 2015). In Ontario, average temperatures have increased 1 to 1.5°C (from 1948 to 2012) (ECCC, 2022). Ice cover has significantly decreased across Ontario lakes, including Lakes Superior, Huron, St. Clair, and Erie, which have all experienced a -5% loss in ice coverage every ten years since the 1970s (Climate Risk Institute, 2023). Although total precipitation has increased during Ontario's winters (+5.2%) from 1948 to 2012, the balance between rain and snow is shifting, with rain becoming more common and snowfall decreasing in every region of the province (Climate Risk Institute, 2023). During the 2023/2024 winter season, average temperatures were the warmest on record for Ontario (and globally), at 5.4 °C above the baseline average for Central and Southern Ontario and at 6.3°C above the baseline average for Northern Ontario (ECCC, 2024).

The observed changes in Ontario's climate, including its consequent impact on snowmobiling, are evident in reports published by the Ontario Federation of Snowmobile Clubs (OFSC). For example, the economic contributions from the 2018/2019 season decreased by $65.6 million compared to the 2013/2014 season, which was directly attributed to a short winter season (down from 14 to 8 weeks). Relatedly, the 2022/2023 winter season had just 11 weeks of snowmobiling, with one district (District 5) experiencing just one week of sledding as precipitation fell mostly as rain or freezing rain (OFSC, 2023). In 2023/2024, Ontario experienced the warmest winter season on record (+5.4°C warmer than average), with media headlines replete with stories that the season was 'doomed' as many trails remained closed for the entirety of the winter season (Table 2.3). For example, in London (southern Ontario), snow conditions were so poor that grooming equipment remained unused throughout the season.

Table 2.3 Examples of media headlines of the snowmobiling season 2023/2024

Headline	Media Source	Date
Fickle Mother Nature not co-operating for winter sports enthusiasts in northeastern Ontario (Rutherford, 2023).	CBC (News)	12/28/2023
Algoma snowmobilers getting 'antsy' over lack of snow; Trailblazers president says local snowmobile season could be latest in recent memory (Darbyson, 2024).	Sault Star	1/6/2024
A winter without ice? Great Lakes' lack of ice cover will impact Waterloo Region and beyond (Waterloo Region Record, 2024)	Waterloo Region Record	1/9/2024
Late start to snowmobiling season in northern Ont. (Arangio, 2024).	CTV (News)	1/9/2024
Mild winter a disappointment for northeastern Ontario snowmobilers. (CBC News, 2024)	CBC (News)	2/12/2024
Everybody has just written off this winter': Snowmobilers talk no snow and its impacts (Toronto Star, 2024).	Toronto Star - Metroland Newspapers	2/14/2024
Not snow fast: Mild weather impacting Kemptville snowmobiling season (Szperling, 2024).	CTV (News)	2/17/2024
Warmer weather slams winter-based businesses 'This was the lost season,' senior climatologist says (Rubin, 2024).	The Toronto Star	2/23/2024
Outdoor activities in northeastern Ontario curtailed by wonky winter weather (Rutherford, 2024).	CBC (News)	2/29/2024
Snowmobile trails across Ontario remain closed due to lack of snow (Cruickshank, 2024).	The Cottage Life	3/26/2024

Snowmobilers were also active on social media channels, expressing discontent with the record warm conditions. Comments on Facebook had numerous complaints by active

snowmobilers who were upset they had purchased a permit but were not able to enjoy it. For example, when OFSC announced the availability of the permits for the season 2024-2025 on their Facebook page, one member commented "Nope not this year, I'll get a temp[orary] permit [and] that's about it. Just not worth it anymore with our weather conditions" (Facebook, 2024). On the same thread, another snowmobiler posted: "Hmm what about the ones we purchased last year and were unable to use due to conditions?" (Facebook, 2024). Snowmobilers are incentivized to buy their trail permits in advance of the season starting (e.g., early bird savings) to ensure associations and clubs receive funds to prepare the trails for the season. However, there is no mechanism for reimbursement to compensate for a shorter than average seasons, including seasons with little to no trail openings. Rutty et al. (2023) empirically notes the shift from season to daily passes, with the assumption that weather is the primary factor behind the shift in purchasing behaviour. The economic and operational implications are significant, yet not well studied.

2.2.2 Future climate projections

Global temperatures are projected to exceed 1.5°C in the early 2030s if emissions continue at their current pace, which is a critical threshold recognized by the science community as having significant and irreversible impacts on human systems and ecosystems (terrestrial, freshwater, coastal) if breached (IPCC, 2023). In Canada, the magnitude of future warming depends significantly on the emission scenario, with annual mean temperatures projected to increase by 1.5-2.3°C by mid-century (2031-2050) and up to 1.8-6.3°C by late-century (2081-2100) under a low- and high-emission scenario (RCP2.6 and RCP8.5), respectively. While overall precipitation is projected to increase, it is projected to increasingly fall as rain versus snow under these warming temperatures (Climate Atlas of Canada, 2019; ECCC, 2019a).

In Ontario, average winter temperatures are projected to increase between 2.5-4.3°C by mid-century (2031-2060) and 2.6-7.4°C by late-century (2081-2100) under a low- and high-emission scenario (Figure 2.2) (ECCC, 2019a), with precipitation increasing 28.8-35.9mm by mid-century and 27-52.4mm by late-century (York University, 2020).

Importantly, during the winter season there will be a general increase in rain-on-snow events, which will lead to faster snow melt and result in an overall decrease in projected snow cover (ECCC, 2019a). However mid-winter snow cover in northern Canada is expected to remain relatively stable due to cold temperatures, and the changes are comparatively small when measured as a percentage (ECCC, 2019b). The values for ice cover are generalized for the country rather than just the province, with ice cover projected to decrease by an average of 15 to 40 days by mid-century, as well as a decrease in ice thickness by 10-50cm, with variability dependent on snowfall and temperature changes, as well as context specific lake factors (e.g., surface area, depth) (ECCC, 2019b).

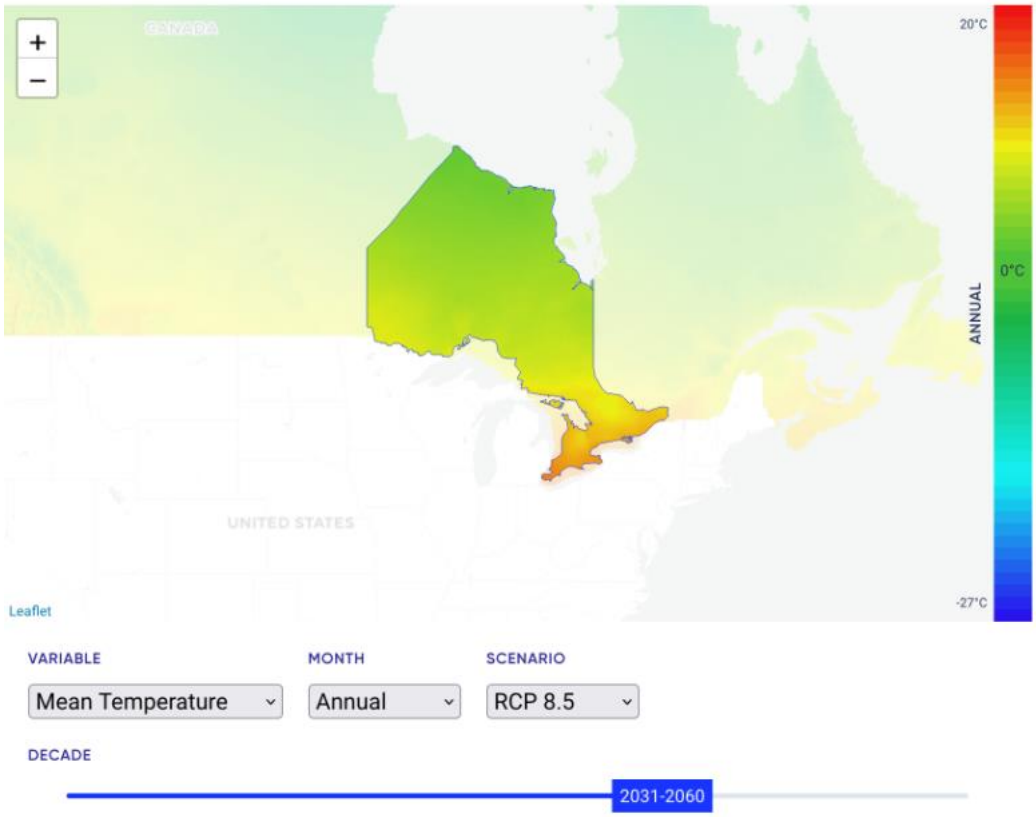


Figure 2.2 Projected mean annual temperatures from 2031-2060 in Ontario under a high-emission scenario (RCP8.5)

Source: ECCC (2022)

2.3 Snowmobile studies

The first study to explore the impacts of projected climate change on the snowmobile industry was Mcboyle et al. (2007), who used daily snow depth, temperature and precipitation data from 13 climate stations across four Canadian regions (Praries, Ontario, Quebec, East Coast) in conjunction with a low- and high- emissions scenario (B2 and A1, respectively). For Ontario, the study projected an 11-44% decrease in season length by the 2020s, with a climatically reliable snowmobile season (i.e., minimum of 30 days) eliminated by the 2050s under the high emissions scenario. The study also underscored that not all regions of Ontario would be impacted homogenously, with southern Ontario projected to experiencing a significantly shorter season compared to northern latitudes (e.g., under a low emission scenario, northern Ontario's winter season would shrink by 25% in 2020 and 32% by 2050, while southern Ontario would reduce by - 44% in 2020 and 56% by 2050). In a follow up study, Scott et al. (2008) explored the US Northeast, projecting that under a high emission scenario, up to 6 of the 15 snowmobile regions would lose over half their current snowmobile season by mid-century, with the season virtually eliminated by late-century. In a more recent study, Wobus et al. (2017) examined 247 winter recreation destinations across the US using a water and energy balance model to simulate snow accumulation under a medium- and high-emissions scenario (RCP4.5 and 8.5, respectively). The results indicated that season length would decline in almost all the locations studied, with the most significant reductions occurring in lower elevation locations such as the upper Midwest and the Northeast (e.g., by 2050s season losses of >80% under an RCP4.5 scenario and >90% for RCP8.5). Moreover, the study estimates that the shortened snowmobile season in the US could amount to economic losses of over $1.4 million by mid-century and over $5.4 million by late-century as snowmobiler visits decline.

A critical limitation to existing modeling studies is that season length is the only determining factor when assessing climate change risk for snowmobiling. As noted by Rutty et al. (2023), snowmobile networks are more nuanced than what is projected by supply-side studies, which fail to capture current operating realities, including seasonal variability (i.e., mid-season interruptions), as well as partial network capacity (i.e., some trails are open

longer within a singular district or network, such as those that traverse through forest versus transecting rivers and lakes). To more accurately assess climate risk, it is imperative to simultaneously explore snowmobiler response(s) to marginal conditions (past, current, projected) since climate alone will not determine the viability of the sport (Rutty et al., 2021).

Despite the economic importance of snowmobiling and bleak future projections, there are only two studies that empirically explore how snowmobilers have, or will, respond to changing climatic conditions. First, an online survey (n=1450) distributed to the members of the Vermont Association of Snow Travelers (Perry et al., 2018; Xiao et al., 2020), which is an organization that grooms more than 8000 kilometres of trails in the state. The survey revealed that more than one-third of respondents have noticed a decline in season length, more variable snow coverage, an increase in winter temperatures, and a decrease in snow depth (Xiao et al., 2020), with the majority (>62%) decreasing their sledding in response (Perry et al., 2018). The sensitivity of riders to poor snow conditions differed between local and non-local snowmobilers, with the latter more likely to decrease their participation in response to a shortened season (Xiao et al., 2020). Key factors that influence snowmobilers' participation included trail connectivity, with trail fragmentation reducing participation by 12-17 days, followed by trail availability (e.g., 62% of the trails need to be open to be deemed acceptable for snowmobiling).

Second, Rutty et al. (2023) used a temporal analogue approach to explore how the Ontario snowmobile industry has responded in the past to record warm winters that are representative of a mid-century (2046-2060) medium- and high- emissions scenario (RCP4.5 and 8.5, respectively). Under the medium-scenario, grooming hours increased (+8%) as the industry sought to maintain the trail network despite climatic disruptions (e.g., rain, freezing rain, snowmelt), whereas the high-emissions scenario reveals a marked decrease in grooming hours (-28%) as temperatures sit well above freezing and trails become inoperable. The results also reveal that although seasonal permits declined in both scenarios (-1% and -8%, respectively), there are important temporal and spatial differences that demonstrate the resiliency of the market. Most notably, several districts in Ontario experienced an increase in permit sales (i.e., market gain), as snowmobilers opted to travel to northern districts and

shifted their purchasing behaviour from seasonal to daily permits. In turn, the results underscore the importance of exploring the demand-side sensitivity to climate, as even under conditions indicative of a mid-century, high-emissions scenario, the industry was not 'eliminated,' as suggested by modeling studies (e.g., Mcboyle et al 2007, Scott et al. 2008, Wobus et al. 2017). Instead, snowmobilers are adapting their behaviour in response to changing trail networks, resulting in a redistribution of riders across the network.

On the whole, research that explores how tourists behave in response to climatic variability and change continues to lag behind supply-side modeling approaches (Peeters et al., 2024; Rutty et al., 2021). Given that neither snowmobilers nor the industry responds to climatic changes in isolation, a systems-based approach is an important next step to assess the synchronous evolution of supply- and demand-side changes. Specifically, an integrated assessment is needed that couples changes in the snowmobile network (e.g., trail availability, season length), with associated shifts in demand (i.e., how snowmobilers will change their participation habits due to marginal snow conditions and trail network closures) if we are to assess climate risk at a regional (e.g., Ontario) and individual destination (e.g., districts) scale (Rutty et al., 2023).

2.4 Agent-Based Modeling (ABM) in tourism and recreation studies

As one of the fastest and largest sectors in the world, tourism is an economic behemoth, with business volume equaling or even surpassing that of oil exports, food products, and automobiles (UNWTO, 2024). The global spread of tourism both requires and contributes to many related sectors (e.g., transportation, accommodations, telecommunication, agriculture, construction), as well as influences environmental and socio-cultural elements (e.g., natural resources, international relationships, policy, community structure) at every geographic scale (international to local). Tourism is therefore exceptionally challenging to analyze (Baggio & Baggio, 2020), with the sector often defined as a complex system due to the number of components (i.e., subsectors) that interact with each other in a dynamic and non-linear way (Sainaghi & Baggio, 2017). Tourism destinations also have a diverse range of agents (e.g., businesses, entertainment facilities, government, NGOs, non-profits, tourists, local

communities) that also interact in dynamic and non-linear ways (Baggio & Baggio, 2020; Baggio, 2008; Baktash et al., 2023). Despite the complexity of the tourism sector and the ways in which the components interact, many researchers continue to rely on conventional research methods to empirically explore the relationships within the system (e.g., statistical analysis of survey data), which can fail to capture the dynamic and interconnected nature of the sector (Baggio & Chiappa, 2017).

Founded in 1984 at the Santa Fe Institute (SFI), ABMs were developed at the intersection of complexity science and computational innovation, representing an interdisciplinary research method to address complex systems through modeling and simulation (i.e., a tool to represent decentralized, interacting entities within adaptive systems) (Waldrop, 1992). In ABMs, an "agent" is a computational entity that follows rules and interacts with other agents and its environment, which can represent individuals, organizations, or collective units. The framework emphasizes a bottom-up approach for emergent behaviour, evident as global patterns arising from local interactions (Anderson, 1972; Holland, 1975; Wolfram, 1983). In turn, the intellectual roots of ABMs are grounded in evolving theories of emergence and adaptation that collectively established ABMs as a methodology uniquely suited for studying systems composed of heterogeneous, interdependent actors. Schelling's (1971) early model of residential segregation illustrated how simple individual preferences could produce large-scale social patterns, demonstrating the power of ABM to link micro-level behaviour to macro-level outcomes. Other notable precedents for ABMs included Anderson's (1972) assertion that "more is different" emphasized how collective phenomena cannot be reduced to individual components, followed by Holland's (1975) concept of complex adaptive systems, whereby agents evolve through interaction. May's (1976) mathematical modeling demonstrated that simple deterministic systems could produce "very complicated dynamics," influencing how ABM practitioners conceptualize system complexity and unpredictability. Wolfram (1983) revealed that simple rule-based systems like cellular automata could generate complex behaviour, with Axelrod's (1984) computational tournaments, and subsequent work on cooperation, demonstrating that simple rules governing individual behaviour could generate sophisticated

social phenomena. Holland and Miller (1991) extended this work through their study of Artificial Adaptive Agents, connecting economic behaviour with adaptive processes in complex systems.

More recently, ABMs have been increasingly applied across social sciences as a means of exploring the interplay between individual decision-making and systemic dynamics (Zhang & Levinson, 2004; Amelung et al., 2016). Within tourism and recreation studies, ABMs offer a powerful approach for simulating visitor flows, land-use conflicts, and the spatial-temporal evolution of destinations. By modeling agent interactions based on explicit rules, ABMs generate data that can be analyzed inductively to identify emergent patterns and test theoretical propositions (Axelrod, 1997; Baggio & Baggio, 2020). ABMs are therefore not only a theoretical tool, but also a practical method for exploring and addressing real-world questions and challenges in dynamic, adaptive systems such as tourism.

For tourism, ABMs have proven particularly valuable for studying interdependent behaviour and feedback effects, whereby individuals' actions are contingent on others' past, present, and predicted future behaviours (Bruch & Atwell, 2015). The strength of ABMs therefore lies in its ability to represent feedback between micro and macro levels of analysis, where individuals both respond to and shape their social and natural environment over time. In turn, ABMs can enable researchers to understand tourism processes by modeling and representing the dynamic relationships between stakeholders in addition to measuring final outcomes (Johnson & Sieber, 2011). For example, ABMs can advance our understanding of how different stakeholders (e.g., tourists, local communities, tourism ministries, regulatory agencies, tourism businesses) make decisions in response to external factors (e.g., weather conditions, provincial regulations, gas prices) and internal factors (e.g., operational costs, grooming hours, riders experience levels), as well as how those agents' decisions affect the overall environment (e.g., market redistribution) (Baktash et al., 2023). ABMs also allow research to explore different scenarios without requiring real-world realization (Majic et al. 2023), such as how climate change might affect snowmobiling patterns through changing snow conditions, or how new trail development might redistribute rider traffic across a region.

Additionally, ABMs can integrate geographic information systems (GIS) to improve both the visual presentation and analysis of spatial data and processes, such as how snowmobilers interact with and move through the physical trail network. Specifically, GIS allows for the creation of detailed maps with accumulative information, which supports advance terrain analysis and accurate distance calculations (Ding et al., 2022; Pagou et al., 2023). For example, Man et al. (2020) used a GIS-based ABM to explore tourists' spatiotemporal patterns in Taiwan, demonstrating the significant impact that future light rail transit development could have on the city. In a snowmobile context, a GIS-enabled ABM can enable specific trail segments to be included (e.g., starting and ending location of the rider), along with realistic simulations of riders' movements, including interactions with their specific environment (e.g., how riders choose routes based on trail availability and preferred riding distance). ABMs can therefore simulate visitor flows to aid in tourism planning (e.g., service station and grooming requirements, trail expansion or closure) (Wallinger et al., 2023), but also support impact assessments through an analysis of the decision-making process and consequent destination(s) selected by riders (e.g., economic spending, capacity limits) (Pagou et al., 2023).

In a systematic review, Baktash et al. (2023) identified 31 peer-reviewed tourism articles that have employed an ABM (48% of which were published in 2019 and 2020), which were categorized as tourism management (n=17), tourism planning (n=9) and tourism development (n=5). Importantly, the authors highlight the value of ABMs to advance sustainable tourism, including climate change impact assessments, as well as to better understanding tourists' destination choices (i.e., decision making processes). The first tourism-ABM studies focused on the impacts of climate change on ski tourism in the European Alps, developing interactive multi-agent scenarios at a national level to simulate various temperature and snowfall conditions, season length, daily skier visits, snowmaking requirements, operating costs, tourist profiles, and adaptation strategies (Balbi et al., 2013; Pons-Pons et al., 2012; Soboll & Dingeldey, 2012; Soboll & Schmude, 2011). Recent updates have broadened the geographic scope, including a study in Canada (Scott et al., 2020), as well as a multi-nation study in Europe (Prettenthaler et al., 2022). Collectively, the

research indicates that ski tourism will shift to larger and higher elevation resorts (i.e., market 'winners'), with increasing snowmaking requirements (including associated resources – energy, water, infrastructure investments) to remain competitive in a more variable winter season and meet the diverse needs of skiers.

In terms of tourist decision-making, Boavida-Portugal et al. (2017) presents a theoretical ABM as a proof of concept, exploring how individual factors influence the destination selection process across five coastal towns in Alentejo (Portugal). Factors included travel preferences, past experiences, awareness, emotions, satisfaction, and social networks. Alvarez and Brida (2019) developed a dynamic model to understand how tourists' personal characteristics (e.g., location, amount of information they have, preferences), inertia (i.e., bias to repeat the same destination) and crowding types (i.e., set of observable characteristics of a tourist that affect the welfare of the other tourists) affect destination choice, including how the destination itself changes over time in response to tourists' choices. The emergent patterns reveal that market concentration is influenced by individual characteristics and decision rules, which can lead to the disappearance of some destinations (e.g., as welfare decreases in response to crowding). Most recently, Zhang et al. (2021) integrated multiple theories of travel decision-making with user-generated content (UGC) distribution to examine how individual tourists' UGC shape tourist flows through online platforms (e.g., travel review and social networking sites). The results provide destination marketing organizations (DMOs) with insights into favorable UGC distribution strategies and offers a prototype for cost-effective UGC assessments.

Despite the potential of ABMs to explore and analyze the tourism system, their adoption remains limited, which is primarily due to the technical complexity of executing an effective ABM (Johnson et al., 2017). Not only is there a lack of standardized methods, but the absence of empirical data to validate and calibrate the models is an ongoing challenge (An et al., 2021), particularly in a tourism context given the proprietary nature of the industry (Rutty et al., 2021; Scott et al., 2020). In turn, tourism scholars are often forced to rely more on assumptions and abstractions when building the models (Nicholls et al., 2017). Furthermore, the complexity of real-world tourism systems needs simplification, with

representations of stakeholders and their relationships typically reduced to only the most essential elements needed to address specific research questions or study objectives (Fan et al., 2019).

ABMs also require interdisciplinary knowledge to blend tourism with complexity science, statistics, and programming (Pons-Pons et al., 2012). Balancing technical programmers' details with conceptual information from the tourism literature requires disciplines to work in tandem (i.e., integrated as a foundational aspect of the research process rather than an afterthought) (Johnson et al., 2017). Working across social and natural sciences can lead to communication challenges, with model descriptions and outputs inherently complex, yet requiring results to be presented in a concise and straightforward manner. Some information may in turn be lost or lead tourism readers to feel overwhelmed with the technical method and subsequent outputs (Boavida-Portugal et al., 2017).

As ABM research continues to expand, both within and outside of tourism, the debate around their predictive capabilities has also grown, with three notable positions: (1) positive – ABMS can and should be used for direct prediction given sufficient quality data, (2) pragmatic - there are challenges and limitations, but ABMs remain the best available tool for exploring possible futures, and (3) skeptical – although their predictive ability is questionable, ABMs are nevertheless valuable for explanation, description, theoretical exploration, and social learning (Elsenbroich & Polhill, 2023). This ongoing debate reflects the complexity of using computational models to understand and forecast social phenomena, while also highlighting the diverse ways in which ABMs can contribute to social science research.

Chapter 3
Methodology

The presented research adopts a multi-method approach to achieve each of the three interconnected research objectives that collectively seek to understand the synchronous evolution of both the supply-side vulnerabilities of trail infrastructure and demand-side behavioural adaptations of snowmobilers. First, to assess snowmobile trail network availability across Ontario, a colour-based trail classification using point sampling technique was used to quantify the impacts of the 2023/2024 warm winter season on Ontario's more than 30,000km snowmobile trail network across all 16 districts. The Ontario Federation of Snowmobile Clubs (OFSC), who are responsible for the management of the province's extensive trail network, publish daily interactive trail guides, that serve as a data source for the geospatial component of this study. Second, to assess snowmobilers' behavioural responses to trail network availability, primary data was collected through an online survey to understand how snowmobilers responded to the record-warm conditions, including their travel patterns, preferences, and adaptation strategies. Third, an Agent-Based Model (ABM) was developed to create a simulation that integrated the trail availability data with snowmobiler behavioural patterns in order to model the redistribution of riders across the provincial trail network under changing climatic conditions. The integration of methods allows for a novel examination of the relationship between climate change, trail availability, and snowmobiler behaviour, ultimately contributing to our understanding of climate adaptation strategies for winter recreation.

The following sections detail the study area, model input data, model development process, as well as the design concepts and details (ODD) protocol used in this study. The ODD is the standard structure to document and describe ABMs to allow for a better understanding on how the model works and ensures other researchers can more easily replicate the developed model (Grimm, 2020; Grimm et al., 2020). The chapter begins with a description of the study area and trail classification system, followed by an explanation of the primary survey data collection, and concludes with the development and validation of the ABM used to simulate snowmobiler behaviour under varying trail conditions.

3.1 Study area

Ontario is the second largest province in Canada, with an area of more than 1 million square kilometres, over 250,000 lakes, and a population of 13.5 million (Government of Ontario, 2024). It borders Quebec to the east, Hudson Bay and James Bay to the north, Manitoba to the west, and the St. Lawrence River and Great Lakes to the south. The OFSC is a non-profit, volunteer-driven organization that is responsible for the operation and maintenance of snowmobile trails in Ontario, serving as the organized voice for its 179 member clubs and 350 grassroot volunteers (OFSC, 2024). OFSC's Executive and Board of Governors are tasked with setting policy (e.g., health and safety), outlining best practices for recreational riding (e.g., to enhance experiences), develop long-term plans (e.g., network expansion, infrastructure investments, marketing), and managing operations and finances on behalf of their member organizations. OFSC is also tasked with issuing trail permits. As shown in Figure 3.1, Ontario is divided into 16 snowmobiling districts (numbered 1-15 and 17). With GPS data generated through grooming activity, the OFSC provides riders with real-time trail network availability (i.e., OFSC's Interactive Trail Guide) which can be accessed directly through OFSC's website (https://www.ofsc.on.ca/trail-maps/) or through their app (*Go Snowmobiling Ontario)*(OFSC, 2023). To legally access the trail network, permits must be purchased through OFSC, with seasonal permits sold for approximately $200 or multi-day passes for approximately $50. Over 100,000 permits are issued annually, with revenue generated by permit sales directly supporting the trail network (e.g., trail preparation, groomer acquisitions and operations, infrastructure replacement and maintenance) (OFSC, 2023).

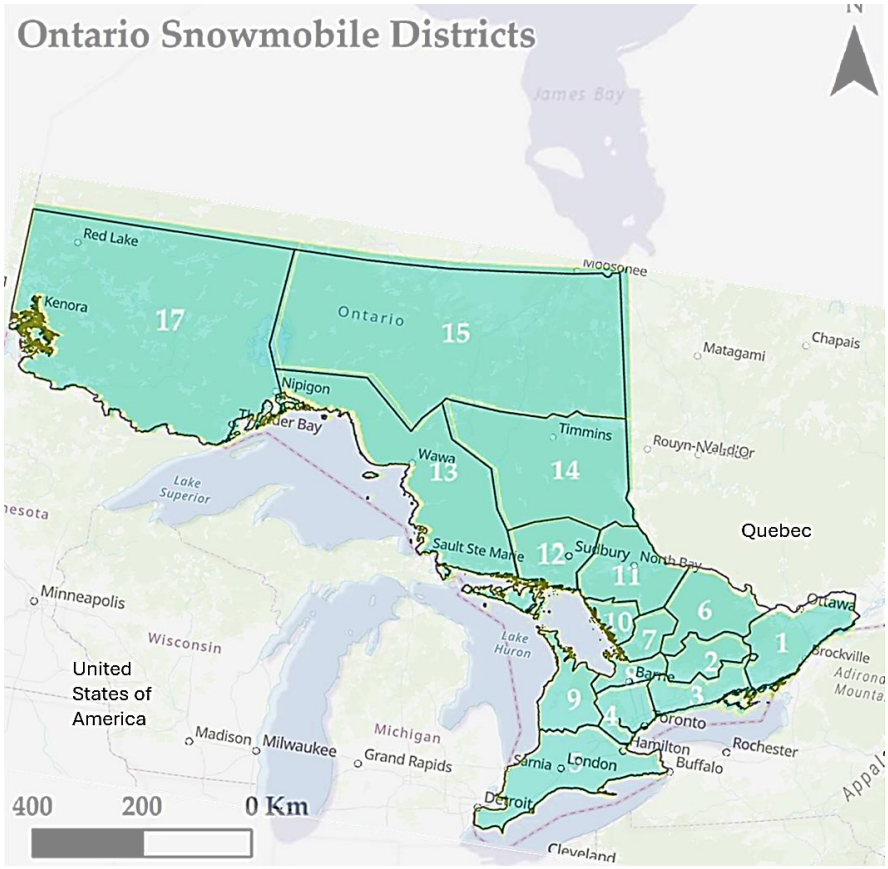


Figure 3.1 Ontario's 16 snowmobile districts
Source: Adapted from OFSC (2023)

3.1.1 Existing snowmobilers' demographic data

While the behavioural parameters and decision criteria in response to changing trail conditions are based on the primary data collected through the electronic survey (Section 3.3), the demographic foundation and initial market distribution are based on past district preferences informed by survey results published in the OFSC (2023) economic impact report. The OFSC survey is distributed via email to approximately 95,000 riders who have purchased a permit in Ontario, with a response rate of 7.57% (*n*=7196). According to the OFSC survey, the greatest share of Ontario snowmobilers resides in District 1 (Ottawa, Kingston; 15%) and District 5 (London, Kitchener, Brantford; 14%), followed by District 3 (Uxbridge, Bellville, Peterborough; 9%) (Table 3.1). The district where respondents primarily ride include District 1 (Ottawa, Kingston; 11%), District 6 (Haliburton, Pembroke;

10%), and District 2 (Bancroft, Bobcaygeon; 9%). An additional 74% of respondents identifying a second district they commonly ride in, with a further 55% selecting a third district they commonly ride in (Table 3.1). In turn, the initial market distribution for the ABM is based on the collective market share (i.e., accounting for primary, second and third riding districts), with District 6 representing the largest share of the Ontario snowmobile market (10.8%), followed by District 6 (10.2%), and District 2 (8.8%) (Figure 3.2).

Table 3.1 Snowmobilers place of residence and stated riding districts.

	Snowmobilers (*n*=4382)				
Districts	**Primary residence**	**Primarily ride**	**2nd Most likely to ride**	**3rd Most likely to ride**	**Riding preference (%)[a]**
1	644	493	148	113	7.58
2	252	397	285	191	8.78
3	405	180	134	105	4.21
4	368	104	103	95	3.04
5	606	138	101	86	3.27
6	238	449	422	206	10.83
7	210	379	271	198	8.53
8	295	256	137	96	4.92
9	346	335	148	115	6.01
10	145	288	248	185	7.25
11	178	350	372	295	10.23
12	279	299	220	162	6.85
13	115	153	78	83	3.16
14	140	214	286	252	7.56
15	58	207	226	190	6.26
17	103	108	23	22	1.54
Total	**4382**	**4,350**	**3,202**	**2,394**	**100**

[a] Total cumulative percentage for primary, secondary, and third most likely district to ride

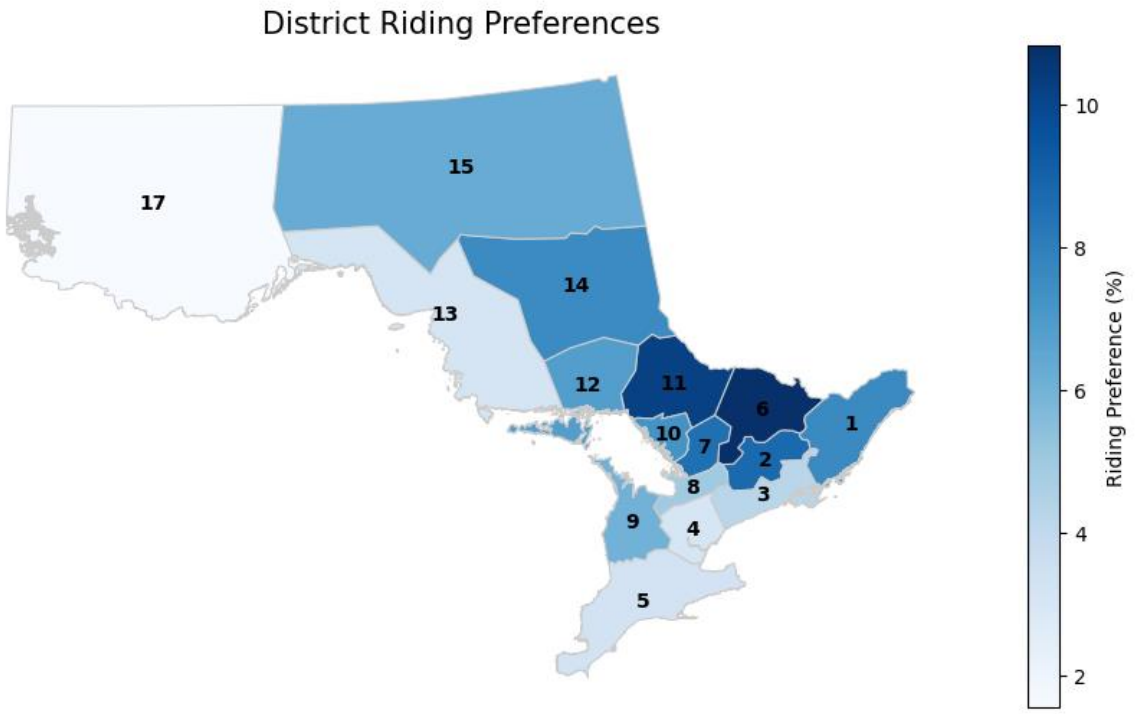


Figure 3.2 Distribution of Ontario snowmobilers by district
Source: OFSC (2023)

3.2 Classification of trial availability

To assess the impact of the record warm 2023/2024 season on the availability of Ontario's trail network across all 16 districts (i.e., supply-side vulnerability; Research Objective #1), weekly screenshots were taken of the OFSC's interactive trail guide between December 12th, 2023, and March 19th, 2024 (Table 3.2). The OFSC interactive travel guide provides notice of trail route accessibility, identifying trails based on one of three colour-coded statuses: (1) Available – Green ("route is accessible with the understanding that the trail will likely vary considerably in quality, attributes and terrain over its length"); (2) Limited Availability – Yellow ("route is limited with marginal riding opportunities, so snowmobilers enter with the understanding that they should ride with extreme care and reduced speed); (3) Unavailable – Red ("route is not available at this time, with access prohibited").

Table 3.2 Sampling dates for snowmobile trail status assessment (2023/2024 season)

Month	Day														
December	12	27	29												
January	8	11	12	16	24	25	27	31							
February	9	12	13	15	16	17	18	20	21	22	25	26	27	28	29
March	1	6	7	8	9	15	19								

To determine the percentage of the trail network that was classified as available, limited, or unavailable, throughout the 2023/2024 season, ArcGIS Pro[1] was used to process the screenshots. The following steps were taken to identify the number of nodes categorized by availability:

1. Georectification and clipping of snowmobile trail maps to individual districts
2. Compilation of trail data into separate geodatabases for each district
3. Creation of a shapefile containing both the trail network and district boundaries
4. Generation of points along trails at 100-meter intervals using the “Generate Points Along Lines” tool
5. Attachment of RGB[2] colour values from the raster data to each trail point using the “Multi Values to Point” tool
6. Categorization of points based on RGB values:
   – Available: $R < 150$ and $G > 160$ (Ranges for green)
   – Limited availability: $R > 150$, $G > 150$, and $B \leq 100$ (Ranges for yellow)
   – Unavailable: $R \geq 160$ and $G < 100$ (Ranges for red)

[1] ArcGIS Pro is a Geographic Information System (GIS) software developed by Esri. It is designed for professional spatial analysis, data management, and cartography. It offers advanced 2D and 3D mapping capabilities, integrates with other ArcGIS platforms, and supports various data formats, making it a versatile tool for complex geospatial projects and research.

[2] RGB (Red, Green, Blue) is an additive colour model used in digital imaging and display technologies. It represents colors by combining varying intensities of red, green, and blue light, which are the primary colors of light, where each colour can have a value between 0 and 255. This model is widely employed in electronic systems for capturing, displaying, and storing color information.

Trail status was assessed on 33 specific dates throughout the 2023/2024 winter season (Table 3.2), representing approximately 27% of the season, providing critical snapshots of trail conditions across Ontario's 16 districts. To generate a complete daily dataset for the entire season, an ARIMA (Autoregressive Integrated Moving Average) model that interpolated conditions between captured images was used. This approach synthesizes a continuous time series of trail availability that preserved the temporal patterns observed in the original imagery while simultaneously filling gaps between the observations. The resulting dataset provided daily trail status information for all districts throughout the winter season, enabling the ABM to simulate snowmobiler responses to changing conditions over the complete winter season timeframe (i.e., December 2023 to March 2024).

3.3 Primary data collection

An electronic close-ended survey questionnaire (see Appendix A) was developed for this research, which consisted of nine questions and 18 sub-questions to assess geospatial snowmobiling patterns in Ontario following the record warm 2023/2024 winter season. The survey incorporated a combination of multiple-choice and Likert scale questions, with several of them (i.e., 1-2, 7-9) adapted from the OFSC economic report (2023) to enable comparability with existing industry research. The survey was optimized for both mobile and desktop access to support in-person and ex-situ data collection. The survey was also made available in both official Canadian languages (English and French) to ensure broad accessibility. The survey received ethics clearance (REB #46258) through the Office of Research Ethics at the University of Waterloo in May 2024.

In-person data collection occurred at the two largest snowmobiling shows in Canada: (1) Toronto Snowmobile Show, held from October 25 to 27, 2024, and (2) Salon de la Motoneige et du Quad Québec, which took place from November 8 to 10, 2024. At both events, trained research assistants approached attendees to participate, with surveys completed by respondents directly on an iPad for immediate digital data entry. At the same time, the survey was launched online (from October 2024 to January 2025), which was facilitated through the support of 28 Ontario snowmobile districts and clubs who sent the

survey link to their members (e.g., listservs) and/or posted on their club Facebook page.[3] A total of 286 surveys were completed, which includes 190 in-person and 96 ex-situ responses, respectively. For the purposes of this research, only respondents who identified Ontario as their primary riding province were included in the analysis, resulting in 161 valid survey responses.

The survey began with question one by asking respondents to identify their primary snowmobiling location (Ontario, Quebec, or Other) and based on their selection, respondents were then asked to specify the top three districts they snowmobile most frequently in, if applicable (i.e., some respondents only ride in one district). Question two explored how riders accessed Ontario trails, whether directly from their property or by towing to trailheads. Those who rode from their property were asked for their postal code and whether they would consider towing if necessary (e.g., due to trail closures) and if so, a follow-up question asked the maximum distance they would be willing to tow their sled for a day trip. In question three, snowmobilers were asked about their riding behaviours in response to trail closures in the 2023/2024 season, indicating whether they rode less, the same amount, or more. Follow-up questions explored riding adaptation strategies, such as traveling to other trails or increasing frequency of riding once trails reopened. Question four asked at what percentage of trail closures would cause riders to stop sledding (i.e., exceeds their threshold of acceptability), while question five asked about the minimum season length needed to justify purchasing a pass. Question six examined the likelihood of riding under various conditions, including an inability to make loops and travel long distances (i.e., fragmented trail availability), closed water crossings, and limited accesses to services. Questions seven and eight focused on riding frequency (days per week) and timing preferences (weekdays, weekends, holidays). Question nine distinguished between day and multi-day trips, with follow-up questions about overnight trip frequency and duration.

[3] Districts (1,2,3,4,5,6,7,9,10,11,12,13,14,15,17), Kemptville Snowmobile Klub, Carleton Regional Snowmobile Club, Glengarry Snowmobile Club, Grenville Snowmobile Association, Nation Valley Snowmobile Association / NVS, Ellice Swampers Snowmobile Club, Athens & District Snowmobile Club, Carleton Regional Snowmobile Club, Glengarry Snowmobile Club, Kempville Snowmobile Klub, Nation Valley Snowmobile Association, Seaway Valley Snowmobile Association, L & A Ridge Runners.

3.4 ABM structure

Although data regarding snowmobilers' behavioural responses to climatic conditions is scant (Perry et al., 2018; Rutty et al., 2023), an ABM was chosen over traditional resampling statistical models (e.g., Monte Carlo, Bootstrapping). Unlike statistical approaches that typically require large datasets for validation, ABMs can produce meaningful results from smaller empirical samples through known causal relationships (Axtell, 2000; Epstein, 2008). As such, ABMs offer greater flexibility and adaptability when working with limited data (Bell et al., 2015). In this context, more agents can be added in the future (e.g., as datasets become available), while maintaining the ability to model heterogeneous agents with varying attributes (e.g., travel preferences and closure thresholds) that are representative of the diversity of snowmobiler preferences and responses to environmental changes. Relatedly, the complexity of the agents can increase (e.g., degree of rationality, ability to learn and evolve, rules of interactions), including an ability for various levels of agents to coexist within the model (e.g., single versus subgroups of snowmobilers or aggregate market trends) (Bonabeau, 2002). In turn, this research supports an incremental model development approach by identifying empirical data gaps that may have otherwise been overlooked in existing data sets that can be used as input in future model iterations (Epstein, 2008).

The ABM developed for this study was executed using NetLogo, an open-source platform for multi-agent environment modeling (Tisue and Wilensky, 2004). NetLogo was selected because it offers robust capabilities for spatial ABMs (Donkin et al., 2017; Macal, 2016), making it particularly suitable for simulating snowmobiler movement across geographic districts. The platform provides extensive support for GIS integration (Jaxa-Rozen et al., 2019), which was essential for incorporating the Ontario district boundary shapefiles and accurately representing the spatial context of snowmobiler decision-making. The spatial integration allows agents to navigate realistically within and between the snowmobiling districts, ensuring that travel distances and district selections accurately reflected real-world geographic constraints.

The conceptual framework of the model centres on three primary components: the snowmobiler agents, the trail network environment, and the decision processes that connect

them. Snowmobilers are represented as virtual agents with heterogeneous attributes, including home locations, travel preferences, and willingness to travel under different trail conditions. The environment consists of the 16 (OFSC) districts that include their associated trail networks and day-to-day operational status (i.e., available, limited availability, unavailable). The core processes in the model are: (1) daily activity decisions, including whether to ride based on day-of-week and weather conditions; (2) district selection based on distance, trail status, previous experience, social influence, and expected enjoyment; (3) social information sharing among snowmobilers; and (4) feedback mechanisms where positive riding experiences influence future decisions and renewal behaviour at the end of the winter season.

3.4.1 Model implementation and process flow

Overview of model structure

The model initializes with the creation of the snowmobilers based on the data loaded from a CSV file. Each snowmobiler is assigned a home district and positioned on a random patch within that district's GIS polygon. Individual attributes are assigned using empirically-derived information such as maximum travel distances and closure thresholds assigned probabilistically based on survey data. It is important to note that the agents in this model do not operate on a one to one basis with individual survey respondents. Instead, the model employs an aggregate approach whereby survey data is used to assign attributes across the agent population. Accordingly, while individual survey responses inform the statistical distributions used for agent parameterization, each agent represents a synthetic individual whose characteristics are drawn from the empirical distributions rather than directly replicating a specific survey respondent. The process allows the model to represent larger populations than the survey sample size while maintaining statistical fidelity to the observed data patterns, ensuring that agent behaviours are reflective of the overall population characteristics rather than being constrained to the exact responses of individual survey participants.

Social influence in this model represents the process by which agents modify their recreational behaviour and location preferences based on positive experiences shared by other agents within the population. The mechanism operates exclusively through positive influence transmission, meaning that only agents who have had successful or satisfying snowmobiling experiences become potential influencers. When an agent experiences a positive outcome, they randomly select other agents from the population to influence, and those agents designated as socially influenced may subsequently modify their behaviour, preferences, or decision-making patterns based on the positive experience shared with them. While agents begin with uncorrelated, independently assigned attributes, the social influence mechanism creates dynamic correlations that emerge during simulation runtime such that individuals initially have independent preferences but develop increasingly similar behaviours through social interaction over time.

At each time step, the model follows these sequential processes:

1. Reset daily status: Snowmobilers return to home locations, activity status reset
2. Reset district densities: Density counts for each district reset to zero
3. Activity decisions: Snowmobilers decide whether to ride based on day of week (i.e., weekday or weekend)
4. Destination selection: Active snowmobilers evaluate all districts and select the highest-scoring destination, incorporating social influence

    Snowmobilers select destinations by calculating a weighted score for each potential district. The scoring system combines practical factors (i.e., proximity, trail availability, and crowding) with social influences (i.e., recommendations and district popularity) and personal experience (i.e., if the rider rode the district before). Each factor is weighted differently, with trail openness (55%) the most influential, followed by distance (25%), and past experience (20%). Social influence accounts for 30% of the final decision, with home districts receiving a bonus. When snowmobilers are evaluating the districts to select their riding destination, the district where they live (i.e., home district) gets an

additional 20 points added to its score (i.e., the home district is more attractive, reflecting the convenience of riding close to home). The 20-point home district bonus represents an initial exploratory value based on empirical evidence (Xiao et al. 2020), indicating that proximity to home provides substantial utility beyond just reduced travel distance. The bonus represents approximately 20% of the maximum possible base score (which ranges 0-100 points), making it an important factor in destination selection that allows home districts to remain competitive when trail conditions are limited, but not overriding unavailable nor high density conditions. Ideally, preferred riding districts emerge organically over time through accumulated positive experiences. Agents ultimately choose the highest-scoring district that meets their minimum trail availability threshold, creating a balance between individual preferences and collective behavioural patterns.

5. Movement: Snowmobilers move to selected destinations if closure percentage is below their threshold
6. Density calculation: Calculate rider density for each district
7. Experience update: Calculate enjoyment based on density and update district experience
8. Update district popularity: Update the popularity of districts based on visitation
9. Spread recommendations: Snowmobilers with good experiences share with others
10. Update statistics: Update district counts and global statistics
11. End of season check: On day 122, determine permit renewal decisions

3.4.2 Design concepts

Basic Principles: Snowmobiler movement is based on both trail availability and rider preferences. The decision for whether or not (and where) a snowmobiler will ride is empirically defined by the stated preferences and thresholds identified in the primary survey data (i.e., Research Objective 2) and whether or not that stated district has trails available to snowmobile on (i.e., Research Objective 1). The model incorporates spatial constraints

through GIS data of OFSC districts. Snowmobilers make decisions based on several factors, including how far they are willing to travel, their tolerance for closed trails, previous experience in different districts, current trail density, and social influence (i.e., recommendations from other snowmobilers based on their experience can influence future district selections by others).

Assumptions: The model makes several key assumptions:

- Snowmobilers always start from their home district and return home after each outing
- Snowmobilers have different tolerance thresholds for trail closures
- Certain percentage of snowmobilers are influenced by social recommendations
- Weekend days have different participation rates than weekdays
- Positive experience with a district increases the likelihood of returning to it
- Successful outings contribute to season permit renewal decisions
- Trail density negatively impacts enjoyment beyond a certain threshold
- Travel distance is a limiting factor in district selection
- Social recommendations decay over time (10% per day)

Emergence: The sum of the individual choices made by each snowmobiler, which is influenced by trail availability (i.e., total market redistribution) and leads to visible patterns of total market redistribution. When trails are available, more snowmobilers are drawn to that district (i.e., market gain), while limited or unavailable trails lead to a decrease in the number of snowmobilers (i.e., market loss). Over time, these interactions create patterns in the distribution of snowmobilers, illustrating how district closures can result in larger-scale trends across the entire district network (i.e., Ontario). Individual choices can also lead to the formation of preference clusters (i.e., as snowmobilers develop positive experience with specific districts through repeated successful visits), self-reinforcing popularity cycles (i.e., where well-attended districts generate positive recommendations), exploratory density-driven redistribution patterns (i.e., as the model tests crowding effects on destination choice using initial threshold parameters), and overall permit renewal patterns based on accumulated successful outings. Note that this model focuses exclusively on positive experiences and positive social influence, such that negative experiences do not reduce district attractiveness

nor generate counter-recommendations, representing an initial exploration of optimistic recreational behaviour patterns.

Adaptation: Snowmobilers adapt their behaviour in several ways. First, they can adjust their individual destination choices based on previous experiences, represented through the district-experience table. They can also avoid overcrowded areas that previously resulted in lower enjoyment, respond to recommendations from other snowmobilers, as well as implicitly learn which districts provide better experiences through the experience points system.

Objectives: A snowmobiler's objective is to maximize their enjoyment by finding the most ideal or suitable places to ride, which is implemented through the calculate-district-score function. The function evaluates potential districts based on travel distance (i.e., shorter distances are preferred), trail openness (i.e., less closure percentage is preferred), previous experience with the district (i.e., higher experience adds bonus points), current trail density (i.e., overcrowded trails reduce score), and social recommendations (i.e., recommended districts get score boosts).

Prediction: The model incorporates implicit prediction in two ways. First, snowmobilers anticipate that the districts they have previously enjoyed will continue to provide good experiences. Second, snowmobilers predict recommended districts will be worth visiting.

Interaction: Social influence is incorporated into the model such that snowmobilers with enjoyable experiences will share their district recommendations directly with 5-14 random snowmobilers across the entire Ontario network, regardless of home district or geographic proximity. This approach reflects today's communication patterns whereby social media platforms, online forums, and digital snowmobiling communities enable riders to share experiences and recommendations with geographically dispersed networks rather than being limited to local, face-to-face interactions. Indirect interaction is incorporated through district density, which is calculated as the total number of active snowmobilers present in each district on a given day. When this district-level density exceeds a threshold value (i.e., set at 3.0 in the current implementation but adjustable as a model parameter), the enjoyment for all agents riding in that district begins to decline. The enjoyment reduction follows a linear

function that simulates how overcrowding within a district can diminish rider experience, creating an emergent negative feedback loop whereby high-density districts may face declining rider enjoyment (i.e., reduction of district experience ratings) and potentially lead snowmobilers to seek alternative districts that are less crowded. This density-based interaction creates an indirect, aggregate form of agent interaction at the district level without requiring direct agent-to-agent communication.

Stochasticity: Several aspects of the model are based on randomness to reflect the natural variation in individual preferences, capabilities, decisions, and network interactions. Initial assignment of closure thresholds follows a probabilistic distribution based on the primary survey responses (Section 4.2), with maximum travel distance assigned using a normal distribution (i.e., mean=240km, SD=100km). The daily decision to go snowmobiling uses different probabilities based on the primary survey results, with higher riding demand on the weekend versus weekdays (e.g., 80% probability on weekends compared to 65% on weekdays). Social influence status is randomly assigned to 70% of snowmobilers such that when snowmobilers share positive experiences, they influence a variable number of other riders (i.e., random 5-14). The multi-layered stochasticity ensures that model runs produce varied but realistic outcomes, preventing deterministic behaviour patterns while maintaining consistency with observed population-level trends. In turn, the randomness captures complex interactions between individual variability and emergent collective behaviour that characterize real systems.

Collectives: While not explicitly organized into formal collectives, emergent groupings form in two ways. First, district preference clusters as snowmobilers develop similar experience profiles. Second, social influence networks as recommendations spread.

Observation: The model collects data on daily counts of active snowmobilers per district, trail density by district (snowmobilers per kilometer), successful riding weeks for each snowmobiler, average enjoyment levels for active snowmobilers, district popularity metric, season-end statistics (e.g., renewal and non-renewal rates), and individual snowmobiler metrics (e.g., experience levels, travel patterns). Average enjoyment level is calculated as the mean enjoyment score across all active snowmobilers on a given day. Individual enjoyment

is determined on a 1-10 scale where agents experiencing district density below the threshold (currently 3.0 riders per kilometer) receive an enjoyment score of 10, while agents in districts exceeding this density threshold experience proportionally reduced enjoyment based on the degree of overcrowding. The average is calculated by summing all individual enjoyment scores for active riders and dividing by the total number of active snowmobilers, providing a system-wide measure of recreational satisfaction that reflects both participation levels and crowding effects across all districts.

3.4.3 Model parameterization

The model was parameterized using primary data (GIS analysis – Research Objective #1; survey results – Research Objective #2), secondary data (OFSC 2023, Xiao et al. 2020), and academic literature (Mauri & Minazzi, 2013; Dunbar et al., 1997; Dunbar & Spoors, 1995; Pham et al., 2015; Yoon & Uysal, 2005). First, individual agent characteristics were derived from the survey data, which includes maximum travel distance following a normal distribution (M = 240 km, SD = 100 km), closure thresholds (see Figure 4.3), activity patterns (participation probability of 80% on weekends and 65% on weekdays), and permit renewal probabilities (see Figure 4.4). Individual agents were initialized using OFSC district preference data (see Table 3.1).

In terms of environmental and operational parameters, the total length of snowmobile trails within each of the 16 district boundaries were calculated using geospatial trail network data from OFSC. Trail statuses are based on the GIS analysis and ARIMA model to calculate daily closure percentages for the 2023/2024 season (see Figure 4.1). A density threshold of 3.0 riders per kilometer represents the point at which enjoyment begins to decline, which was set as an exploratory parameter in the absence of empirical data. The 3.0 threshold implies that riders would encounter another snowmobiler approximately every 300-350 meters on average, representing a balance between social interaction opportunities and maintaining the perception of uncrowded recreational space. The threshold was selected based on the assumption that snowmobile trails, typically 2-4 meters wide, would begin to feel congested as riders would be required to slow down to allow one another to safely pass, impacting the

sense of wilderness and freedom that characterizes quality snowmobiling experiences (Perry et al., 2018; Xiao et al., 2020).

District popularity follows a daily decay rate of 10%, which is based on Pham et al. (2015), who developed a general graph-based recommendation model for event-based social networks to explore how recreational participants select activities and venues based on user data from Meetup.com in New York City and California (n=46,895 and n=59,989 respectively). The researchers found that participation in events significantly influenced future choices, with temporal decay patterns showing that users were more likely to attend events similar to those they recently experienced. The 10% decay rate represents a conservative adaptation of their temporal decay function, which identified that user preferences for activities diminished over time when not reinforced by new positive experiences.

The decision-making parameters use a scoring system that evaluates potential riding destinations based on five factors, which include distance, trail openness, experience, social influence, and home district. The weights assigned to each factor are based on Xiao et al.'s (2020) survey results. For example, trail conditions were consistently rated as the most important factor in destination selection (80.6% stating it "adds a great deal" to experience), followed by travel distance considerations (70.1% viewing long driving distances negatively). In turn, a district with fully open trails but requiring long travel might score similarly to a closer district with partially closed trails, reflecting the trade-offs snowmobilers make when planning trips. The distance factor weight (0.25) is based on the 70.1% of snowmobilers that view long driving distances negatively, while the trail openness weight (0.55) reflects that 80.6% prioritize trail conditions as adding "a great deal" to their experience. These weights ensure that distance remains a significant factor in destination selection while maintaining trail quality as the primary determinant, allowing the model to replicate the trade-offs snowmobilers make between proximity and trail conditions when planning trips.

Social network parameters

Due to limited research that empirically explores snowmobilers' behavioural and social influence patterns, the model parameters are drawn from studies in social network theory, consumer behaviour, and tourism satisfaction research. While these studies do not directly work with snowmobile populations, they provide an approximation for understanding recreational decision-making and social information transmission that can be applied to this context until snowmobile-specific data becomes available.

The influence susceptibility parameter is set at 70% of agents being influenced by positive peer recommendations, which draws on evidence from tourism and recreation studies with adjustment made for the demographic profile of snowmobilers. Specifically, Mauri and Minazzi (2013) conducted an experimental study with 349 young travelers in Italy, whereby 75% of respondents consult comments from other reviewers before booking, with purchase intentions increasing from 4.26 to 4.72 (on a 7-point scale) when exposed to predominantly positive reviews. Litvin et al. (2008) concluded that interpersonal influence is the most important information source when purchasing tourism products based on a literature review and conceptual model development of word-of-mouth communication, while a study conducted by the Travel Industry Association (TIA) (2004) found that 67% of US travelers used the Internet to search for travel information, based on telephone interviews with 1,300 randomly selected American adults conducted in July 2004. Moreover, in a study of online hotel booking intentions in Italy (*n=557),* Confente and Vigolo (2018) found that how travelers respond to word-of-mouth information differs by generation, such that the influence of electronic word-of-mouth is highest amongst Gen Y (19-35 years) at 66.5% susceptibility, followed by 46.5% for Gen X (36-56 years), and 16.6% for Baby Boomers (57-71 years), with traditional (offline) word-of-mouth influence more consistent and generally stronger across age groups (e.g., Gen Y at 54.5%, Gen X at 69.3%, Baby Boomers at 74.6%). Since snowmobilers typically have a demographic profile that skews toward older age groups (e.g., ISMA (2023) estimates the average snowmobiler to be 54 years old), the 70% represents an estimated proportion that accounts for the age distribution of typical snowmobilers and their differential responsiveness to various recommendation channels.

This parameter reflects the proportion of snowmobilers whose destination choices can be affected by social recommendations, with the remaining 30% making decisions based solely on personal experience and preferences.

The recommendation reach parameter, whereby 5-14 random agents receive positive experience information, is derived from social network research conducted on British populations, which collectively established that people typically maintain a sympathy group of 12-15 individuals and a closer support clique of 4-5 people with whom they actively share personal experiences and recommendations (Dunbar et al. 1997, Dunbar & Spoors 1995, Hill and Dunbar 2003). Similar network patterns have also been recorded in Western societies, including the US using the National Survey of Families and Households (Kim and McKenry 1998). Their findings showed that while sources of support differed (with ethnic minorities more likely to rely on children and Caucasians more likely to engage broader networks), the functional size of support networks (i.e. 5-6 people) remained relatively consistent across groups when controlling for socioeconomic status. The range of 5-14 agents receiving recommendations in the model represents this documented variability in social network sizes across Western populations, while accounting for the fact that not all network members may be reached in every information-sharing instance. This parameter captures how positive snowmobiling experiences might spread through similar social network patterns.

The parameter for the enjoyment threshold where recommendations are triggered when satisfaction exceeds 7/10 is supported by multiple research findings in tourism satisfaction studies. Perles-Ribes et al. (2020) used a 0.7 reliability threshold in their structural equation modeling of tourist satisfaction in Mediterranean destinations, demonstrating that indicators exceeding this threshold reliably represent tourist experience quality. This statistical approach aligns with Yoon & Uysal (2005), who examined destination loyalty amongst tourists in Northern Cyprus using structural equation modeling with survey data (n=148). Their study found that satisfaction levels above 70% on standardized scales directly led to positive word-of-mouth recommendations and repeat visitation. Specifically, they discovered that when tourists rated their experience quality above 7 on a 10-point scale, they were significantly more likely to actively recommend the

destination to others and return themselves. This threshold is further supported by Wang et al. (2017), who found that tourists with high satisfaction respond positively through greater intention to recommend the destination to others. Additionally, Antón et al. (2014) examined destination loyalty drivers and confirmed a strong relationship between satisfaction and recommendation behaviour, noting that tourists transition from passive satisfaction to active advocacy when reaching satisfaction levels above 7 on their 10-point scale. In the model, this translates to snowmobilers sharing positive trail experiences only when their satisfaction score exceeds 7/10, reflecting the natural tendency for people to recommend experiences only when they meet a high-quality standard.

Model population and scaling

The model simulated the movement of 1,000 snowmobiler agents across the 16 districts throughout the 2023/2024 winter season (i.e., December through March), tracking how riders redistributed themselves in response to changing trail availability. The number of 1000 agents were selected rather than the full population of approximately 155,000 Ontario snowmobilers. This sample size (representing 0.65% of the total population) exceeds the minimum required for statistical representativeness (i.e., 383). Using standard statistical sampling formula[4] for a population of 155,000, with a 95% confidence level and 5% margin of error, a minimum sample of 383 is sufficient for valid statistical inference (Cochran, 1977). The sample of 1000 agents therefore provides a statistically robust representation while maintaining computational efficiency. Computational efficiency testing showed that doubling the number of agents increased processing time by 25%, while behavioural patterns remained similar across different population sizes.

3.4.4 Decision-making framework and submodels

The final score for each district is a weighted combination of a base score (personal factors) and a social score (social influence). Specifically:

[4] Cochran's formula: $n = \frac{z\text{^}2xpx(1-p)}{e\text{^}2}$

- Final-score = (base-score * (1 - social-influence-weight)) + (social-score * social-influence-weight)

Where:

- Base score = (distance-factor * 0.25 + openness-factor * 0.55 + experience-bonus * 0.2 - density-penalty) * 100
- Social score is derived from district recommendations and popularity

Base score components:

Distance factor = (1 - (travel-distance / max-dist))

Openness factor = (open-percentage[5] / 100)²

Experience bonus = min(experience * 0.03, 0.3)

Density penalty = min(0.5, (current-density - density-threshold) / (density-threshold * 2)) if density > threshold, otherwise 0

Social score components: The model employs a default social influence weight of 0.3, meaning that the decision-making score is 30% based on social factors and 70% on personal considerations (Cho et al., 2011). The weight applies only to agents flagged as socially influenced, which is a separate parameter affecting 70% of the total snowmobiler population (i.e., determined during agent initialization). The remaining 30% of snowmobilers make decisions based entirely on personal factors without any social component. For those agents who are socially influenced, their decisions incorporate both personal considerations and social factors according to the 70/30 split. Agents only select destinations with scores above 20, and if no destinations meet this threshold, they remain inactive for that day. The social score is calculated such that:

- Recommendation boost: 50 points if the district is in the agent's influenced-districts list
- Popularity score: min(50, current-popularity * 2)

Enjoyment calculation: An adjustable model parameter that is calculated on a 1-10 scale. If district density is below a defined threshold (currently set at 3.0 riders per kilometer), enjoyment equals 10, but when density exceeds the defined threshold, enjoyment decreases proportionally to the degree of overcrowding.

[5] Percentage of trails that are open in a district (calculated as 100 minus the closure percentage).

Experience accumulation: After each ride, experience for the visited district is increased by enjoyment/10, capped at a maximum value of 10. The experience accumulated creates a feedback loop where positive experiences increase the likelihood of return visits. Under optimal conditions (enjoyment = 10), an agent would reach the maximum experience cap of 10 points after 10 successful visits to the same district, which could realistically occur within 1-2 seasons depending on riding frequency.

Social influence mechanism: The model incorporates social influence through (1) direct recommendations and (2) district popularity update. This dual approach to social influence reflects both direct, interpersonal information sharing and broader awareness of popular destinations. Specifically:

- District Recommendations are set so that snowmobilers with enjoyment > 7 share recommendations by (1) each recommender randomly selects 5-14 other socially influenced snowmobilers, (2) the district they visited is added to the influenced-districts list of these selected agents, and (3) each agent's influenced-districts list is capped at 5 entries (most recent recommendations).
- District Popularity Update is done daily, such that (1) existing popularity decays by 10%, and (2) the added count of active snowmobilers visiting the district today

Permit renewal decision: At the end of the winter season, renewal probability is based on the number of successful riding weeks the snowmobiler was able to complete.

Due to limited historical data on snowmobiler movement patterns across the Ontario trail system, a full empirical calibration of the model was not possible. The parameters were selected based on survey responses of snowmobilers in Vermont (n =1450, Xiao et al. 2020). Trail conditions (openness factor): "Consistent snow cover along the trail" has the highest positive rating with 80.6% saying it "adds a great deal," which strongly supports the decision to give openness factor the highest weight in the decision-making formula (i.e., 0.55). Distance considerations: "Having to drive to snowmobile trails" is viewed negatively by 70.1% of respondents, while "being able to begin your ride at home" is highly valued (78.0% state it "adds a great deal"), which supports the inclusion of distance as a factor. Social density factors: "Encountering other snowmobiles along the trail" has mixed impact, with

22.4% seeing it as a detractor and only 18.9% seeing it as positive, which aligns with the model's density penalties when trails become overcrowded. Trail connectivity: "Interconnectivity of trails for making loops and tours" is highly valued having 56.9% of respondents saying it "adds a great deal", which supports the squared relationship for openness - partially closed trail systems disproportionately reduce utility because they break connectivity.

3.4.5 Input data

- GIS shapefile for district boundaries.
- CSV file for daily district open/closed rates.
- CSV file for snowmobiler preferences.

3.5 Model verification and validation

The model underwent several verification procedures to ensure computational correctness:

1. Code reviews and unit testing of key functions
2. Consistency checks for agent attribute distributions
3. Boundary condition testing for extreme parameter values
4. Conservation of agent counts throughout simulation runs

3.5.1 Model execution

The ABM was developed using NetLogo, which simulates the movement of snowmobilers across 16 snowmobiling districts (Figure 3.3) based on a combination of snowmobilers' behaviour patterns and whether or not the trails within their stated preferred districts are available. The interface of the model depicts the GIS shapefiles with the OFSC district information, which are uploaded as part of the model setup (Figure 3.3). Additionally, monitors are included in the interface to allow the users to follow the changes (or evolution) of snowmobile demand in each district in response to trail availability (i.e., supply). The ABM code is provided in Appendix B.

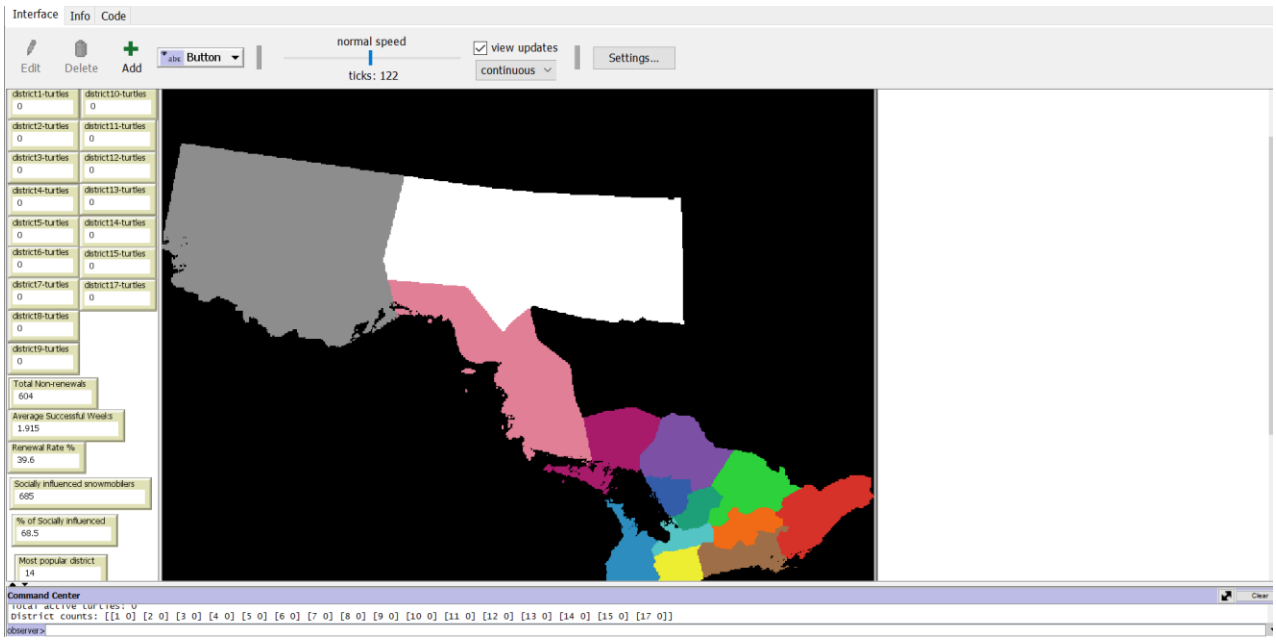


Figure 3.3 ABM user interface

3.5.2 Uncertainty analysis

An uncertainty analysis was performed to assess the number of simulation runs required to support reliable model results. With stochastic ABMs, increasing the number of runs helps capture the range of possible outcomes due to random elements. According to the Central Limit Theorem, larger sample sizes provide better approximations to true parameter values (De Veaux et al., 2021). Therefore, the objective of this analysis was to determine the optimal number of runs needed to adequately characterize the variability in snowmobiler numbers across districts under different trail closure scenarios. The model's stochasticity is not cumulative by day because agents and their decisions are recreated at each tick (day). Instead, the analysis was conducted using the parameter values described in Section 3.4.4.

Initially, District 1 was examined in detail because it consistently exhibits the highest average number of snowmobilers across the entire 122-day season. Figure 3.4 shows the mean snowmobiler counts for District 1 after 10, 30, and 50 runs.

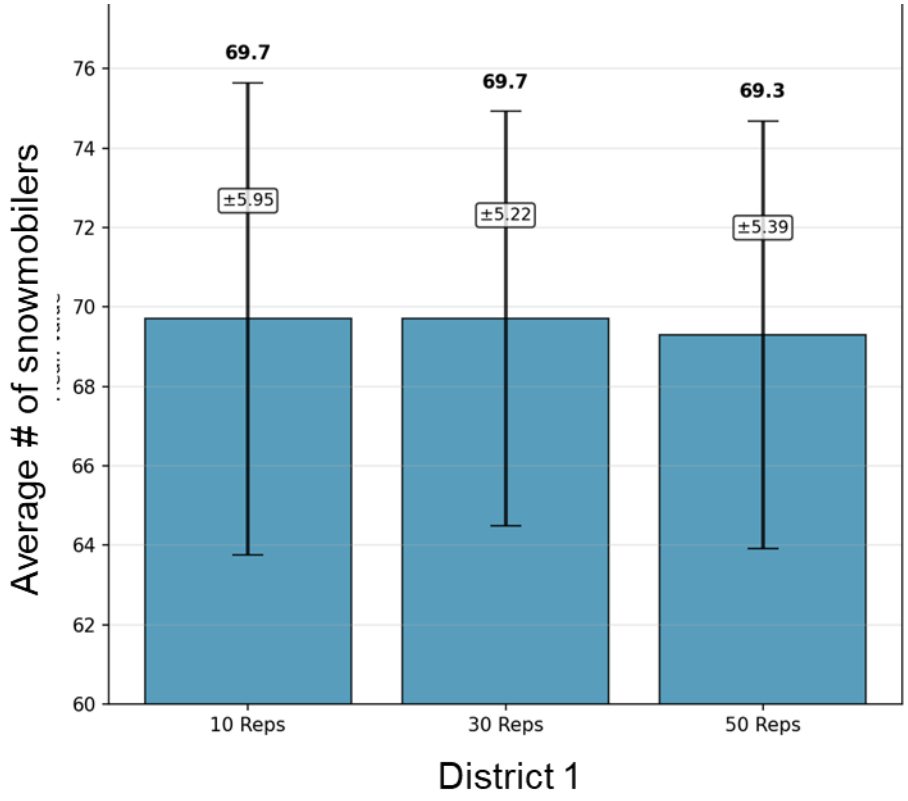


Figure 3.4 District 1 Mean value comparison after 10, 30 and 50 runs

The mean number of snowmobilers for District 1 across 10, 30, and 50 repetitions remain consistent (69.7, 69.7, and 69.3, respectively), while the standard deviations show a decreasing trend (5.95, 5.22, and 5.39), suggesting improved characterization of variability with more runs. To understand this pattern across all regions, Figure 3.5 shows the standard deviations for all 16 districts at different run counts.

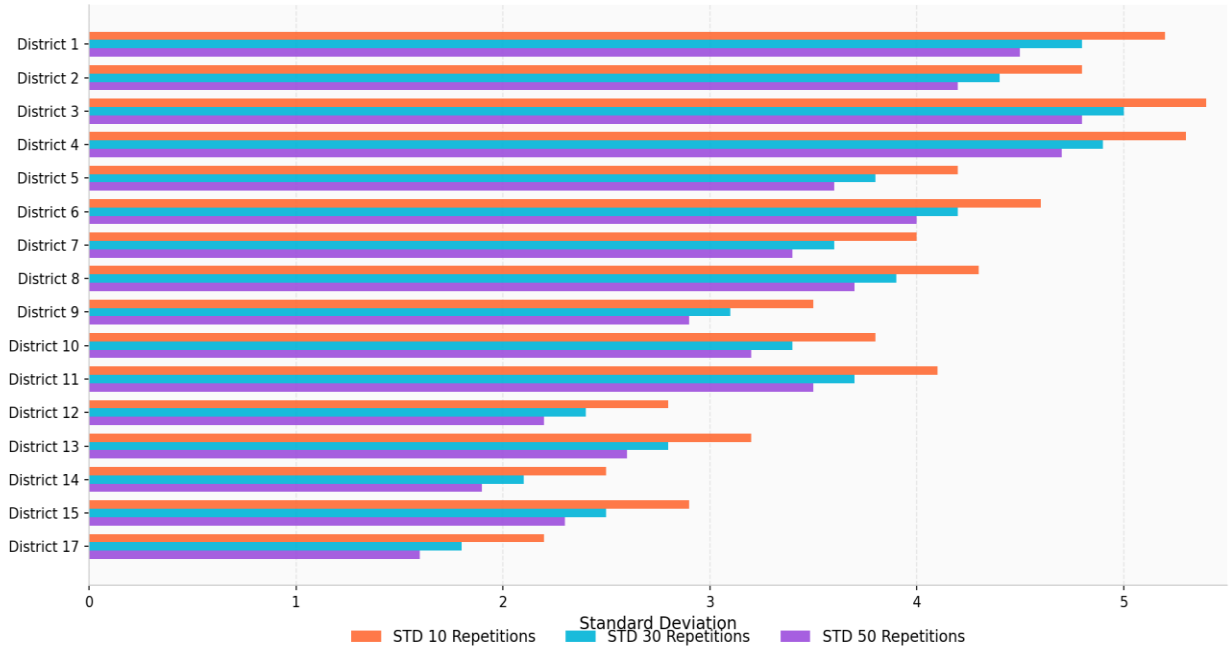


Figure 3.5 Standard deviation comparison per district

Most districts show decreasing standard deviations as the number of runs increases, indicating improved model stability with larger sample sizes. Districts 13, 14, and 15 consistently exhibit lower standard deviations across all run counts, suggesting more predictable snowmobiler patterns in these areas regardless of stochastic model elements.

While Zhang and Robinson (2021) in their paper found that 100+ model runs were needed to capture the variability produced by the model they were replicating, the model's computational complexity made this impractical within the available research timeframe. Each model run requires approximately 10 hours to simulate one season, with a complete season simulation involving over 122,000 agent decisions per run. Given these limitations, 30 runs were conducted to balance statistical reliability with resource constraints. The comparison of results between 10, 30, and 50 runs showed diminishing improvements in variance reduction, suggesting that 30 runs captured the essential patterns of model behaviour while remaining computationally feasible. Future research with access to greater computational resources could expand this analysis to determine if additional insights emerge

with larger run counts, though our sensitivity analysis indicates that the primary findings regarding district redistribution patterns would likely remain stable.

3.6 Comparative analysis of stated versus simulated preferences

To evaluate whether and how trail closures may reshape snowmobile patterns in Ontario, the model's simulated rider distribution was compared with OFSC survey preference data. In other words, the difference between where snowmobilers stated they would prefer to ride (based on survey data) and where they actually ride when constrained by trail availability (based on model simulations). This was done because existing climate change impact studies have mainly focused on supply-side factors like season length while overlooking the ways in which snowmobilers change their behaviour in response to changing trail conditions (Rutty et al. 2023). As noted by Rutty et al. (2024), research that explores how tourists behave in response to climatic variability and changing environmental conditions continues to lag behind supply-side modeling approaches. By comparing survey versus simulated responses to trail closures, the presented study addresses a critical gap by revealing snowmobilers' potential behavioural adaptations in response to changing conditions that have not been adequately captured in traditional supply-side models.

The comparative process involved the following sequential steps:

Baseline preference establishment: For each district, the baseline is the "expected" market share under ideal climatic conditions as stated by snowmobilers in the OFSC (2023) economic report (i.e., primary, secondary, and tertiary riding locations; Table 3.1).

Simulation of constrained behaviour: Using the ABM parameterized with empirical data, the snowmobiler redistribution throughout the 2023/2024 season based on actual trail availability conditions was simulated. The model tracked the daily count of active snowmobilers in each district over the entire season.

Extraction of peak distribution patterns: From the simulation results, three key distribution metrics were calculated, including maximum participation rate (i.e., highest percentage of total riders active in each district at any point during the season), average weekly participation (i.e., mean percentage of riders active in each district during each

week), and peak week distribution (i.e., percentage distribution of active riders across all districts during the three most active weeks [weeks 9, 10, and 12]).

Calculation of market share changes: For each district, the difference between the expected market share (i.e., stated preferences) and the actual simulated market share was calculated using:

$$\Delta_i = S_i - P_i$$

Where:

- Δ_i = Market share change for district i
- S_i = Simulated market share for district i (from model)
- P_i = Preference-based market share for district i (from survey)

Categorization of districts: Based on market share changes, the districts were classified as districts with (1) Major Gains (i.e., market share change >20%), (2) Moderate Gains (i.e., market share change 5-20%), (3) Slight Gains (i.e., market share change 0-5%), (4) Slight Loss (i.e., market share change -5-0%), (5) Moderate Loss (i.e., market share change -20--5%), or (6) Major Loss (i.e., market share change <-20%).

Temporal evaluation: The comparative process was repeated for different time periods (monthly and weekly) to identify temporal patterns in market redistribution throughout the season This involved comparing data at both monthly intervals (December through March) and weekly intervals (weeks 1-16), tracking how snowmobilers shifted their destinations in response to changing trail conditions.

While the results do not track individual decision processes, it reveals population-level redistribution patterns that show collective behavioural responses to changing environmental conditions. The divergence between stated preferences and simulated participation demonstrates how trail access constraints due to warm temperatures can alter movement patterns beyond what would be predicted by stated preference data alone.

Chapter 4
Results

This chapter presents the findings from an ABM exploring the geographic patterns of Ontario snowmobilers during the record warm 2023/2024 winter season, which was characterized by temperatures between 5.4-6.3°C above the 30-year average (ECCC, 2024). The first section documents the impact of warm winter conditions on Ontario's trail network availability, quantifying the temporal and spatial patterns of trail closures across 16 districts based on GIS image processing. The second section reveals snowmobiler preferences and behavioural adaptations based on empirical survey data, including district preferences, responses to trail closures, and threshold conditions that influence participation decisions. The final section integrates these findings using an ABM that simulates the redistribution of 1000 snowmobiler agents across the province in response to changing trail availability, highlighting differential market gains and losses throughout the winter season.

4.1 Trail availability status

Research Question #1: Assess the impact of the record warm 2023/2024 winter season on the availability of Ontario's trail network across all 16 districts (i.e., supply-side vulnerability).

The total number of nodes per district that resulted from the processing of the 33 images of the trail network status (see section 3.2) are highlighted in Table 4.1. The variability in the number of nodes in each district reflects the different trail lengths, with District 1 home to the most expansive trail network in Ontario (28928 nodes) and District 4 the smallest (3846 nodes). For some images, not all nodes had a valid corresponding RGB value (i.e., Available: $R < 150$ and $G > 160$, Limited availability): $R > 150$, $G > 150$, and $B \leq 100$ or Unavailable: $R \geq 160$ and $G < 100$). For example, trails may have other features captured in the images (e.g., road markers, route numbers, labels, trails limits), resulting in nodes that returned invalid values (e.g., grey, black, white). Correspondingly, all images were visually checked by the researcher to confirm the nodes were located on top of the trails, with the remaining invalid colour values removed.

Table 4.1 Number of nodes per district after the images were processed

District	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	17
Number of nodes	28928	11394	7887	3846	17694	16693	9865	7716	19136	6530	16840	12807	19168	14023	16643	20526

After removing the invalid nodes, the relative percentages for each status category (available, limited, unavailable) were obtained for each of the 33 images. To inform the ABM, a conservative approach was taken, such that a limited trail status was deemed as available and acceptable to ride. As such, only the unavailable percentage values for each of the 16 districts (Figure 4.1) were recorded as the trail status.

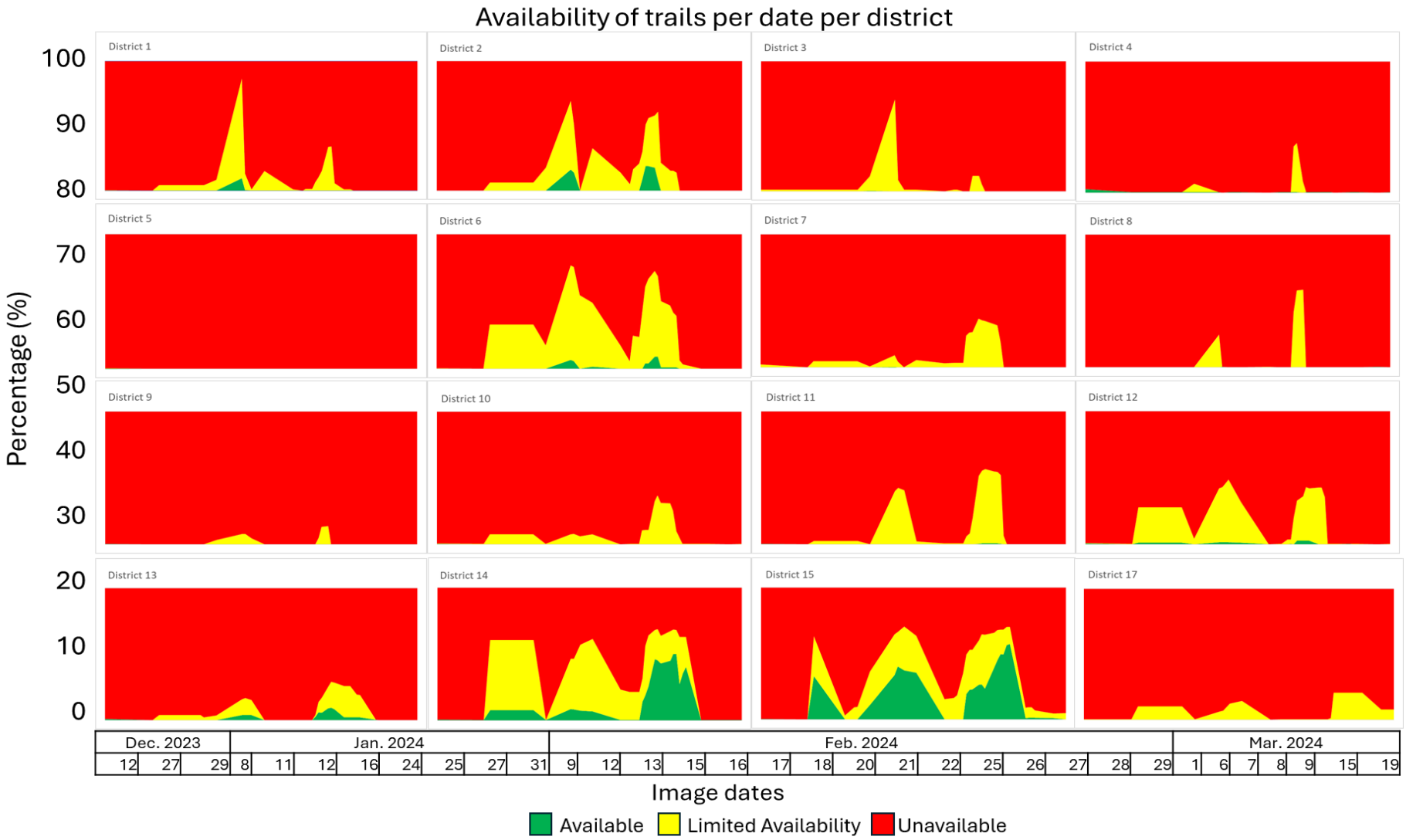


Figure 4.1 Classification of trail status by district for the Ontario 2023/2024 snowmobile season

In general, the trail status for the majority of the 2023/2024 was unavailable, with only a few weeks of highly variable available trails. The influence of climatic seasonality is evident, with fewer trails available at the beginning (i.e., December) and end (i.e., March) of the winter season (i.e., when temperatures are warmer in Ontario), with trail conditions improving in late January through February. The start of the snowmobile season was delayed across the province, with 14 districts experiencing ≤5% trail availability in the month of December, with no trails available in any of the 16 districts on December 12th or December 27th. Districts 14 and 15 had the strongest start to the season, though still marginal, with combined limited and available trail status reaching a maximum of 35%. The season began to improve in January, with the highest trail availability for the 2023/2024 season occurring between January 24th and February 27th. By March 6th, most trails across Ontario were closed, with ≤1% of trails available in Ontario, with the exception of Districts 15 and 17, who had 10% and 21% of availability, respectively. On March 19th, no trails were available in any of the 16 districts. Overall, District 5 experienced the greatest network closures in 2023/2024, with no trail availability (i.e., 100% unavailable) on any of the image dates. Conversely, Districts 14 and 15 had the most favourable conditions, maintaining 20-30% availability (i.e., available or limited) throughout the season.

4.2 Snowmobilers' preferences and behaviours

Research Question #2: Design and conduct a survey to examine the preferences and behavioural responses of snowmobilers under changing climatic conditions, including how they adjust their travel plans in response to trail closures and reduced trail availability (i.e., demand-side vulnerability).

4.2.1 Snowmobiler riding habits and preferences

To understand snowmobilers' current preferences and riding habits, the first survey question asked respondents where they snowmobile most often, second most often, and third most often (Table 4.2). District 1 was selected as the most selected riding district (32.3%), followed by District 15 (17.1%). Of the 161 survey respondents, 101 selected a 2nd district most likely to ride, of which District 6 was selected the most (33.7%), followed by District 2 (11.9%). An additional 66 respondents selected a 3rd district most likely to ride in, with

District 15 (16.7%) selected the most, followed by District 11 (15.2%). When examining overall district selection patterns (i.e., the sum of selected districts for primarily ride, second most likely to ride, third most likely to ridden), Districts 1, 6, and 15 were selected the most, accounting for 17.1%, 14.0%, and 14.3% of total selections, respectively.

Table 4.2 Snowmobilers preferred riding districts

District	Primarily Ride (%) *(n=158)*	2nd Most likely to ride (%) *(n=101)*	3rd Most likely to ride (%) *(n=66)*	Proportion of market total[b] (%)
1	32.3	4.0	1.5	17.1
2	8.9	11.9	9.1	9.8
3	6.3	5.0	7.6	6.4
4	1.9	2.0	0.0	1.5
5	2.5	1.0	0.0	1.5
6	1.9	33.7	13.6	14.0
7	4.4	3.0	3.0	3.7
8	1.3	4.0	1.5	2.1
9	1.9	1.0	1.5	1.5
10	1.9	1.0	6.1	2.7
11	4.4	8.9	15.2	7.9
12	5.1	3.0	9.1	5.2
13	3.8	2.0	1.5	2.7
14	5.1	8.9	12.1	7.6
15	17.1	7.9	16.7	14.3
17	1.3	3.0	1.5	1.8

[b]Sum of the selected district for primarily, secondarily and third most likely to ride.

In terms of riding frequency, nearly one-third of the respondents ride three days per week (32.7%), followed by 2 days per week (24%). The distribution of responses suggests a core of dedicated riders, with some riding even more frequently (e.g., 18% ride 4 to 6 days per week, and 4.7% ride daily). Only a small portion (4.7%) ride less than once per week, indicating that most survey respondents are active participants in the sport. Moreover, the majority (80.7%) of respondents ride on the weekend, with slightly less (65.2%) riding during the weekdays. Winter holidays are another important period of riding, with approximately half of the respondents opting to snowmobile on long weekend and during winter holidays (e.g., Christmas and New Year) (52.8% and 46.0%, respectively).

Most respondents (44.8%) engage exclusively in day trips, while 40.7% engage in both day- and multi-day (i.e., overnight) trips, and 14% exclusive ride on multi-day trips. Of those riders that take overnight trips, 51.9% travel for 2-3 nights and 41.8% travel for 4+ nights (i.e., tours). When asked how they typically travel to their snowmobile trails, the majority (50%) indicated they ride directly from their property, while 30.4 % combine direct property access with towing to a trail head, and 19.6% exclusively tow to trailheads. If those respondents who ride directly from their property were faced with poor snow conditions that required towing, 90.5% (114 of 126 respondents) indicated they would be willing to do so, suggesting a high level of adaptability.

Next, respondents were asked the maximum distance they would tow their sled for a day trip, resulting in an average distance of 240km (Figure 4.2). However, there was considerable variation within the sample, with the majority (78,2%) indicating a maximum of < 300km, with 15.0% of respondents willing to travel between 300-500km, and 6.8% that would be willing to travel > 500km for a day trip. The maximum reported day trip distance of 2000km appears to be an outlier, as fewer than 3% of respondents indicated willingness to travel more than 800km for a single day of riding. For overnight trips, respondents are willing to travel longer distances, resulting in an average of 861km (Figure 4.2). Less than 20% would travel less than 400km, 14.3% would travel between 400-500km, another 35.1% would travel between 500-1000km, and a significant 18.2% were willing to travel between 1000-2000km for overnight trips. A small but notable group (5.1%) reported extraordinary travel distances exceeding 2000km, with the maximum at 3000km. The difference in maximum travel distances for a day versus overnight trips highlights the distinct nature of these two types of snowmobiling activities and their respective planning considerations. Day trip participants typically operate within a limited geographic radius, suggesting the importance of climatically viable trail networks within 200-300km of primary residences. Overnight participants, by contrast, demonstrate a willingness to travel much farther for extended experiences, indicating the value of destination trail systems that can support longer

stays and more extensive exploration.

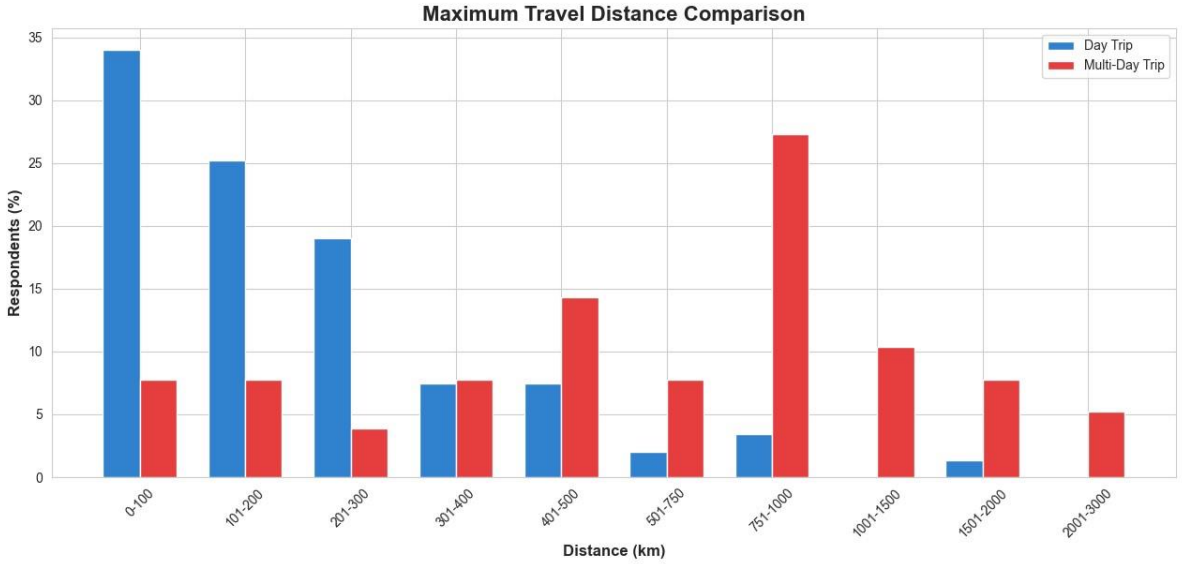


Figure 4.2 Maximum travel distance for day trips versus multi-day snowmobile trips

Several survey questions were deliberately designed to align with the OFSC (2023) economic report to enable direct comparison between our sample and the broader Ontario snowmobiling population. When compared to the OFSC (2023) economic report, the results from the survey are not representative of Ontario snowmobilers district riding preferences nor frequency of riding. For example, there is an overrepresentation of snowmobilers that indicated they primarily ride in District 1 (i.e., 32.3% versus11.3%) and 15 (i.e., 17.1% versus 4.8%), with an underrepresentation of snowmobilers that primarily ride in District 6 (i.e., 1.9% versus 10.3%) (Table 4.3). However, when comparing overall riding preferences (i.e., inclusive of primary, secondary, and third most likely to ride), the survey results align more closely with total provincial distributions (notable exceptions include district 1 and 15 with an over representation of 9.5 and 8%, respectively). For the purposes of the ABM and limit representation bias, the distribution of riders within the ABM is based on current district market share as outlined by OFSC (Figure 3.2).

In terms of riding frequency, 79.4% of respondents in this study ride two or more times per week with 4.7% riding less than once per week, compared to 27.3% and 40.8% in

the OFSC report, respectively. Additionally, the survey reported higher participation in overnight trips (54.7% versus 32.4%). These differences suggest that the sample includes more active snowmobilers who ride more frequently and take more overnight trips than the average OFSC member, which could be the result of several factors, most notably self-selection bias where more dedicated enthusiasts are more motivated to participate in both in-person and online surveys), as well as differing distribution methods (e.g., the researcher did not have access to all OFSC permit holders and the locations of the in-person survey limits widespread distribution). These sampling differences likely reflect variations in survey distribution channels, regional response rates, or potentially stronger engagement from select district communities (discussed further in Section 6.3).

Table 4.3 Comparison of district preference between survey and OFSC (2023)

District	Primarily ride		Difference	Proportion of total market		Difference
	Primary Survey	OFSC (2023)		Primary survey	OFSC (2023)	
1	32.3	11.3	+21.0	17.1	7.6	9.5
2	8.9	9.1	-0.2	9.8	8.8	1
3	6.3	4.1	+2.2	6.4	4.2	2.2
4	1.9	2.4	-0.5	1.5	3.0	-1.5
5	2.5	3.2	-0.7	1.5	3.3	-1.8
6	1.9	10.3	-8.4	14	10.8	3.2
7	4.4	8.7	-4.3	3.7	8.5	-4.8
8	1.3	5.9	-4.6	2.1	4.9	-2.8
9	1.9	7.7	-5.8	1.5	6.0	-4.5
10	1.9	6.6	-4.7	2.7	7.3	-4.6
11	4.4	8.0	-3.6	7.9	10.2	-2.3
12	5.1	6.9	-1.8	5.2	6.9	-1.7
13	3.8	3.5	+0.3	2.7	3.2	-0.5
14	5.1	4.9	+0.2	7.6	7.6	0
15	17.1	4.8	+12.3	14.3	6.3	8
17	1.3	2.5	-1.2	1.8	1.5	0.3

4.2.2 Behavioural responses to marginal conditions

The 2023/2024 season's trail closures significantly impacted riding behaviour, with all (100%) of respondents indicating they experienced trail closures. As a result, almost all (90.4%) indicating they reduced their riding frequency (i.e., stopped and waited for their preferred trails to open). An additional 8.3% maintained their usual riding frequency by waiting for their trails to open and then snowmobiling more frequently to make up for a shortened season (38.5%) and/or traveling to trails either outside or within their preferred district (61.5% and 38.5, respectively). Only two respondents (<1%) indicating they rode more than usual, with one participant reporting they traveled to other districts and the other selecting "other".

Next, the survey asked snowmobilers at what percentage of trail closures would they not go snowmobiling and wait for better trail conditions (i.e., trail closure threshold). The majority of snowmobilers (54.1%) indicated that if trail closures exceeded 60%, they would not go snowmobiling, which increases to 74.0% that would not snowmobile if over 80% of trails were closed (Figure 4.3). The results indicate there is a highly committed segment of snowmobilers that will continue to ride despite near complete trail closures, with over one-quarter (26%) opting to ride until over 90% of the trail are closed.

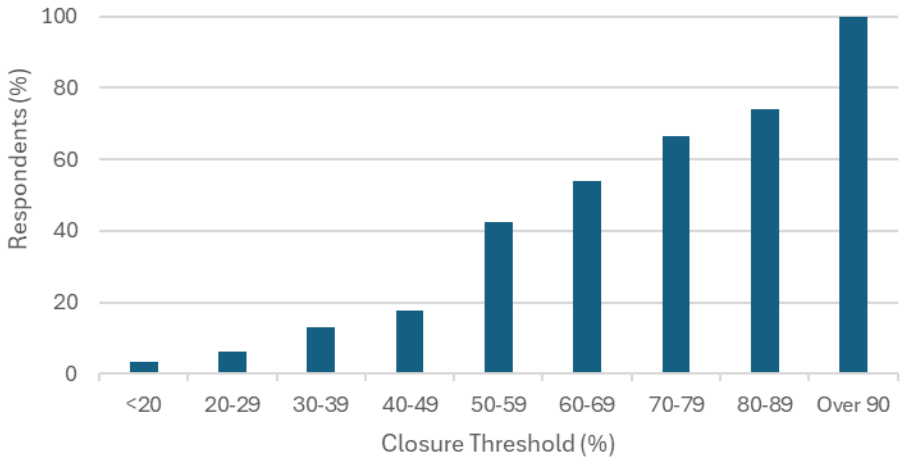


Figure 4.3 Percentage of snowmobilers who would stop riding at different trail closure thresholds

If the length of the snowmobile season is 10-11 weeks, 100% of respondents would purchase a permit for the following season (Figure 4.4). Having a snowmobile season length of 8-9 weeks, 94.7% would renew their permit, which decreases slightly to 91.3% for a season length of 6–7 weeks. If the snowmobile season were to be reduced to 4-5 weeks of riding, 78.7% would purchase a permit for the following season, dropping to 51.3% should the season decrease to only 2-3 weeks of riding. With a season length of 1 week or less, only 21.3 % of respondents in Ontario would be willing to purchase a snowmobile permit.

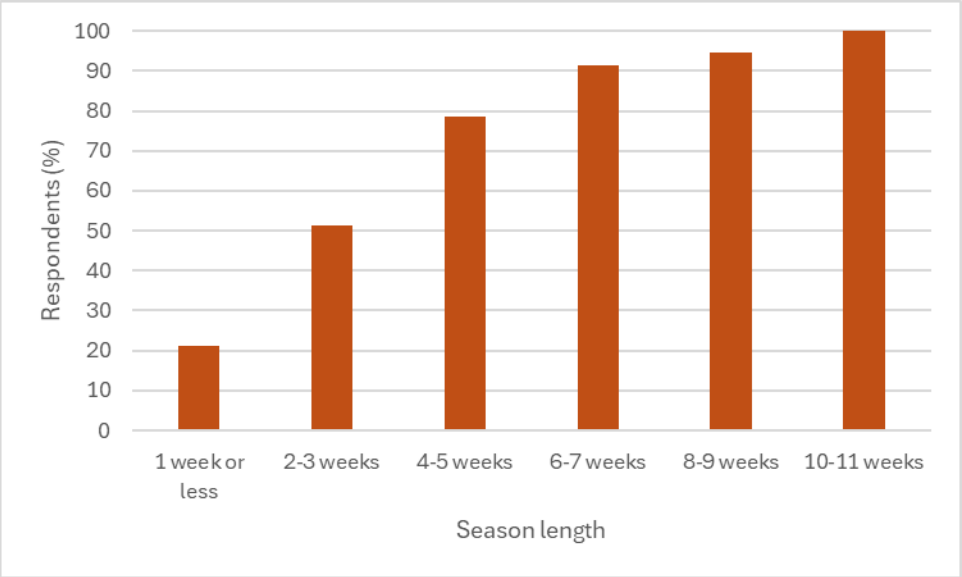


Figure 4.4 Willingness to purchase a snowmobile permit based on season length

To better understand the likelihood of snowmobiling under various marginal conditions, a 5-point Likert scale from very unlikely (1) to very likely (5) was presented for four key variables as identified in the literature (see Section 2.3). Importantly, over 85% of respondents indicated that they actively seek information on the status of trail conditions (i.e., available, limited, unavailable) using the OFSC interactive trail map prior to riding, including 71.2% who are "very likely" and 15.3% who are “likely” to check the trail status prior to snowmobiling. This information seeking behaviour (M = 4.5, SD = 1.1) indicates that real-time trail condition reporting systems are a key decision-making factor when deciding whether and where to participate in the sport (Table 4.4).

In terms of conditions that would limit riding, respondents were largely split down the middle. For example, if snowmobilers were unable to make loops or ride long distances (e.g., full trail length closed or not connected to other trails), 41.3% stated they were “likely” or “very likely” to go, while 43.6% would be "unlikely" or "very unlikely" to go (M = 3.0, SD = 1.4). Similarly, if access to services were limited, 40.0% would be “likely” or “very likely” to continue riding, and 36.0% “unlikely” or “very unlikely” to go (M = 3.1, SD = 1.2). The closure of water crossing (e.g., rivers, lakes) emerged as the most limiting barrier (M = 2.9, SD = 1.3), but respondents were nevertheless largely divided, with 37.8% “likely” or “very likely” and 43.6% of respondents “unlikely” or “very unlikely” to continue riding if these areas were inaccessible. A Mann-Whitney U test revealed no statistically significant differences between riders who are unlikely to snowmobile when they cannot make loops or sled long distances and riders who are unlikely to snowmobile when water crossings are closed (U=1187, p=0.343).

Table 4.4 Likelihood of snowmobiling under marginal conditions

	Very Unlikely (1)	Unlikely (2)	Neutral (3)	Likely (4)	Very likely (5)	Average	Standard Deviation
Inability to make loops or sled long distances (e.g., full trail length closed or not connected to other trails)*	21.3%	21.3%	16.0%	15.3%	26.0%	3.0	2.3
Water crossing closed (e.g., river, lake)*	20.1%	23.5%	18.8%	24.2%	13.4%	2.9	1.3
Limited access to services and facilities	10.7%	25.3%	24.0%	27.3%	12.7%	3.1	1.2
When planning to go snowmobiling, how likely are you to check the trail status before riding (e.g., interactive trail map)?	5.9%	0.8%	6.8%	15.3%	71.2%	4.5	1.1

*Statistically significant difference ($p<0.05$)

Given the bimodal distribution for each of the three conditions (inability to make loops, water crossings closed, limited access to services), the respondents were divided into

two group to explore whether mean trail closure thresholds differed between those who selected "likely" or "very likely" versus "unlikely" or "very unlikely." Snowmobilers who are likely to continue riding despite loop or distance limitations have a higher mean closure threshold compared to those unlikely to continue riding (M=67.4% and 59.1%, respectively), with a Mann-Whitney U test revealing statistically significant difference (p=0.031). A similar result was found for water crossing closures (M=69.1% and 58.1%, respectively; p=0.007), with no statistically significant differences (p=0.120) between those who are or are not likely to ride when access to services is limited and their mean trail closure thresholds (M=67.5% and 60.6%, respectively).

To explore whether different types of snowmobilers respond differently to various trail conditions, a comparative analysis was conducted based on trip type (i.e., day versus overnight), as well as riding frequency (i.e., two-three times per week versus four or more times per week). With respect to likelihood of riding when unable to make loops or sled long distances, mean responses ranged from 2.8 for day trips to 3.2 for overnight trips, which suggests riders that engage in day trips are less likely to snowmobile when conditions are marginal, but a Mann-Whitney U test indicated no statistically significant differences between groups (p=0.098). Similarly, for water crossing closures, mean responses revealed a comparable pattern (day: 2.7, overnight: 3.0), as did limited access to services and facilities (day: 2.9, overnight: 3.2) but neither were statistically significant (p=0.092 and p=0.135, respectively). In terms of riding frequency, there were no statistically significant differences for any of the conditions when comparing those who ride two-three times per week versus those who ride four or more times per week, including an inability to make loops or sled long distances (M=3.2 and 2.9; p=0.342), water crossing closed (M=2.9 and 2.9; p=0.956), and limited access to services and facilities (M=3.1 and 3.2; p=0.638). These results suggest that despite different riding frequencies; riders share similar attitudes toward marginal trail conditions. In turn, the survey sample's overrepresentation of frequent riders may not substantially bias the conclusions about snowmobiler responses to trail conditions and may apply broadly to the Ontario snowmobiling community.

4.3 Snowmobilers' simulated movement in response to trail availability

Research Question #3: Develop an agent-based model (ABM) to simulate how trail availability (i.e., objective 1) influences the spatial redistribution of snowmobilers across Ontario's districts (i.e., objective 2) to evaluate the synchronous evolution of demand- and supply-side vulnerabilities.

4.3.1 Temporal patterns of snowmobile activity

Given the results from the uncertainty analysis, the model was run 30 times for reliability (see Section 3.5.2). The results of the simulation showed that there are clear fluctuations in snowmobile activity in response to trail network availability (Figure 4.5). For example, the delayed start to the snowmobile season is evident in December, with limited trail availability resulting in low activity (i.e., 0% of active snowmobilers in weeks 1-4). A peak in snowmobile activity is notable in the month of February, which includes week 9 (9%), week 10 (12%) and week 12 (21%), which marks the highest level of active snowmobilers in the ABM for the 2023/2024 season. Similar to the slow start to the snowmobile season, the season also ended early, with a notable decline in snowmobile activity in March (i.e., <5% of total snowmobilers are active in week 14, dropping to 0% by week 16). The pattern is consistent with the classification of trail status (Figure 4.1), with two notable peaks in activity (>10%) that align with the dates that had the greatest trail network availability (i.e., January 24-31 and February 16-27). The results suggest that trail status play an important role in the active participation of snowmobilers in Ontario.

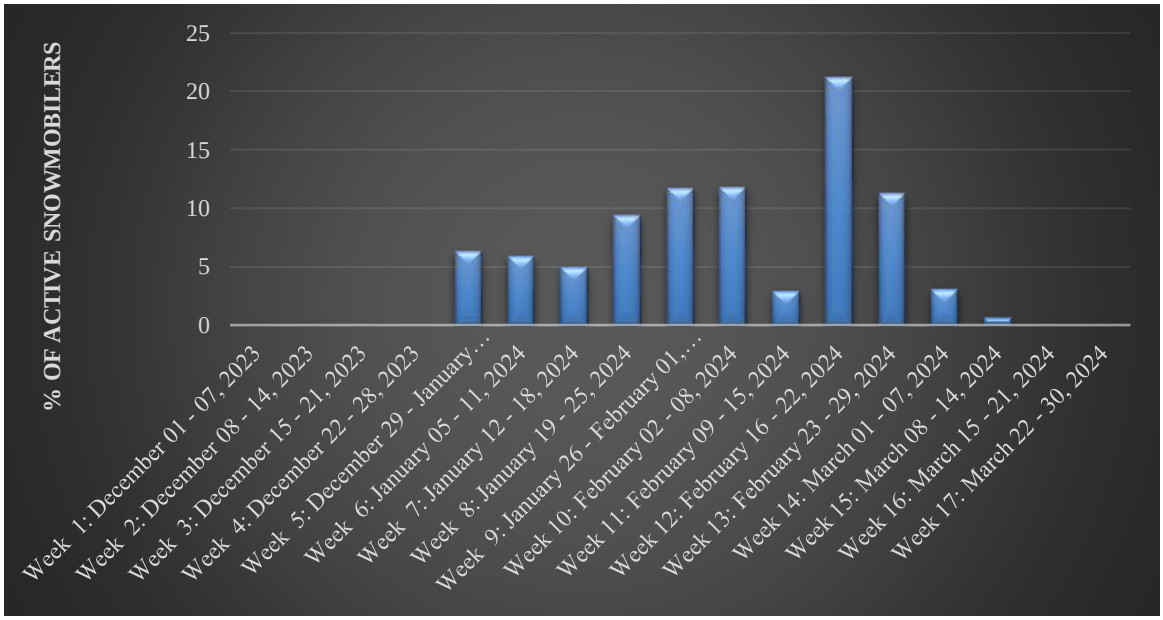


Figure 4.5 Simulated weekly snowmobile activity (%) during the 2023/2024 winter season

4.3.2 Geographic redistribution of snowmobile activity

To assess potential changes in market share for each of the 16 snowmobile districts, a comparative analysis was conducted to explore the difference between the stated market share in 2022/2023 (Table 3.1) and the simulated market share based on the ABM results. First, a highly conservative, best-case scenario approach was taken, comparing stated market share with the maximum number of active snowmobilers simulated per district *at any given time* in the season. Next, a monthly comparison was done for the winter season (i.e., December to March), followed by a weekly comparison for the month of February, which was the month with the highest percentage of available trails. By calculating the redistribution of snowmobilers by various timeframes (i.e., seasonal, monthly, weekly) across the 16 districts, the comparison highlights the dynamic and coupled relationship between supply (i.e., trail availability) and demand (i.e., snowmobilers).

Using the maximum simulated activity per district, market share changed in all but one district (District 4 - southcentral Ontario), with two districts gaining a slight market share (<2%), and the remaining districts losing market share (-0.5% to -7.6%) (Table 4.5). For example, District 1 (Upper Canada) had the largest simulated market share, with snowmobile

activity increasing from 7.6% of Ontario's riders to 9.5%, which occurred in week 10 when 15% of trails were available. District 3 (southeast) also had a slight increase from 4.2% to 5.6%, which occurred in week 8 when 20% of trails were available. On the other hand, District 11 (near north) had the greatest decrease in market share, dropping from 10.2% to 2.7%, with the maximum activity occurring in week 13 when 40% of trails were open. District 6 (Haliburton, Bancroft, Ottawa Valley) experienced similar losses, dropping from 10.8% to 3.8% at its maximum activity (week 9, 66% trails open). Interestingly, because District 5 (southwestern Ontario) represents a smaller share of the total Ontario snowmobile market (3.3%), despite not having any snowmobile activity (i.e., 0% of trails available throughout the 2023/2024 season), the simulated market loss on a provincial scale is less than District 5 (i.e., -3.3 versus -7.0%). The localized implications within the district would nevertheless be significant, with direct losses for those businesses reliant on the industry during the winter months (e.g., hotels, service stations, restaurants).

Table 4.5 Redistribution of snowmobilers based on maximum simulated activity per District

Districts	Stated market share (%)	Simulated market share (%)	Change in potential market share (%)
1	7.6	9.5	1.9
2	8.8	3.8	-5.0
3	4.2	5.6	1.4
4	3.0	3.1	0.0
5	3.3	0.0	-3.3
6	10.8	3.8	-7.0
7	8.5	1.7	-6.8
8	4.9	4.5	-0.5
9	6.0	1.7	-4.4
10	7.3	1.2	-6.1
11	10.2	2.7	-7.6
12	6.9	2.9	-3.9
13	3.2	0.7	-2.5
14	7.6	2.3	-5.3
15	6.3	1.0	-5.3
17	1.5	0.7	-0.9

Next, geographic redistributions were explored by comparing stated market share with the simulated share on a monthly basis. Given that the winter season began with no snowmobiler activity due to complete trail closures across the province, the ABM simulation reflects market losses across all 16 districts between week 1 (Dec 1 – Dec 7) and week 5 (Dec 29 – Jan 4) (Figure 4.5). In January, several districts experienced significant market share increases relative to December's complete inactivity, with some districts exceeding their expected market share based on the stated riding districts selected in the OFSC survey. Specifically, Districts 6 (Haliburton, Ottawa Valley region; +13.2%), District 12 (Sudbury, Espanola and Manitoulin; +11.4%), and District 14 (Northeastern Ontario, New Liskeard, Kirkland Lake, Timmins; +11.3%) had the highest simulated gains, with more snowmobilers selecting these districts.

February evidenced a more geographically distributed market, with positive changes expanding eastward to include Districts 1 (Ottawa, Kingston area; +3.4%) and District 2 (Bancroft, Bobcaygeon region; +5.4%), while Districts 6 and 12 maintained their positive market position (+5.9 and +5.1%, respectively). Southern districts continued to experience simulated losses but showed improvements compared to January, with Districts 4 (Toronto area) and 8 (Collingwood, Barrie region) nearing market stability (-0.4% and -0.4%). The most dramatic redistribution occurred in March, with northeastern districts experiencing substantial gains, including District 14 (Cochrane area; +33.3%), District 17 (Kenora region; +30.0%), and District 15 (Timmins area; +10.8%), while all southern and central districts reverted to significant market losses, creating a north-south divide in snowmobiling activity (Figure 4.6).

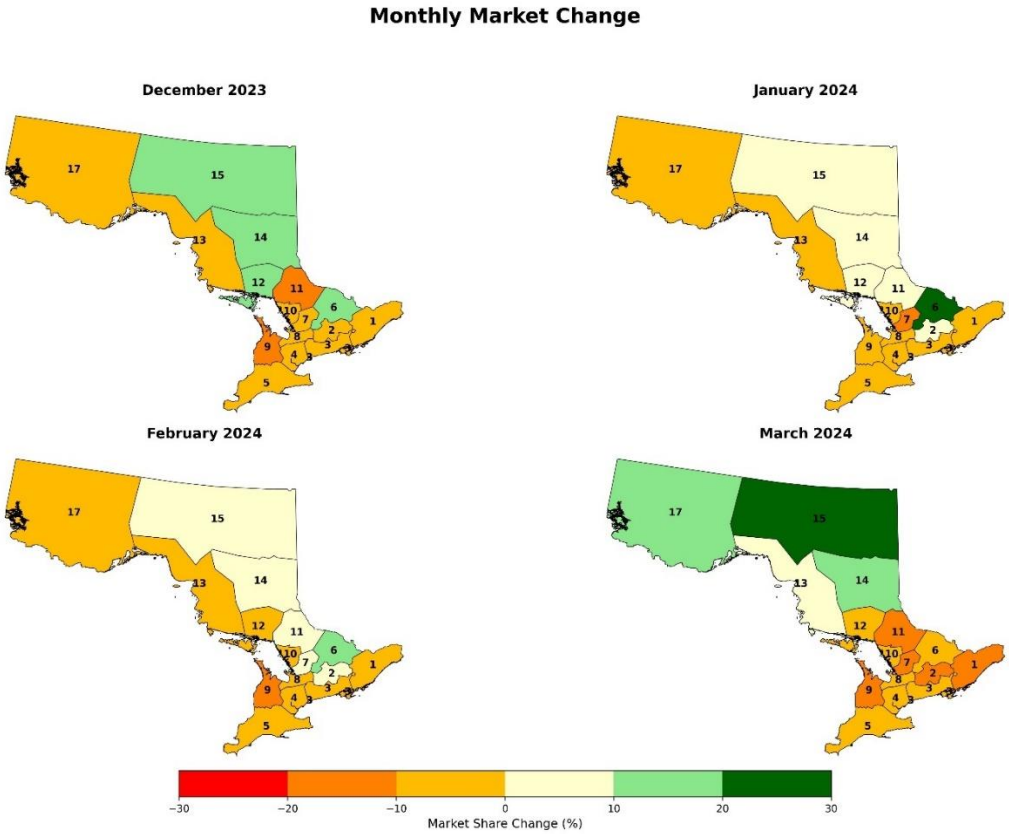


Figure 4.6 Percentage change in stated versus simulated market share by month

A weekly comparison of snowmobile patterns for February, which had the highest snowmobile activity throughout the 2023/2024 season, provides a more detailed view of redistribution trends compared to the monthly analysis (Figure 4.7). During week 9 (Jan 26 – Feb 2), provincial snowmobile activity was highest in Districts 6 (24.4%) and District 12 (20.3%), substantially exceeding their stated preferences of 10.8% and 6.9%, respectively. Meanwhile, seven districts (3-5, 7-10) recorded no activity despite collectively representing 37.2% of the stated market share. In week 10 (Feb 2 – Feb 8), there was a shift in market distribution, with District 1 simulating 22.4% of active snowmobilers, which is a substantial increase from its stated market share of 7.6% (+14.8%), with a complete market loss in District 11 (-9.6% from the week prior and -10.2% compared to stated market share). Week 11 (Feb 9 – Feb 15) had the most concentrated distribution pattern of the month, with activity limited to just four districts. For example, District 2 (Bancroft, Bobcaygeon region) had 34%

of the simulated market share (+25.2%), followed by 31.53% of riders in District 6 (+20.7%) and 23.8% in District 14 (+16.2%). The remaining 10.7% of snowmobile activity occurred in District 15 (+4.4%), while the other twelve districts recorded no simulated activity despite collectively representing 57% of the stated market share. Finally, week 12 (Feb 16 – Feb 23) recorded the highest overall participation, which simulated riding activity in 14 of the 16 districts, revealing the system's capacity for temporary geographical recovery when conditions improved (Fig. 4.8). Nevertheless, while the system demonstrated capacity for geographical recovery, the distribution remained uneven with certain districts still vulnerable, including Districts 10 (Georgian Bay region), 11 (near north), and 5 (southwestern Ontario) which experienced losses of 3.8%, 4.8%, and 3.3% respectively.

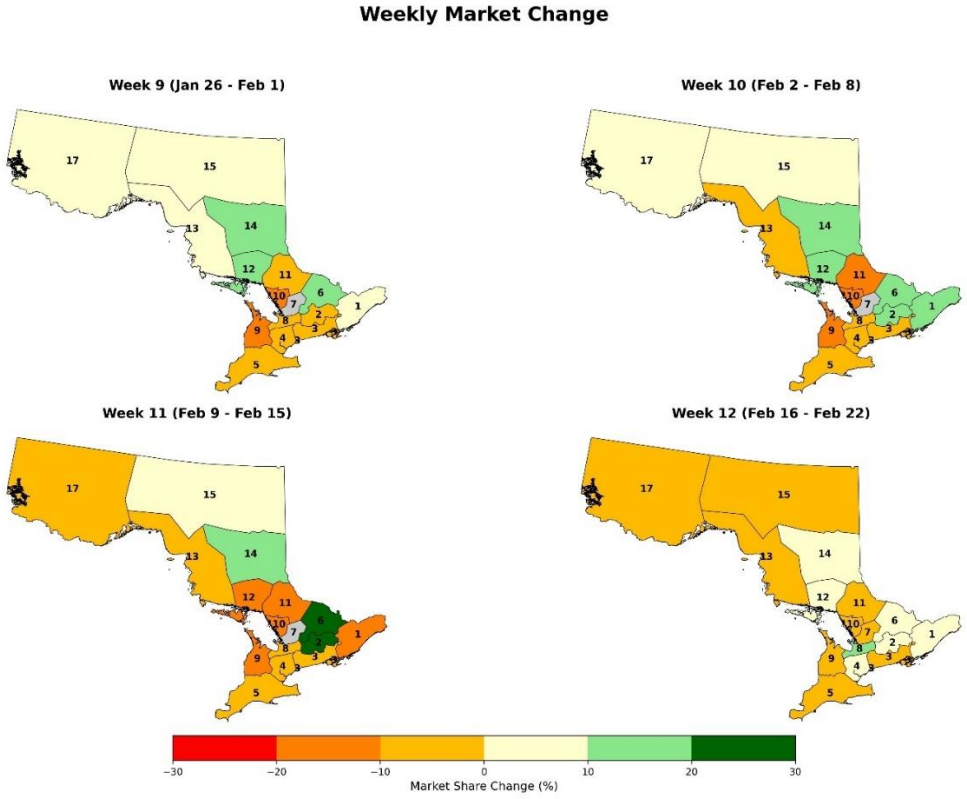


Figure 4.7 Weekly percentage change in stated versus simulated market for the month of February (weeks 9-12)

The weekly comparison between stated versus simulated snowmobile activity reveals a more dynamic geographic pattern than the monthly comparison, suggesting that rider distribution can change rapidly in response to trail availability. At the monthly scale, there is a general north-south divide indicative of riders' willingness to travel long distances to access available trails. Whereas on a weekly level, as trails became briefly available in the south, riders are more likely to choose them. The spatial redistribution suggests that the provincial market is not at uniform risk to climatic variability and change. The willingness of riders to adapt underscores demand-side flexibility, which may temporarily precede supply-side contraction (i.e., reduction in trail availability) as the climate continues to warm in the future. The results highlight the climatic dependence of the system, with market gains (or losses) predicated on trail availability. The traditionally popular southern districts exemplify the vulnerability of lower-latitude snowmobile regions to warming trends, even when those regions have substantial infrastructure investments and established rider preferences.

Chapter 5
Discussion

The presented chapter discusses the implications of trail closures for the snowmobile industry Ontario, including the temporal and spatial patterns of the simulated market redistribution and the parameters that influenced these movement patterns the most. While the current parameterization provided valuable insights into the geographical redistribution of Ontario snowmobilers, future improvements that include empirically-derived social influence metrics, snowmobile-specific decay functions for district popularity, and Ontario-specific decision weights derived through choice experiments are discussed.

5.1 Impacts on trail availability (supply-side)

The 2023/2024 winter season saw significant snowmobile trail closures across Ontario due to record warm temperatures, with greater trail availability in eastern versus southern districts, including District 5 (southwestern) which experienced complete trail closure throughout the season. The snowmobile season experienced a delayed start (≤5% trails available in December across 14 districts), an early end (≤1% trails available by March 6th except Districts 15 and 17), with the greatest network availability in February (reaching a maximum in week 12 at 21%).

It is important to note that District 17 is an outlier in the dataset. Located in the northwest, it was anticipated that there would be less seasonal variability and longer stretches of trail availability. However, the district did not have any available trails in 2023/2024, with limited availability in January (10% to 14.1%) no available trails in February until the 29th (20.3%), before closing by March 9th. A possible explanation is that the district has a significant number of trails that cross water (e.g., over 70,000 lakes in the region; Destination Ontario, 2025), that would require longer periods of cold temperatures to ensure the ice is thick enough to safely travel across. Moreover, the availability of the trails is not solely dependent on weather and snow patterns, but also trail management, with trail maintenance and grooming reliant on volunteers. As such, even if snow conditions are present, without available volunteer, trails could remain closed for longer periods of time. At present, the

average age of OFSC volunteers is 50, with some members raising concerns about the longevity of the organization if they are unable to attract younger volunteers moving forward (OFSC, 2023).

The high supply-side vulnerability evidenced in 2023/2024 align with the warnings heeded by Mcboyle et al. (2007) who estimated that a reliable snowmobile season in Ontario (i.e., minimum of 30 days) was at risk of being eliminated by the 2050s, with southern districts at greatest risk. Based on the results, 8 districts did not meet the minimum reliable season of 30 days in 2023/2024, and if only available trails were included then none of the districts would be deemed reliable. The findings also align with Scott et al. (2008) who estimated that over half of the US Northeast snowmobile regions would lose their current snowmobile season by mid-century, and Wobus et al. (2017) who estimated season length would be most significantly impacted in the upper Midwest and Northeast (e.g., >80% season loss by mid-century under an RCP4.5 scenario).

When evaluating the vulnerability of the trail network, this study used a conservative approach by classifying both available and limited availability trail statuses as suitable for snowmobiling. In reality, trails with limited availability are defined by OFSC as "limited with marginal riding opportunities, [and] snowmobilers enter with the understanding that they should exercise extreme care and reduce speed." The actual usability of trails is therefore overestimated in this study, such that the movement of snowmobilers within the ABM is likely greater than reality, which was purposeful to minimize projected market loss (i.e., best case scenario to yield conservative estimates). Had snowmobiler movement been based only on available trails, agents would have been restricted to 11 weeks, and seven districts would not have had any activity throughout the 2023/2024 season (i.e., Districts 1, 2, 6, 12-15). The rationale for such a conservative approach is based on the understanding that researchers seeking to enhance destination climate responsiveness should avoid the persuasive tactic of arousing fear, which is neither effective nor appropriate in the context of climate change risk communication and industry engagement (e.g., Reser & Bradley 2017, Knowles & Scott 2021).

Another methodological consideration is that the analysis relied on 33 trail status images representing the 2023/2024 season. This sampling, while providing some insights into seasonal patterns, may not fully account for daily fluctuations in trail conditions. Rapid changes in weather and trail status between sampling dates may have created additional disruptions or opportunities for snowmobile activity that is not captured in the results. As such, daily trail statuses, including daily datasets that span multiple winter seasons, would be valuable in future runs of the ABM.

5.2 Impact on riding behaviours (demand-side)

The survey findings revealed that Ontario snowmobilers are highly adaptive to marginal conditions. While all respondents (100%) experienced trail closures, the majority opted to travel long distances to trails outside their preferred district (61.5%) or wait until their trails opened and then increasing their riding frequency to make up for lost time (38.5%). Moreover, most respondents (78.6%) would continue to purchase a permit even if the season was as shortened to four weeks, including a dedicated minority (26%) that would continue to ride even if over 90% of the trails were closed. Similar to survey results from Vermont (Perry et al. 2018, Xiao et al. 2020), the importance of being able to ride long distances and access water crossings was found, with statistically significant differences found based on mean closure thresholds.

However, given that the overrepresentation of active riders in the survey (i.e., 79% of respondents ride two or more times per week compared to the provincial average of 27%), the results may overestimate the acceptance of marginal conditions. Survey data that better reflects the Ontario market is needed to both calibrate and validate the ABM. It also remains unclear whether, and to what degree, a trail status marked as available versus limited availability influences a riders' decision on when or where to go, including the influence trail status has on positive and negative experiences. Given the heavy reliance of snowmobilers on the OFSC interactive trail map prior to riding (i.e., 87% are likely to check), which aligns with Rutty and Andrey (2014) who found that 97% of Ontario snowmobilers use weather

forecasts when planning a trip, additional research on how the trail map informs snowmobiler decision-making is warranted.

Based on snowmobilers' behavioural responses to trail availability and stated preferences, the ABM simulated significant market redistributions across Ontario's 16 districts, with 14 of the 16 districts resulting in market losses. A north-south divide was evident at a monthly level, with northeastern districts gaining market share as riders travelled from southern districts that were particularly hard hit by the record warm temperatures. In turn, weekly comparisons showed a more dynamic redistribution, revealing riders' preference for southern districts when trails were briefly available. Unlike the supply-side models that projected an elimination of the industry if the season were less than 30 days (e.g., Mcboyle et al. 2007; Scott et al. 2008), the findings suggest a more complex market response pattern similar to the one observed by Rutty et al. (2023), whereby riders redistribute geographically rather than abandon the activity entirely. The research underscores the need for further systems-based approaches for assessing climate risks in winter sports, recognizing that participants are not passive recipients of environmental changes but rather active agents making timely decisions in response to changing trail conditions.

5.3 Future ABM considerations

The ABM applied in this thesis explores the synchronous evolution of demand- and supply-side changes in response to climate, addressing a notable gap in not only winter sports tourism, but climate and tourism research more broadly (TPCC 2023, Scott & Gossling 2022, Rutty et al. 2021). To further build on the success of the research, a number of refinements to the ABM are offered to calibrate model assumptions.

First, the sample size used to empirically inform the decision-making rules of the ABM was low (n=161), with a larger and more representative sample of the 155,000 snowmobilers in Ontario needed. A future survey could also expand on the questions asked in this study, directly informing district popularity decay rates, such as asking snowmobilers about their recent visits to specific districts and their corresponding satisfaction ratings (i.e., how recent trail experiences, including both positive and negative experiences, influence

subsequent riding decisions). To address the assumptions of the social influence parameter, future research could explore the information snowmobilers share with their community network (e.g., about trail status, snow conditions, riding experiences), along with the types of communication channels used (e.g., social media, word of mouth, online forums), with whom the information is shared (group size, relationship types), and the influence of peer recommendations on riding choices, including the influence of both positive and negative information. Snowmobilers likely develop adaptive strategies through complex social networks, and understanding these collective learning processes could reveal advanced decision-making strategies that go beyond individual preferences and a simplified social influence.

The introduction of non-linear weights that consider context-dependent choices would also advance the ABM. A conjoint analysis or discrete choice experiments with Ontario snowmobilers would help inform decision weights, exploring items such as seasonal timing (e.g., willingness to accept various trail conditions based on early vs mid- vs end-of season expectations) and trip type, including who is participating on the trip (e.g., riding solo versus with family or friends), as well as rider experience level. The method would require participants to evaluate trade-offs between competing district attributes (e.g., trail availability versus travel distance), revealing how riders prioritize different environmental factors when deciding when or where to ride (i.e., preference hierarchies). Sensitivity testing of the decision weights could also be performed, yielding additional insights into how variations in these parameters affect model outcomes and identify which factors most significantly influence simulated redistribution patterns.

Next, the ABM is currently set so that snowmobilers always start from, and return to, their home district. The oversimplification of the travel patterns would not accurately capture those riders engaged in multi-day trips, nor those who ride from second homes in different snowmobiling districts (e.g., cottages and recreational properties). In the same way, while the model incorporates different closure thresholds based on survey data, it considers these thresholds as static rather than evolving through experience or changing expectations. To address the lack of empirical real-time tracking data of snowmobiler movements, mobile

phone data could be leveraged to obtain geographical and temporal details on snowmobiler movement across trail networks. The data would also be useful for validating the spatial and temporal patterns simulated through this research, though the successful exploitation of mobile apps and smartphone-based GPS technology data for producing meaningful tourism statistics has been criticized (e.g., Grassini & Dugheri 2021; Reif & Schmucker 2020). An alternate validation option could include participatory modelling sessions with OFSC leadership (e.g., executive board, District governors) and volunteers (e.g., club organizers, trail groomers). By leaning on their experiential knowledge, including local rider preferences and trail management decisions, model assumptions could be discussed and revised in an iterative process. Collaborative research between tourism scholars and industry stakeholders to adequately assess and respond to climate risks, including data sharing to support climate action, remains a pertinent gap (Scheyvens & Cheer 2022, Becken & Loehr 2024).

The assumption that successful riding experiences directly influence permit renewal decisions is a critical link for long-term market sustainability, and while drawn from the survey, it does not consider when permits are purchased (e.g., how far in advance of the season) nor how the decision may change should there be multiple seasons with marginal conditions. The integration of historic permit sales data by district would transform the model's validation capabilities. If historical permit data were available, the model could be calibrated to match observed market shifts during previous seasons with anomalous conditions. Extending the ABM to include economic expenditure patterns would also support the exploration of how market redistribution affects local economies, such that different spending profiles could be assigned to agents and then track their movements and associated spending under different trail conditions. Given that the sport generates over $2.5 billion in provincial revenue, the redistribution of direct spending across rural economies will have consequent impacts on businesses and communities, necessitating continued research to inform climate risk assessments.

As empirical data becomes available to refine the ABM, increasing the number of simulated agents from the 1,000 operationalized in this study to 155,000 agents would better represent the number of registered permit holders in Ontario. In turn, the ABM would offer

greater heterogeneity in agent characteristics while reducing stochastic effects in smaller districts. It would also influence the density parameter, as the additional agents would trigger more density-related enjoyment penalties. Furthermore, the model calculates trail density based on total trail kilometers per district rather than accounting for the percentage of trails that are actually open on a given day. This can potentially underestimate real-world density issues, as riders in reality would be concentrated on the limited available trail sections rather than distributed across the entire network. Future improvements should incorporate a dynamic density calculation that considers only available trail kilometers, which would better represent the crowding effects that might influence rider satisfaction and subsequent district selection decisions.

Chapter 6
Conclusion

The purpose of this research was to assess the differential climate risk of snowmobile tourism across Ontario's 16 districts through three interconnected objectives: (1) assess the impact of the record warm 2023/2024 winter season on snowmobile trail availability through a geospatial analysis, (2) examine the preferences and behavioural responses of snowmobilers under changing climate conditions through primary survey collection, and (3) develop an ABM to simulate and compare the coupled evolution of demand- and supply-side vulnerabilities. The findings yield insight into how climatic variability and change will reshape the geographic distribution of snowmobile activity across Ontario's trail system, offering future research directions to further refine the ABM.

As the first empirical study to not only explore the impact of a record warm winter on snowmobiling but also develop an ABM to compare the dynamic relationship between riders and their environment, the presented research makes a novel contribution to the climate change and winter tourism literature. The stated and simulated movement of snowmobilers across Ontario's 34,000 network indicates a high degree of adaptability, with a clear willingness among riders to pursue the sport despite marginal trail conditions. The 2023/2024 Ontario winter season was +5.4°C warmer than average, which exceeds mid-century climate change projections for the province (up to 4.3°C under a high emission scenario), yet snowmobilers continued to ride, adapting spatially and temporally. In turn, the findings stand in contrast to studies that explore supply-side and demand-side risks in isolation, suggesting that the resilience of the sport may be greater than currently assumed in climate change studies. Traditionally, model-based research has presented the industry as either being viable or eliminated, failing to capture the nuance of both the partial operating capacity of the industry and snowmobilers' willingness to ride despite fragmented trail networks. The record warm season also fell well below the 30-day threshold that has been held in the literature as the minimum viable season, with evidence that the majority of riders will continue to purchase permits even if there are fewer than four weeks to ride.

While the geographic redistribution of tourists in response to climate change is to be anticipated (Scott & Gossling 2022), researchers rarely seize the opportunity to use record breaking events (i.e., climate analogues) to empirically explore climate sensitivities and responses (Steiger et al., 2019). As demonstrated through this research, ABMs are a valuable tool for studying behaviour that is contingent on environmental conditions, enabling shifts in tourism flows over time and space to be empirically explored. Although the ABM was developed for Ontario, it can be readily modified to simulate snowmobiler behaviour in other major markets, including Quebec (the largest Canadian market with 236,973 of riders), the United States (over 1.2 million riders), and European destinations (e.g., Scandinavian countries with over 20,000 registered sleds). A cross-market comparison would also be valuable, particularly for those districts in Ontario that border Quebec, as riders are likely travelling between provinces to ride (e.g., Districts 1,6,11,14,15). However, it's important to note that the selection of a single analogue year cannot capture annual variability, where snowmobilers are likely to face alternating favorable and unfavorable seasons rather than consistent decline. For instance, the following season (2024/2025), Ontario's southern districts experienced significant above-average snowfall, with the deepest snowpack in decades (The Weather Network, 2025) that would have provided snowmobilers with an exceptional season that contrasted markedly with previous years' conditions. A multi-year study with varying temperature and precipitation scenarios, or alternatively, using downscaled climate model projections to generate synthetic trail availability data across a range of potential future conditions, would provide further insight into redistribution patterns across different climate futures.

Based on past emissions and current trajectories, we have committed ourselves to a future of warming (IPCC, 2023), which requires careful sectoral risk assessments in anticipation of seasonal disruptions, loss of critical assets (e.g., snow), and the resultant implications for tourism demand, destination competitiveness, and the sector's economic viability (Steiger et al., 2024, Scott et al., 2024). Tourism is complex, with differential supply- and demand-side climate vulnerabilities. Climate change will not affect the snowmobile industry uniformly, requiring different adaptation strategies to support tourism

planning and rural economic development in the face of unavoidable market changes. Clubs in northern districts with climatic advantages might prepare for increased market share during marginal periods (e.g., expanding and improving the trails infrastructure), while those in climatically vulnerable districts might consider alternate pricing or permit strategies to attract riders (e.g., flexible or transferable permits), along with targeted marketing during the shorter optimal weather windows (e.g., reduced price for last minute multi-day permits, develop a notification system that alerts riders when ideal conditions are present in the different districts). The development of response strategies requires continued research, ideally alongside industry stakeholders, to address ongoing data and knowledge gaps in support of climate preparedness.

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Appendix A: Survey

Snowmobilers' movements

Consent:
Hello, You are invited to participate in a master's research study being conducted by researchers at the University of Waterloo, Canada. Over the past few years, variable temperature and snowfall conditions have caused interruptions to the snowmobiling season. Your participation in this study involves completing an online 10-minute survey to better understand snowmobilers' perspectives on changes in trail conditions. Participation in this study is voluntary, with the freedom to decline to participate at any point, and no personal information is required to participate. You may decline to answer any question(s) you prefer not to answer by skipping to the next question and may stop participating at any time by not submitting your responses and closing your web browser. Only responses that have been completed and submitted will be included in the study analysis. Your identity will be kept strictly confidential. When results are reported they will be combined with other responses so that your individual identity is confidential. Data collected during this study will be retained for at least seven years in a locked office or on a password-protected computer and then erased. There are no known or anticipated risks to participation in this study. This study has been reviewed and received ethics clearance through a University of Waterloo Research Ethics Board (REB #46070). If you have questions for the Board, contact the Office of Research Ethics, toll-free at 1-833-643-2379 (Canada and USA), 1-519-888-4440, or reb@uwaterloo.ca For all other questions contact mvrubiano@uwaterloo.ca Sincerely, Maria Rubiano Consent to participate By agreeing to participate in the study you are not waiving your legal rights or releasing the investigator(s) or involved institution(s) from their legal and professional responsibilities. With full knowledge of all foregoing, I agree, of my own free will, to participate in this study.

- ○ I agree to participate (1)
- ○ I do not wish to participate (Please close the web browser now) (2)

Skip To: End of Survey If Consent Hello, You are invited to participate in a master's research study being conducted by res... = I do not wish to participate (Please close the web browser now)

Q1 Rank the district/region you snowmobile in **most** often:

- ○ Ontario (1)
- ○ Quebec (2)
- ○ Other (3) _____

Display this question:

If Rank the district/region you snowmobile in most often: = Ontario

Q1a I snowmobile

	Most often in this district (4)	**Second most** often in this district (if applicable) (5)	**Third most** often in this district (if applicable) (6)
District 1 – Kingston, Ottawa, Cornwall (1)	○	○	○
District 2 – Kawrthas, Bancroft, Mazinaw (2)	○	○	○
District 3 – Port Perry, Rica Lake, Tweed (3)	○	○	○
District 4 – Newmarket, Orangeville, Sutton (4)	○	○	○
District 5 – Strathroy, Grand Bend, St Thomas (5)	○	○	○
District 6 – Haliburton, Bancroft, Ottawa Valley (6)	○	○	○
District 7 – Muskoka (7)	○	○	○
District 8 – Collingwood, Barrie, Midland, Orillia (8)	○	○	○
District 9 – Grey Bruce, Perth, Huron, Wellington (9)	○	○	○
District 10 – Muskoka/Parry Sound – Georgian Bay Region (10)	○	○	○
District 11 – North Bay, Mattawa, Burk's Falls (11)	○	○	○
District 12 – Sudbury, Espanola, Manitoulin (12)	○	○	○
District 13 – Algoma Country (13)	○	○	○

District 14 – New Liskeard, Kirkland Lake, Timmins (14)	○	○	○
District 15 – Cochrane, Kapuskasing, Hearst (15)	○	○	○
District 17 – Thunder Bay, Dryden, Kenora (17)	○	○	○

Display this question:

If Rank the district/region you snowmobile in most often: = Ontario

Q1i Do you also ride in Quebec?

○ Yes (1)

○ No (2)

Display this question:

If Do you also ride in Quebec? = Yes

Q1aii
I snowmobile

	Most often in this region (1)	**Second most** often in this region (if applicable) (2)	**Third most** often in this region (if applicable) (3)
Region 1 – Gaspésie / Iles-de-la-Madeleine (1)	○	○	○
Region 2 – Bas-Saint-Laurent (2)	○	○	○
Region 3 – Chaudière-Appalaches (3)	○	○	○
Region 4 – Côte-Nord (4)	○	○	○
Region 5 – Saguenay – Lac-Saint-Jean (5)	○	○	○
Region 6 – Québec / Charlevoix / Portneuf (6)	○	○	○
Region 7 – Mauricie / Centre-du-Québec (7)	○	○	○
Region 8 – Lanaudière (8)	○	○	○
Region 9 – Abitibi-Témiscamingue (9)	○	○	○
Region 10 – Cantons-de-l'Est (10)	○	○	○
Region 11 – Montérégie (11)	○	○	○
Region 12 – Laurentides (12)	○	○	○
Region 13 – Outaouais (13)	○	○	○

Display this question:

If Rank the district/region you snowmobile in most often: = Quebec

Q1b
I snowmobile

	Most often in this region (1)	**Second most** often in this region (if applicable) (2)	**Third most** often in this region (if applicable) (3)
Region 1 – Gaspésie / Iles-de-la-Madeleine:Right (1)	○	○	○
Region 2 – Bas-Saint-Laurent:Right (2)	○	○	○
Region 3 – Chaudière-Appalaches:Right (3)	○	○	○
Region 4 – Côte-Nord:Right (4)	○	○	○
Region 5 – Saguenay – Lac-Saint-Jean:Right (5)	○	○	○
Region 6 – Québec / Charlevoix / Portneuf:Right (6)	○	○	○
Region 7 – Mauricie / Centre-du-Québec:Right (7)	○	○	○
Region 8 – Lanaudière:Right (8)	○	○	○
Region 9 – Abitibi-Témiscamingue:Right (9)	○	○	○
Region 10 – Cantons-de-l'Est:Right (10)	○	○	○
Region 11 – Montérégie:Right (11)	○	○	○
Region 12 – Laurentides:Right (12)	○	○	○
Region 13 – Outaouais:Right (13)	○	○	○

Display this question:

If Rank the district/region you snowmobile in most often: = Quebec

Q1bi Do you also ride in Ontario?

- ○ Yes (1)
- ○ No (2)

Display this question:

If Do you also ride in Ontario? = Yes

Q2 How do you typically travel to your snowmobile trails? (check all that apply)

- ☐ I ride my snowmobile directly from my property (1)
- ☐ I tow my snowmobile from a property to a trail head (2)

Display this question:

If How do you typically travel to your snowmobile trails? (check all that apply) = I ride my snowmobile directly from my property

Q2ai What are the first three digits of your postal code?

_____

Display this question:

If How do you typically travel to your snowmobile trails? (check all that apply) = I ride my snowmobile directly from my property

Q2aiii If you could not ride directly from your property due to poor snow conditions, would you be willing to tow your snowmobile to a trail head?

- ○ Yes (1)
- ○ No (2)

Skip To: Q3 If you could not ride directly from your property due to poor snow conditions, would you be willi... = No

Q2bi What is the maximum distance you would travel/tow your sled for a day trip (km)?

_____

Display this question:

If How do you typically travel to your snowmobile trails? (check all that apply) = I tow my snowmobile from a property to a trail head

Q2bii What are the first three digits of your postal code?

_____

Q3 When the trails you snowmobiled on were closed last season (2023-2024) due to poor snow conditions, what did you do?

- ○ I snowmobiled less (i.e., stopped and waited for my trails to open) (1)
- ○ I snowmobiled the same amount (2)
- ○ I snowmobiled more (3)
- ○ I have never experienced trail closures (4)

Display this question:

If When the trails you snowmobiled on were closed last season (2023-2024) due to poor snow condition... = I snowmobiled the same amount

Q3a In order to snowmobile the same amount despite trail closures, what did you do? (check all that apply)

- ☐ Once my trails were open I snowmobiled more frequently to make up for the shortened season
- ☐ I travelled to other trails WITHIN my district/region
- ☐ I travelled to other trails OUTSIDE my district/region
- ☐ Other _____

Display this question:

If When the trails you snowmobiled on were closed last season (2023-2024) due to poor snow condition... = I snowmobiled more

Q3b In order to snowmobile more despite trail closures, what did you do? (check all that apply)

- ☐ Once my trails were open I snowmobiled more frequently to make up for the shortened season
- ☐ I travelled to other trails WITHIN my district/region
- ☐ I travelled to other trails OUTSIDE my district/region
- ☐ Other _____

Display this question:

If When the trails you snowmobiled on were closed last season (2023-2024) due to poor snow condition... = I have never experienced trail closures

Q3c If you were to experience trail closures due to poor snow conditions, what would you do?

- ○ I would snowmobile less (i.e., stop and wait for my trails to open) (1)
- ○ I would snowmobile the same amount (2)
- ○ I would snowmobile more (3)
- ○ Other (4) _____

Display this question:

If If you were to experience trail closures due to poor snow conditions, what would you do? = I would snowmobile the same amount

Q3ci In order to snowmobile the same amount despite trail closures, what would you do?

- ○ I would travel to other trails WITHIN my district/region (1)
- ○ I would travel to other trails OUTSIDE my district/region (2)
- ○ Other (3) _____

Display this question:

If If you were to experience trail closures due to poor snow conditions, what would you do? = I would snowmobile more

Q3cii In order to snowmobile more despite trail closures, what would you do?

- ○ I would travel to other trails WITHIN my district/region (1)
- ○ I would travel to other trails OUTSIDE my district/region (2)
- ○ Other (3) _____

Q4 If ____% of the trails I typically snowmobile on were closed, I would not go snowmobiling and wait for better snow conditions:

- ○ Over 90% (1)
- ○ 80-89% (2)
- ○ 70-79% (3)
- ○ 60-69% (4)
- ○ 50-59% (5)
- ○ 40-49% (6)
- ○ 30-39% (7)
- ○ 20-29% (8)
- ○ < 20% (11)

Q5 If the snowmobile season in my district/region were to shorten to ____ weeks, I would stop purchasing a snowmobile pass/permit:

- ○ 10-11 weeks (1)
- ○ 8-9 weeks (2)
- ○ 6-7 weeks (3)
- ○ 4-5 weeks (4)
- ○ 2-3 weeks (5)
- ○ 1 week or less (6)

Q6 How likely are you to snowmobile in the following conditions?

	Very Unlikely (1) (1)	Unlikely (2) (2)	Neutral (3) (3)	Likely (4) (4)	Very Likely (5) (5)
Inability to make loops or sled long distances (e.g., full trail length closed or not connected to other trails) (1)	○	○	○	○	○
Water crossing closed (e.g., river, lake) (2)	○	○	○	○	○
Limited access to services and facilities (3)	○	○	○	○	○
When planning to go snowmobiling, how likely are you to check the trail status before riding (e.g., interactive trail map)? (8)	○	○	○	○	○

Q7 How many days per week do you typically snowmobile in a season?

- Less than once per week (< 1 day) (1)
- 1 day (2)
- 2 days (3)
- 3 days (4)
- 4 days (5)
- 5 days (6)
- 6 days (7)
- Every day (7 days) (8)

Display this question:

If How many days per week do you typically snowmobile in a season? = Less than once per week (< 1 day)

Q7a How many times per month do you typically snowmobile?

- 3 times per month (1)
- 2 times per month (2)
- Once per month (3)
- Less than once per month (4)

Q8 When do you typically go snowmobiling? (Check all that apply):

- ☐ Weekday (1)
- ☐ Weekend (2)
- ☐ Winter holidays (e.g. Dec 23 - Jan 5) (3)
- ☐ Long weekend (e.g. Family Day) (4)
- ☐ School break (e.g. March Break) (5)
- ☐ Other (6) _____

Q9 What type of snowmobile trip do you typically take each season (Check all that apply):

- ☐ Day trips (1)
- ☐ Multi-day (overnight) trips (2)

Display this question:

If What type of snowmobile trip do you typically take each season (Check all that apply): = Multi-day (overnight) trips

Q9a How many multi-day (overnight) trips do you typically take each season?

- 1 (1)
- 2 (2)
- 3 (3)
- 4 (4)
- 5+ (5)

Display this question:

If What type of snowmobile trip do you typically take each season (Check all that apply): = Multi-day (overnight) trips

Q9b How many nights do you typically stay over?

- 1 night (1)
- 2 nights (2)
- 3 nights (3)
- 4 nights (4)
- 5+ nights (5)

Page Break

Display this question:

If What type of snowmobile trip do you typically take each season (Check all that apply): = Multi-day (overnight) trips

Q9c What is the maximum distance you would travel/tow your sled for a multi-day (overnight) trip (km)?

_____

Appendix B: ABM Code

```
extensions [gis csv table]

globals [
  OFSC-District
  snowmobilers-data
  district-status
  current-day
  district1-turtles
  district2-turtles
  district3-turtles
  district4-turtles
  district5-turtles
  district6-turtles
  district7-turtles
  district8-turtles
  district9-turtles
  district10-turtles
  district11-turtles
  district12-turtles
  district13-turtles
  district14-turtles
  district15-turtles
  district17-turtles
  initial-snowmobilers
  world-envelope
  total-non-renewals
  average-successful-weeks
  renewal-rate
  all-district-numbers
  snowmobiler-stats      ; Global list to track all snowmobilers
  district-trail-lengths ; Store trail lengths of each district for density
calculations
  district-densities     ; Store current density of each district
  density-threshold      ; Density at which enjoyment starts to decline

  ; Social influence globals
  district-popularity    ; Table storing the current popularity of each district
  ;social-influence-weight ; How much social influence affects decision-making
(0-1)
]

turtles-own [
  my-district
  max-travel-distance
  current-trip-distance
```

```
  home-location
  has-moved?          ; Tracks if snowmobiler moved on the current day
  active-today?       ; Tracks if snowmobiler is active on current day
  closure-threshold
  successful-weeks
  last-ride-week
  will-renew?
  snowmobiler-id      ; Unique ID for each snowmobiler
  district-experience ; Table to store experience points for each district
  last-visited-district ; Last district successfully visited
  enjoyment-today     ; Today's enjoyment level (affected by density)

  ; Social influence variables
  social-influence?     ; Whether this snowmobiler is influenced by others (70%
are)
  influenced-districts  ; List of districts the snowmobiler has heard good things
about
]

to setup
  clear-all
  resize-world -500 500 -500 500
  set-patch-size 0.5
  setup-maps
  set-trail-lengths
  load-snowmobilers-data
  set initial-snowmobilers []
  set snowmobiler-stats []  ; Initialize the tracking list
  ; Create a list of all district numbers
  set all-district-numbers (list 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 17)
  ; Initialize district densities table
  set district-densities table:make
  foreach all-district-numbers [ d ->
    table:put district-densities (word d) 0
  ]
  ; Set density threshold (snowmobilers per km of trail)
  set density-threshold 3.0

  ; Initialize district popularity
  set district-popularity table:make
  foreach all-district-numbers [ d ->
    table:put district-popularity (word d) 0
  ]

  ; Set default social influence weight (adjustable via slider)
  set social-influence-weight 0.3

  create-snowmobilers
  set current-day 0

  ; Load district status data
```

```
  file-open "daily_status_2.csv"
  set district-status []
  while [not file-at-end?] [
    let line csv:from-row file-read-line
    set district-status lput line district-status
  ]
  file-close
  reset-ticks
end

to setup-maps
  set OFSC-District gis:load-dataset "OFSC_Districts_Project1.shp"
  set world-envelope gis:envelope-of OFSC-District
  gis:set-world-envelope world-envelope
  let districts gis:feature-list-of OFSC-District
  let colors [gray red orange brown yellow green lime turquoise cyan sky blue
violet magenta pink black white gray]

  foreach districts [ district ->
    let district-number gis:property-value district "OFSCDIST"
    let district-color item (district-number mod length colors) colors
    ask patches with [gis:intersects? district self] [
      set pcolor district-color
    ]
  ]
end

to set-trail-lengths
  set district-trail-lengths table:make

  ; Set trail lengths based on provided node counts (100m per node)
  table:put district-trail-lengths "1" 28928 * 0.1  ; Convert to km (100m = 0.1km
per node)
  table:put district-trail-lengths "2" 11394 * 0.1
  table:put district-trail-lengths "3" 7887 * 0.1
  table:put district-trail-lengths "4" 3846 * 0.1
  table:put district-trail-lengths "5" 17694 * 0.1
  table:put district-trail-lengths "6" 16693 * 0.1
  table:put district-trail-lengths "7" 9865 * 0.1
  table:put district-trail-lengths "8" 7716 * 0.1
  table:put district-trail-lengths "9" 19136 * 0.1
  table:put district-trail-lengths "10" 6530 * 0.1
  table:put district-trail-lengths "11" 16840 * 0.1
  table:put district-trail-lengths "12" 12807 * 0.1
  table:put district-trail-lengths "13" 19168 * 0.1
  table:put district-trail-lengths "14" 14023 * 0.1
  table:put district-trail-lengths "15" 16643 * 0.1
  table:put district-trail-lengths "17" 20526 * 0.1
end

to load-snowmobilers-data
```

```
  set snowmobilers-data csv:from-file "preferences2.csv"
end


to-report netlogo-to-world-coords [x y]
  let gis-width item 1 world-envelope - item 0 world-envelope
  let gis-height item 3 world-envelope - item 2 world-envelope

  let real-x item 0 world-envelope + (gis-width * (x - min-pxcor) / (max-pxcor -
min-pxcor))
  let real-y item 2 world-envelope + (gis-height * (y - min-pycor) / (max-pycor -
min-pycor))

  report list real-x real-y
end

; Calculate real-world distance between two points
to-report gis-distance [coord1 vertex]
  let x1 item 0 coord1
  let y1 item 1 coord1
  let coords gis:location-of vertex
  let x2 item 0 coords
  let y2 item 1 coords

  let dist sqrt ((x2 - x1) ^ 2 + (y2 - y1) ^ 2)
  report dist / 1000  ; Convert to kilometers
end

; Find the closest point in target district and return distance
to-report find-closest-district-distance [target-district-num start-x start-y]
  let target-district one-of (gis:find-features OFSC-District "OFSCDIST" target-
district-num)
  if target-district = nobody [ report false ]

  let start-coords netlogo-to-world-coords start-x start-y
  let min-distance 999999
  let closest-point false

  let boundary-points gis:vertex-lists-of target-district

  foreach boundary-points [ points ->
    foreach points [ point ->
      let dist gis-distance start-coords point
      if dist < min-distance [
        set min-distance dist
        set closest-point point
      ]
    ]
  ]

  report min-distance
```

```
end

to-report assign-closure-threshold
  let rand random-float 100
  if rand < 26.0 [ report 90 ]  ; Most flexible group
  if rand < 33.5 [ report 80 ]
  if rand < 45.8 [ report 70 ]
  if rand < 57.4 [ report 60 ]
  if rand < 82.1 [ report 50 ]
  if rand < 86.9 [ report 40 ]
  if rand < 93.7 [ report 30 ]
  report 20                     ; Least flexible group
end

; create-snowmobilers to include social influence variables
to create-snowmobilers
  let id-counter 0
  foreach snowmobilers-data [ row ->
    let district-name item 0 row

    set initial-snowmobilers lput (list district-name) initial-snowmobilers
    let district one-of (gis:find-features OFSC-District "OFSCDIST" district-
name)

    if district != nobody [
      create-turtles 1 [
        set my-district district-name
        set max-travel-distance random-normal 239.8 100
        if max-travel-distance > 2000 [ set max-travel-distance 2000 ]
        if max-travel-distance < 50 [ set max-travel-distance 50 ]
        set successful-weeks 0    ; Initialize successful weeks counter
        set last-ride-week -1     ; Initialize last ride week
        set will-renew? true      ; Initialize renewal status
        set closure-threshold assign-closure-threshold
        set snowmobiler-id id-counter
        set active-today? false   ; Will be determined each day
        set district-experience table:make  ; Initialize empty experience table
        set last-visited-district 0
        set enjoyment-today 0

        ; Initialize social influence variables
        set social-influence? random-float 1 < 0.7  ; 70% of snowmobilers are
socially influenced
        set influenced-districts []

        let new-entry (list snowmobiler-id district-name max-travel-distance
successful-weeks will-renew?)
        set snowmobiler-stats lput new-entry snowmobiler-stats

        let target-patch one-of patches with [gis:intersects? district self]
        if target-patch != nobody [
```

```
          move-to target-patch
          set home-location netlogo-to-world-coords xcor ycor
        ]
      ]
      set id-counter id-counter + 1
    ]
  ]
end

to go
  ; Reset all snowmobilers to their home district and reset active-today status
  ask turtles [
    let home-district one-of (gis:find-features OFSC-District "OFSCDIST" my-
district)
    let home-patch one-of patches with [gis:intersects? home-district self]
    if home-patch != nobody [
      move-to home-patch
    ]
    set has-moved? false
    set active-today? false
    set enjoyment-today 0
    show-turtle  ; Make sure all turtles are visible at the start of the day
  ]



  ; Reset daily density counts
  foreach all-district-numbers [ d ->
    table:put district-densities (word d) 0
  ]

  let current-week floor (current-day / 7)
  let is-weekend (day-of-week current-day) = 6 or (day-of-week current-day) = 0
  print (word "Is weekend: " is-weekend)

  ; Process each snowmobiler
  ask turtles [
    if (is-weekend and random-float 1 <= 0.8) or (not is-weekend and random-float
1 <= 0.65) [
      ; First try: check if home district is viable
      let home-district-num 0
      ifelse is-string? my-district [
        set home-district-num read-from-string my-district
      ] [
        set home-district-num my-district  ; It's already a number
      ]
      let home-district one-of (gis:find-features OFSC-District "OFSCDIST" home-
district-num)
      let home-district-index ifelse-value (home-district-num = 17) [15] [home-
district-num - 1]
```

```
      ; Make sure index is within bounds
      if home-district-index >= 0 and home-district-index < length item 0
district-status and
         current-day >= 0 and current-day < length district-status [

        let home-closure-percentage item home-district-index item current-day
district-status

        ; If home district is open enough, stay there
        ifelse home-closure-percentage <= closure-threshold [
          let home-patch one-of patches with [gis:intersects? home-district self]
          if home-patch != nobody [
            move-to home-patch
            set has-moved? true
            set active-today? true
            set current-trip-distance 0  ; No travel distance for home district

            ; Update last visited district
            set last-visited-district home-district-num

            ; Increment the density counter for this district
            let district-key (word home-district-num)
            let current-count 0
            if table:has-key? district-densities district-key [
              set current-count table:get district-densities district-key
            ]
            table:put district-densities district-key (current-count + 1)

            ; Update successful weeks if this is first activity in this week
            if current-week != last-ride-week [
              set successful-weeks successful-weeks + 1
              set last-ride-week current-week

              ; Update the stats in the global list
              update-snowmobiler-stats snowmobiler-id successful-weeks will-
renew?
            ]


          ]
        ]
        [
          ; Home district is too closed, try all districts by distance including
home
          let available-districts all-district-numbers  ; Include all districts
          let sorted-districts []
          let current-pos (list xcor ycor)

          ; First calculate distances to all districts
          let district-distances []
          foreach available-districts [ target ->
```

```
            let dist find-closest-district-distance target xcor ycor
            if dist != false and dist <= max-travel-distance [
              ; For home district, might want to give it special consideration
              if target = home-district-num [
                ; Home district gets distance 0 or a very small value to
prioritize it
                ; This ensures it's always first in the sorted list
                set dist 0.1
              ]
              set district-distances lput (list target dist) district-distances
            ]
          ]

          ; Sort districts by distance (closest first)
          set sorted-districts map first (sort-by [ [a b] -> item 1 a < item 1 b
] district-distances)

          ; Variables to track the selected district
          let selected-district 0
          let selected-patch nobody
          let found-district? false

          ; Try districts in order of increasing distance
          foreach sorted-districts [ target ->
            ; Skip if we already found a district
            if not found-district? [
              let target-district one-of (gis:find-features OFSC-District
"OFSCDIST" target)
              let target-patch one-of patches with [gis:intersects? target-
district self]

              if target-patch != nobody [
                ; Calculate closure percentage
                let target-status-index ifelse-value (target = 17) [15] [target -
1]

                ; Make sure index is within bounds
                if target-status-index >= 0 and target-status-index < length item
0 district-status and
                   current-day >= 0 and current-day < length district-status [

                  let target-closure-percentage item target-status-index item
current-day district-status

                  ; If district is open enough, select it
                  if target-closure-percentage <= closure-threshold [
                    set selected-district target
                    set selected-patch target-patch
                    set found-district? true

                  ]
```

```
                ]
              ]
            ]
          ]

          ; If we found a district, move the snowmobiler there
          if found-district? [
            move-to selected-patch
            set has-moved? true
            set active-today? true
            set current-trip-distance find-closest-district-distance selected-
district [pxcor] of patch-here [pycor] of patch-here



            ; Increment the density counter for this district
            let district-key (word selected-district)
            let current-count 0
            if table:has-key? district-densities district-key [
              set current-count table:get district-densities district-key
            ]
            table:put district-densities district-key (current-count + 1)

            ; Update last visited district
            set last-visited-district selected-district

            ; Update successful weeks if this is first activity in this week
            if current-week != last-ride-week [
              set successful-weeks successful-weeks + 1
              set last-ride-week current-week

              ; Update the stats in the global list
              update-snowmobiler-stats snowmobiler-id successful-weeks will-
renew?
            ]
          ]
        ]
      ]
    ]
  ]

  ; Calculate density based on trail length and update enjoyment
  calculate-trail-densities

  ; Process each active snowmobiler to determine enjoyment and update experience
  ask turtles with [active-today?] [
    ; Get the density of their current district
    let district-key (word last-visited-district)
    let current-density 0
    if table:has-key? district-densities district-key [
      set current-density table:get district-densities district-key
```

```
    ]

    ; Calculate enjoyment (1-10 scale)
    ifelse current-density <= density-threshold [
      ; Full enjoyment if below threshold
      set enjoyment-today 10
    ][
      ; Decreasing enjoyment as density increases
      let density-ratio current-density / density-threshold
      set enjoyment-today max list 1 (10 - (density-ratio - 1) * 5)
    ]

    ; Add experience based on enjoyment
    add-district-experience last-visited-district enjoyment-today
  ]

  ; Update district popularity and spread recommendations
  update-district-popularity
  spread-district-recommendations

  ; Hide inactive snowmobilers from view (those who didn't move today)
  ask turtles with [not active-today?] [
    hide-turtle
  ]

  ; If it's the last day of the season, determine renewal decisions and update
global statistics
  if current-day = 121 [
    ; Process renewal decisions for all snowmobilers
    foreach snowmobiler-stats [ stats-entry ->
      let sm-id item 0 stats-entry
      let sm-weeks item 3 stats-entry
      let renewal-decision determine-renewal sm-weeks

      ; Update renewal status in global tracking list
      update-snowmobiler-renewal sm-id renewal-decision

      ; Also update turtles
      ask turtles with [snowmobiler-id = sm-id] [
        set will-renew? renewal-decision
      ]
    ]
    update-global-statistics
  ]

  update-district-counts

  set current-day (current-day + 1) mod 122
  tick
  if ticks >= 122 [stop]
end
```

```
to-report calculate-district-score [target-district-num start-x start-y current-
threshold max-dist]

  ; Handle special case for home district
  let is-home-district? false
ifelse is-string? my-district [
  set is-home-district? target-district-num = read-from-string my-district
] [
  set is-home-district? target-district-num = my-district
]
  let home-district-bonus 0

  if is-home-district? [
   ; print "  This is agent's home district - applying home bonus"
    set home-district-bonus 20
  ]

  ; Calculate travel distance
  let travel-distance find-closest-district-distance target-district-num start-x
start-y
  print (word "  Travel distance: " travel-distance)

  if travel-distance = false [

    report 0
  ]

  ; Skip distance check for home district
  if (not is-home-district?) and travel-distance > max-dist [
    ;print (word "  FAILED: Distance " travel-distance " exceeds max " max-dist)
    report 0
  ]

  ; Calculate status index
  let status-index ifelse-value (target-district-num <= 15)
    [target-district-num - 1]
    [15]


  ; Check if it's an invalid district number
  if target-district-num != 17 and target-district-num > 15 [
    print "  FAILED: Invalid district number"
    report 0
  ]

  ; Check bounds
  if status-index < 0 or status-index >= length item 0 district-status [
    print (word "  FAILED: Invalid status index: " status-index)
    report 0
  ]
```

```
  if current-day < 0 or current-day >= length district-status [

    report 0
  ]

  ; Check closure
  let closure-percentage item status-index item current-day district-status
  let open-percentage 100 - closure-percentage


  if closure-percentage > current-threshold [

    report 0
  ]

  ; Calculate factors
  let distance-factor 0
  ifelse is-home-district? [
    ; For home district, use perfect distance factor
    set distance-factor 1
  ] [
    ; For other districts, calculate based on distance
    set distance-factor (1 - (travel-distance / max-dist))
    if distance-factor < 0 [ set distance-factor 0 ]
  ]


  let openness-factor (open-percentage / 100) ^ 2
  ;print (word "  Openness factor: " openness-factor)

  ; Get experience bonus
  let experience-bonus 0
  if table:has-key? district-experience (word target-district-num) [
    let exp-points table:get district-experience (word target-district-num)
    set experience-bonus min list (exp-points * 0.03) 0.3
  ]

  ; Calculate density penalty
  let density-penalty 0
  if table:has-key? district-densities (word target-district-num) [
    let current-density table:get district-densities (word target-district-num)
    if current-density > density-threshold [
      set density-penalty min list (0.5) ((current-density - density-threshold) /
(density-threshold * 2))
    ]
  ]


  ; Calculate base score
  let base-score (distance-factor * 0.25 + openness-factor * 0.55 + experience-
```

```
bonus * 0.2 - density-penalty) * 100
  if base-score < 0 [ set base-score 0 ]
  ;print (word "  Base score: " base-score)

  ; Calculate social influence score
  let social-score 0

  if social-influence? [
    if member? target-district-num influenced-districts [
      set social-score 50
      ;print "  Socially influenced for this district"
    ]

    let district-key (word target-district-num)
    if table:has-key? district-popularity district-key [
      let popularity table:get district-popularity district-key
      let popularity-score min list 50 (popularity * 2)
      set social-score max list social-score popularity-score
    ]
  ]


  ; Ensure social-influence-weight is defined
  let influence-weight 0.3  ; Default value
  carefully [
    set influence-weight social-influence-weight
  ] [

  ]

  ; Calculate final score
  let final-score (base-score * (1 - influence-weight)) + (social-score *
influence-weight) + home-district-bonus
  print (word "  Final score: " final-score)

  report final-score
end

; Calculate the density (snowmobilers per km of trail) for each district
to calculate-trail-densities
  foreach all-district-numbers [ d ->
    let district-key (word d)

    ; Get the count of snowmobilers in this district
    let snowmobiler-count 0
    if table:has-key? district-densities district-key [
      set snowmobiler-count table:get district-densities district-key
    ]

    ; Get the trail length of this district
    let trail-length 1 ; Default to 1 km to avoid division by zero
```

```
    if table:has-key? district-trail-lengths district-key [
      set trail-length table:get district-trail-lengths district-key
    ]

    ; Calculate density (snowmobilers per kilometer of trail)
    let density snowmobiler-count / trail-length

    ; Update the district density
    table:put district-densities district-key density
  ]
end

; Add experience to a district based on enjoyment level
to add-district-experience [district-num enjoyment]
  let district-key (word district-num)  ; Convert to string for table key

  ifelse table:has-key? district-experience district-key [
    ; Current experience points
    let current-exp table:get district-experience district-key

    ; Calculate experience gain based on enjoyment (0.1 to 1.0)
    let exp-gain enjoyment / 10

    ; Add experience, but cap at maximum of 10
    table:put district-experience district-key min list (current-exp + exp-gain)
10
  ] [
    ; First visit to this district - start with experience based on enjoyment
    table:put district-experience district-key (enjoyment / 10)
  ]
end

;Procedure to update district popularity based on activity
to update-district-popularity
  ; Decay popularity over time (10% decay each day)
  foreach all-district-numbers [ d ->
    let district-key (word d)
    if table:has-key? district-popularity district-key [
      let current-popularity table:get district-popularity district-key
      table:put district-popularity district-key (current-popularity * 0.9)
    ]
  ]

  ; Count today's active snowmobilers by district
  foreach all-district-numbers [ d ->
    let district-key (word d)
    let active-count count turtles with [active-today? and last-visited-district
= d]
    if table:has-key? district-popularity district-key [
      let current-popularity table:get district-popularity district-key
      table:put district-popularity district-key (current-popularity + active-
```

```
count)
    ]
  ]
end


to spread-district-recommendations
  ; Snowmobilers with good experiences (enjoyment > 7) will share with others
  ask turtles with [active-today? and enjoyment-today > 7] [
    ; Randomly share with a percentage of other snowmobilers
    let recommender-district last-visited-district
    let number-to-influence 5 + random 10  ; Influence 5-14 other snowmobilers

    ask up-to-n-of number-to-influence other turtles with [social-influence?] [
      ; Only add the recommendation if it's not already there
      if not member? recommender-district influenced-districts [
        set influenced-districts lput recommender-district influenced-districts


        if length influenced-districts > 5 [
          set influenced-districts but-first influenced-districts
        ]
      ]
    ]
  ]
end

to update-snowmobiler-stats [id weeks renewal]
  let i 0
  foreach snowmobiler-stats [ entry ->
    if item 0 entry = id [
      ; Create updated entry
      let district-name item 1 entry
      let max-dist item 2 entry
      let new-entry (list id district-name max-dist weeks renewal)


      set snowmobiler-stats replace-item i snowmobiler-stats new-entry
    ]
    set i i + 1
  ]
end


to update-snowmobiler-renewal [id renewal-decision]
  let i 0
  foreach snowmobiler-stats [ entry ->
    if item 0 entry = id [
      ; Create updated entry with new renewal status
      let district-name item 1 entry
      let max-dist item 2 entry
```

```
      let weeks item 3 entry
      let new-entry (list id district-name max-dist weeks renewal-decision)

      set snowmobiler-stats replace-item i snowmobiler-stats new-entry
    ]
    set i i + 1
  ]
end

; Determine the day of the week given the current day
to-report day-of-week [day]
  report (day + 5) mod 7 ; December 1, 2023 is a Friday (5th day of the week
starting from Sunday)
end

to-report determine-renewal [weeks]
  let will-renew false
  let rand random-float 100
  let probability 0

  if weeks <= 1 [ set probability 21.33 ]
  if weeks > 1 and weeks <= 3 [ set probability 51.33 ]  ; 21.33 + 30.0
  if weeks > 3 and weeks <= 5 [ set probability 78.66 ]  ; 21.33 + 30.0 + 27.33
  if weeks > 5 and weeks <= 7 [ set probability 91.33 ]  ; 21.33 + 30.0 + 27.33 +
12.67
  if weeks > 7 and weeks <= 9 [ set probability 94.66 ]  ; 21.33 + 30.0 + 27.33 +
12.67 + 3.33
  if weeks > 9 and weeks <= 11 [ set probability 99.99 ] ; 21.33 + 30.0 + 27.33 +
12.67 + 3.33 + 5.33
  if weeks > 11 [ set probability 100 ]  ; Always renew if more than 11 weeks

  if rand < probability [ set will-renew true ]

  report will-renew
end

to update-global-statistics
  ; Calculate statistics from our global tracking list
  let total-count length snowmobiler-stats
  let renewal-count 0
  let total-weeks 0

  foreach snowmobiler-stats [ stats ->
    let weeks item 3 stats
    let will-renew item 4 stats

    set total-weeks total-weeks + weeks
    if will-renew [
      set renewal-count renewal-count + 1
    ]
  ]
```

```
  ; Update global variables
  set total-non-renewals total-count - renewal-count
  set average-successful-weeks ifelse-value (total-count > 0) [total-weeks /
total-count] [0]
  set renewal-rate ifelse-value (total-count > 0) [(renewal-count / total-count)
* 100] [0]
end

to-report get-average-successful-weeks
  report average-successful-weeks
end

to-report get-renewal-rate
  report renewal-rate
end

to-report get-total-non-renewals
  report total-non-renewals
end


to update-district-counts
  ; Create a list to temporarily store counts for debugging
  let district-counts []

  ; Count active snowmobilers by their last visited district (where they're
currently active)
    foreach all-district-numbers [ d ->
    let count-in-district count turtles with [active-today? and last-visited-
district = d]
    set district-counts lput (list d count-in-district) district-counts

    if d = 1 [ set district1-turtles count-in-district ]
    if d = 2 [ set district2-turtles count-in-district ]
    if d = 3 [ set district3-turtles count-in-district ]
    if d = 4 [ set district4-turtles count-in-district ]
    if d = 5 [ set district5-turtles count-in-district ]
    if d = 6 [ set district6-turtles count-in-district ]
    if d = 7 [ set district7-turtles count-in-district ]
    if d = 8 [ set district8-turtles count-in-district ]
    if d = 9 [ set district9-turtles count-in-district ]
    if d = 10 [ set district10-turtles count-in-district ]
    if d = 11 [ set district11-turtles count-in-district ]
    if d = 12 [ set district12-turtles count-in-district ]
    if d = 13 [ set district13-turtles count-in-district ]
    if d = 14 [ set district14-turtles count-in-district ]
    if d = 15 [ set district15-turtles count-in-district ]
    if d = 17 [ set district17-turtles count-in-district ]
  ]
```

```
  ; Debug print to check total active
  print (word "Total active turtles: " count turtles with [active-today?])
  print (word "District counts: " district-counts)
end
; Reporter to get the total number of active snowmobilers today
to-report get-active-today-count
  report count turtles with [active-today?]
end

; Reporter to get current density of a district
to-report get-district-density [district-num]
  let density 0
  if table:has-key? district-densities (word district-num) [
    set density table:get district-densities (word district-num)
  ]
  report density
end

; Reporter to get trail length of a district
to-report get-district-trail-length [district-num]
  let trail-len 0
  if table:has-key? district-trail-lengths (word district-num) [
    set trail-len table:get district-trail-lengths (word district-num)
  ]
  report trail-len
end

; Reporter to get a snowmobiler's experience for a specific district
to-report get-district-experience [sm-id district-num]
  let experience 0

  ask turtles with [snowmobiler-id = sm-id] [
    if table:has-key? district-experience (word district-num) [
      set experience table:get district-experience (word district-num)
    ]
  ]

  report experience
end

; Reporter to get average enjoyment across all active snowmobilers
to-report get-average-enjoyment
  ifelse any? turtles with [active-today?] [
    report mean [enjoyment-today] of turtles with [active-today?]
  ] [
    report 0
  ]
end

to-report export-snowmobiler-stats
  report snowmobiler-stats
```

```
end

; Reporter to get the current popularity of a district
to-report get-district-popularity [district-num]
  let popularity 0
  let district-key (word district-num)

  if table:has-key? district-popularity district-key [
    set popularity table:get district-popularity district-key
  ]

  report popularity
end

; Reporter to check if a snowmobiler is socially influenced
to-report is-socially-influenced? [sm-id]
  let influenced? false

  ask turtles with [snowmobiler-id = sm-id] [
    set influenced? social-influence?
  ]

  report influenced?
end

; Reporter to get the number of socially influenced snowmobilers
to-report count-socially-influenced
  report count turtles with [social-influence?]
end
```

Appendix C: Entities and Scales

The model has two types of entities (snowmobilers, the environment) and two scales (spatial, temporal), which are detailed below.

Snowmobilers (agents): Each snowmobiler agent has 16 attributes including:

my-district: Home district (integer 1-15 or 17)

max-travel-distance: Maximum distance willing to travel (kilometers)

current-trip-distance: Distance of current trip (kilometers)

home-location: Coordinates (x, y) of home location

has-moved?: Boolean indicating if snowmobiler moved today (true or false)

active-today?: Boolean indicating if snowmobiler is active today (true or false)

closure-threshold: Maximum percentage (%) of closed trails tolerated

successful-weeks: Count of weeks with successful riding (counter)

last-ride-week: Last week in which the agent went riding (counter)

will-renew?: Boolean indicating renewal decision, will snowmobilers buy their permit again next season (true or false)

snowmobiler-id: Unique identifier (integer)

district-experience: Table storing experience points for each district (scale 1-10)

last-visited-district: Most recently visited district (district number)

enjoyment-today: Enjoyment level for today's riding (scale 1-10)

social-influence?: Boolean indicating if this snowmobiler is influenced by others (true or false)

influenced-districts: List of districts the snowmobiler has heard good things about

Environment: The environment represents Ontario's 30,000km snowmobile trail system which are divided into 16 individual districts and include the following five environmental state variables:

district-status: Percent of trails closed in each district for each day

district-trail-lengths: Length of trail network in each district (kilometers)

district-densities: Current snowmobiler density in each district (riders/km)
density-threshold: Density level at which enjoyment begins to decline (riders/km)
district-popularity: Table storing the current popularity of each district (calculated value)

Spatial scale: The model incorporates actual geographic boundaries of Ontario's 16 snowmobiling districts through a shapefile loaded with the GIS extension for NetLogo. The patches in NetLogo are the basic units of the grid that make up the world. In this case the spatial resolution of each patch represents an area of approximately 5x5 meters.

Temporal scale: One winter snowmobile season (122 days, December through March), with each time step representing one day (i.e., temporal resolution).