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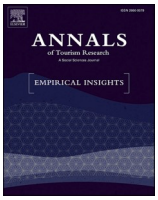

Systems thinking to adapt tourism to climate change: Application to summer glacier skiing in Switzerland

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ABSTRACT

Climate change affects mountain tourism and summer glacier skiing, a highly vulnerable activity. This paper explores the complex dynamics affecting summer glacier skiing in Swiss Alpine destinations. The methodology involved conducting 26 semi-structured interviews followed by three workshops with tourism stakeholders. Applying systems thinking, this research highlights the challenges faced by summer glacier skiing destinations and the ongoing commitment required amid evolving cryosphere dynamics. Sustaining summer glacier skiing touches on vulnerability factors in climatic and socioeconomic dimensions. The disappearance of the activity has implications for the cable car companies, the hospitality sector and the wider mountain tourism industry. The systems thinking approach in this research reveals feedback loops and leverage points, such as uncertainties about the future of the activity.

1. Introduction

Tourism faces dual challenges with respect to climate change: adapting to its impacts as well as reducing the industry's contribution to greenhouse gas emissions (Scott, 2024). Tourism researchers have explored the impacts of climate change on tourism and the adaptation measures that can be implemented in response (Steiger, Knowles, Pöll, & Rutty, 2022). However, the complex interrelationships among destination stakeholders—especially in mountain areas, where both climate change impacts and tourism specialization are very high—require a systemic perspective. The study of mountain tourism through this lens is particularly noteworthy, as some activities are highly vulnerable to climate change. One such activity is summer glacier skiing, which is both a recreational and athletic sports activity that involves skiing outside the conventional winter season, on glaciers, from May to November (Mayer & Abegg, 2022). The cryosphere, which includes snow cover and glacier surfaces, serves as a core element for glacier skiing. Several studies over recent decades have generated insights into the dynamics of glacier skiing (Fischer, Olefs, & Abermann, 2011; Mayer & Abegg, 2022; Salim, Ravanel, Bourdeau, & Deline, 2021); however, in the context of continuing cryospheric degradation (IPCC, 2022), much remains to be understood about the role of niche activities (such as summer glacier skiing) at a destination.

In the mid-1960s, the development of high-altitude glacier skiing infrastructures—including ski lifts, slopes, and access and exits—began in the Alps (Schmude & Berghammer, 2015). These developments, often referred to as the "Invention Phase", were characterized by rapid growth in the product life cycle of skiing (König, 1994; Schmude & Berghammer, 2015). During the 1970s and early 1980s, summer glacier skiing experienced an upswing before it stagnated and then declined (Falk, 2016; König & Abegg, 1997; Schmude & Berghammer, 2015). In Switzerland, seven of the nine destinations have had to cease their summer glacier skiing operations since the 1980s, due to poor snow conditions (König & Abegg, 1997). Saas-Fee and Zermatt, the remaining destinations with summer glacier skiing infrastructures, still operate in July and August (Marx, 2021; Schmude & Berghammer, 2015), but they face significant challenges due to glacier retreat (Abegg & Mayer, 2023).

During summer 2022, Zermatt and Saas-Fee were forced to restrict access to summer glacier skiing infrastructures due to lack of snow and high temperatures (Baur, 2022). Such climate-related challenges, coupled with a strong specialization in ski tourism (Bonnemains, 2014; Mayer & Abegg, 2022) and a declining trend in ski visitors (Demiroglu, Dannevig, & Aall, 2018; Vanat, 2022), reveal the limitations of current snow management (Mayer & Abegg, 2022) and pose a problematic

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vulnerability to small destinations that rely on snow-related tourism (Movono, Dahles, & Becken, 2018; Parsons, Brown, Nalau, & Fisher, 2018). Imagining that the business model of summer glacier skiing might be approaching a tipping point—possibly leading to the end of the activity—raises the question about the impact of such an outcome on the destination, given the activity's contribution to regional development.

A systems thinking approach that is centered on the destination will provide a deep and comprehensive understanding of the causative dynamics with respect to the following research questions (Loehr & Becken, 2023; Wilbanks & Kates, 1999): *How do climate-related vulnerability factors affect the diverse summer glacier skiing stakeholders in Saas-Fee and Zermatt, including both customers and producers?; How do these stakeholders develop and implement adaptation strategies to mitigate vulnerability factors?; How do the implemented adaptation strategies interact with other actors and factors within the system?* Here, a *system* is defined as a group of agents (stakeholders, companies, customers, etc.) who are interconnected and produce their own patterns of behavior (Meadows & Wright, 2008). Summer glacier skiing serves as an example of an activity that is highly vulnerable to climate change; identifying the actors and their interrelationships in the face of the effects of climate change will facilitate exploration of the consequences for the region.

2. Literature review

2.1. Systems thinking approaches in tourism

Systems thinking draws inspiration from systems theory, developed by von Bertalanffy (1968) and Forrester (1973), which was then further elaborated by subsequent scholars such as Cristiano and Gonella (2020). In essence, systems thinking acknowledges that changes in one part of a system can have far-reaching effects on other parts of the system (Meadows & Wright, 2008). It has been applied across various disciplines, including social sciences, environmental research, and ecological studies (Boardman & Sauser, 2008; Cristiano & Gonella, 2020), and it is widely applied in biology, management, and ecology (Mingers & White, 2010).

From an epistemological perspective, systems thinking places emphasis on studying the structure of pattern configurations, which result from the self-organized network of feedback that ultimately defines the system's stability, resilience, and adaptation capacity (Cristiano & Gonella, 2020; Meadows & Wright, 2008; Sterman, 1994). Arnold and Wade (2015)) identified the components that define systems thinking: a clear goal, the elements that make up the system, and the interconnections between these elements. This approach seems particularly attractive for issues related to climate change, as Abson et al. (2017) show that systems thinking is useful for identifying leverage points and facilitating change for the purpose of sustainability. Systems thinking also appears to be a particularly necessary approach to the sustainability transitions agenda, recognizing that sustainability transitions have a number of complex and multi-dimensional characteristics, which are also evolutionary in nature and multi-actor (Niewiadomski & Brouder, 2024).

Systems thinking in tourism considers the tourism industry as a complex system made up of multiple elements that are not separate but rather interconnected and interacting (Loehr, 2020; Loehr & Becken, 2023; Wilbanks & Kates, 1999). Tourism destinations encompass public and private actors, institutions, products, tourists who perform actions (make decisions, negotiate, take initiatives, change their behavior, etc. [Hartman, 2021]), and places with specific geomorphological and ecological characteristics and behaviors (e.g., glaciers and their retreat dynamics). Systems thinking makes it possible to delve into the dynamics of a destination by going beyond the linear relationship between causes and effects to understand the workings of a myriad of interconnected and interdependent parts, thereby identifying feedback loops and non-linear dynamics. The roots of systems thinking as applied to tourism can be found in Butler (2006) life cycle of the tourism destination; since this preliminary work, the field of evolutionary economic geography has used systems thinking to understand the evolution of tourist destinations (Brouder & Eriksson, 2013; Hartman, 2021). More recently, systems thinking has been widely used to manage the sustainability of destinations (Crabolu, Font, & Miller, 2024), although thus far only a few studies have addressed the issue of climate change and tourism in a comprehensive and systemic manner (for exception, see Loehr, 2020, Dawson et al., 2007, or Loehr & Becken, 2023). In our case, the systems thinking approach will integrate environmental and social considerations in relation to tourism activities in such a way as to understand how different factors influence each other (Buckley, 2012).

Defining the different elements of the system clarifies the interplay underpinning how a tourism system responds to climate-related threats. In the case of summer glacier skiing, stakeholders who benefit from the activity, both from the supply side and the demand side, are considered (Salim, Fournier, Gerber, Fragnière, & Kebir, 2024). The supply-side components have been referred to as the destination production system, wherein a change in one component (such as transportation or accommodation) will condition the behavior of others by means of feedback cycles and delays, resulting in nonlinear outcomes (Pearce, 2014; Serra, 2014). The demand side is structured in a similar way, and the components of both sides interact with each other. Furthermore, the system includes the environmental dimensions and components of the cryosphere in mountain areas that are affected by warming temperatures (Barry & Gan, 2022). Such environmental factors, which include natural resources relevant to tourism, have significant effects on skiing activities that affect both service providers and service recipients (Steiger et al., 2022). In that sense, skiing in high-altitude glacier areas—such as Saas-Fee and Zermatt—is highly dependent on environmental factors such as snow conditions, weather conditions, and microclimatic characteristics, and these destinations are regarded as the final frontiers for sustaining winter sports (Abegg, König, & Maisch, 1994; König & Abegg, 1997; Mayer, Demiroglu, & Ozcelebi, 2018). For the sake of simplicity, our systems thinking model refers to anthropospheric and environmental factors as actors. In short, this study uses a systems thinking approach to understand the relationship between environmental factors and summer glacier skiing stakeholders at the destination by identifying stakeholder vulnerability, adaptation strategies, and the interrelationship between the two.

2.2. Vulnerability to climate risk for mountain tourism

The Intergovernmental Panel on Climate Change (IPCC, 2022, p. 2927) defines vulnerability as "*the propensity or predisposition* [of a system] *to be adversely affected* [by climate impacts]." The assessment of vulnerability is multifaceted, encompassing not only a system's exposure to potential hazards but also its capacity for adaptation (IPCC, 2022). In climate change research, the primary components of vulnerability consist of exposure, sensitivity, and adaptive capacity (Brooks, Neil Adger, & Mick Kelly, 2005). *Exposure* refers to the degree to which a system or community is likely to experience climate change factors, such as temperature increases, precipitation changes, and extreme events (Brooks et al., 2005). *Sensitivity* is the degree to which a system or a community is affected by climate change factors once exposed (Brooks et al., 2005; IPCC, 2022). *Adaptive capacity* is the ability and opportunity to adapt to climate change impacts (Brooks et al., 2005; Bruno Soares, Gagnon, & Doherty, 2012).

In mountainous regions, tourism is predominantly centered on outdoor activities such as hiking, mountaineering, and skiing, which rely heavily on the presence of snow and glaciers (Apollo & Wengel, 2021; Nepal & Chipeniuk, 2005). The phenomenon of climate change, characterized by a reduction in snow cover and glacier retreat, thus poses a substantial threat to mountain tourism (Gilaberte-Búrdalo, López-Martín, Pino-Otín, & López-Moreno, 2014; Steiger et al., 2022; Willibald et al., 2021). Glacier skiing, which is particularly dependent on cryosphere conditions, is extremely vulnerable to warming temperatures

(Mayer & Abegg, 2022; Steiger et al., 2022). Specifically, glaciers are necessary for the activity, and the global rise in temperatures is causing rapid glacier retreat, particularly in the European Alps (IPCC, 2022); recent decades have witnessed an alarming acceleration in glacier mass loss in the Alps, primarily due to the increased frequency of summer heatwaves (Huss, Schwyn, Bauder, & Farinotti, 2021). For example, Swiss glaciers have lost 10 % of their mass in just two years: 6 % in 2022, and 4 % in 2023 (Swiss Academy of Sciences (SCNAT), 2023). These developments have profound implications for tourism activities around glaciers, causing infrastructure destabilization, increased risks on certain routes, and potential reduction of the aesthetic value of glacier landscapes (Salim, Ravanel, Bourdeau, & Deline, 2021). For over two centuries, the Alpine tourist experience has been intimately intertwined with these glaciers, and their disappearance is now causing a significant decline in the commercial appeal of mountainous areas that affects both winter and summer tourism, leading to economic losses (Salim, Ravanel, Deline, & Gauchon, 2021; Welling, Árnason, & Ólafsdottír, 2015).

Furthermore, the retreat of glaciers poses significant challenges to the operational efficiency and financial viability of summer glacier skiing destinations in the European Alps (Fischer et al., 2011; Huss et al., 2021; Senese et al., 2020). The broad-scale recession of the mountain cryosphere translates into a reduction in snow cover, in terms of both duration and volume (Spandre et al., 2019), which directly impacts the skiing industry, particularly in the context of glacier skiing. Consequently, climate change and progressive snowmelt are making suitable skiing conditions harder to maintain, while glacier retreat reduces skiable areas and increases icy slopes (Mayer & Abegg, 2022).

The rapid glacier retreat makes the ski industry vulnerable to environmental and economic factors (Demiroglu et al., 2018). It is crucial to recognize that natural and demand conditions fluctuate throughout the year; for instance, the demand decreases faster than the snow cover in May and June but rises faster in October (Mayer et al., 2018). Not only is there an interdependence among local actors that relies on every single actor involved in the offer system (Buhalis & Cooper, 1998), but there is also a causal link between the supply and demand side, as well as among different customers within the latter.

2.3. Adaptation strategies

Adaptation can be defined as "*the process of adjustment to actual or expected climate and its effects, in order to moderate harm or exploit beneficial opportunities*"; its aim is to reduce climate-related risks and the vulnerability of human systems (IPCC, 2022, p. 2898). However, adaptation efforts may not always be successful; in some cases, they are successful at one level but detrimental at another level and can even increase the vulnerability of other groups and sectors in a system (Neil Adger, Arnell, & Tompkins, 2005), a phenomenon referred to as "maladaptation" (Barnett & O'Neill, 2010). In order to comprehend adaptation strategies and the risks of maladaptation from a socio-ecological perspective, a systems thinking approach is required so as to identify and mitigate maladaptive outcomes.

Developing sustainable strategies can maximise the benefits and minimise the risks associated with climate change impacts, thereby ensuring a resilient and thriving tourism industry (Loehr, 2020). However, Scott, Knowles, and Steiger (2022) point out that snowmaking and other adaptation strategies are important to future climate change vulnerability but can also lead to maladaptation, depending on the other socio-eco-environmental vulnerabilities of stakeholders or the destination. Such adaptation strategies also have technical, financial, and environmental limits that must be considered before implementation (Damm, Köberl, & Prettenthaler, 2014; Pickering & Buckley, 2010; Steiger & Mayer, 2008).

Research in the field of climate adaptation has identified three primary strategies: reactive strategies, which are employed in response to hazards that have already occurred; incremental strategies, which involve minor adjustments to the system; and transformative strategies, which address the root causes of vulnerability (Fedele, Donatti, Harvey, Hannah, & Hole, 2019). In the tourism sector, adaptation strategies are frequently reactive and thus do not guarantee the long-term sustainability of activities and the associated stakeholders (Salim, Ravanel, Deline, & Gauchon, 2021). In its view of summer glacier skiing, systems thinking will identify the vulnerabilities of each stakeholder to climate change and the adaptation strategies they develop. Identifying and understanding the relationships between stakeholders' vulnerabilities and adaptations, the non-linear impacts on stakeholders, and the feedback loop will provide a better understanding of the dynamics of this system and prevent maladaptation.

3. Research design

3.1. Methodological approach

To gain an integrated understanding of the different vulnerability and adaptation factors of Saas-Fee and Zermatt, the two remaining ski resorts offering summer glacier skiing in Switzerland, we adopted a three-step methodology consisting of three modes of data collection (Fig. 1): desk research and field investigation (Step 1); semi-structured interviews (Step 2); and workshops (Step 3).

In Step 1, our on-site investigations played an essential role in providing first-hand data and insights; these involved direct observations, engagement with the environment, and conversations and interviews with skiers and other individuals present at the sites. Gray literature—including newspapers and reports—and visual documentation—including photographs—were used to convey the atmosphere, facilities, and activities, as well as to provide a context for the summer glacier skiing experience and to identify relevant stakeholders with whom to conduct semi-structured interviews. In addition, active participation, namely experiencing glacier skiing ourselves, allowed us to see how this activity is actually carried out.

In Step 2, the semi-structured interviews ($N = 26$) were held with local stakeholders from the tourism sector ($N = 11$) and with ski athletes ($N = 15$). The latter were selected through purposive snowball sampling involving ski coaches and athletes, while the list of local stakeholders was (at this stage) further refined based on the lessons learned at Step 1. The interview protocols are presented in Appendices A and B. Each interviewee was contacted and asked to be interviewed on-site or, if this was not possible, by video conference. Local stakeholders included representatives from cable car companies, hotel operators, and tourism office managers. On the customer side, our focus was on ski athletes, including both snowboarders and skiers; recreational skiers were excluded from our interview pool, as the first phase revealed that their presence in the study context was limited. Interviews were conducted in the summer and autumn of 2023. All interviews with local stakeholders took place at the destination, and the interviews with ski athletes were conducted in Valais, Haute-Savoie, and through video conferencing. Twenty-four interviews were recorded with the participants' agreement and were transcribed for analysis using NVivo, a software for qualitative analysis. Two interviews were not recorded, but minutes were taken. The interviews lasted between one and two hours.

In Step 3, after the interviews were conducted and analyzed, an initial draft of the systems thinking model was presented and discussed in workshops with local stakeholders from Saas-Fee in December 2023 and with stakeholders from Zermatt in February 2024, in order to validate our initial analysis and address possible limitations. The first workshop, with participants from Saas-Fee, included local hoteliers and former and current representatives of the cable car company. The second workshop engaged stakeholders from Zermatt, including local hoteliers and representatives of the cable car company. The third workshop involved representatives from the Zermatt tourism office. The workshop procedure went as follows: initially, we presented the systems thinking model (a prototype of Fig. 7), which was then followed by a discussion. These discussions contributed to identifying and addressing

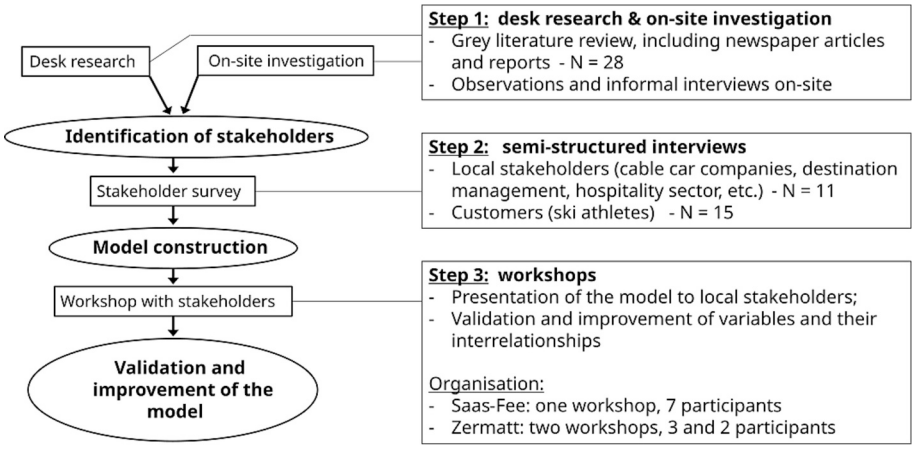

Fig. 1. Design and research method process. The methodologies employed are presented in the rectangles, with the specific objectives of each method delineated in the ovals.

misinterpretations. Through these workshops, the results were further refined and completed.

3.2. Systems thinking visualization with casual loop diagram

In order to visualize the gathered data from a systems thinking perspective, we drew inspiration from Loehr's (2020) visualization of adaptation systems. To build the systems thinking model, first, the literature and the interviews were used to identify key variables that comprise both vulnerability factors and adaptation strategies of each identified stakeholder. After that, connections between the variables were added using the results of the interviews. Then, during the data analysis phase after the observations and the interviews were completed (November 2023), the relational dynamics and extended variables were included and further reconceptualized. Finally, our systems thinking model was further refined and complemented with the comments and ideas from the workshops. Our diagram was drawn using the online Kumu software (https://kumu.io) and was then graphically developed in more detail through the graphic vector software Inkscape.

4. Results

4.1. Summer glacier skiing in Zermatt and Saas-Fee

Investigations in Zermatt and Saas-Fee reveals that in the summer, both destinations are visited by ski athletes who utilize the glacier slopes as training facilities to prepare for upcoming races. The results reveal differences between the two locations in terms of tourism diversity and operational timelines. Zermatt emerges as the more diverse destination compared to Saas-Fee; it offers a wide range of tourist activities for a diverse international audience, with summer glacier skiing used by both ski athletes and recreational skiers. Saas-Fee relies on glaciers skiing as one of its primary attractions in the summer, drawing a clientele composed predominantly of both domestic and international ski athletes who are primarily drawn to Saas-Fee not for recreational but for training purposes. A local hotelier succinctly identified the significance of summer glacier skiing to Saas-Fee, stating that without it, the destination would lack a substantial draw. This insight underscores the pivotal role of summer glacier skiing in shaping the offering of Saas-Fee. In contrast, at Zermatt, the destination's popularity ensures a steady flow of tourists year-round. While amateur skiers do visit the summer glacier infrastructures and add some diversity to the demand, the primary clientele for summer glacier skiing remains ski athletes using the slopes for training.

Both Zermatt and Saas-Fee can draw on a variety of expertise and equipment assets to accommodate the demands of ski athletes. This proficiency is attributed to the dual identity of these destinations as both winter-sport and summer hotspots. Notably, summer glacier skiing activities align closely with conventional winter snow sports, with the distinction lying in their specialized focus on ski athletes during the summer. Multiple interviews indicate that over 60 % of skiers in Zermatt and 90 % of skiers in Saas-Fee fall under the "athlete" category; accordingly, in both destinations, the hospitality industry is largely designed to satisfy these athletes' needs, with off-snow training/gym facilities and ski workshops for preparing skis.

There is a notable difference in the operating times of the cable cars between Zermatt and Saas-Fee: while Zermatt operates without interruption, thanks to a redundant cable car system that duplicates critical sections and thus increases the reliability of the system, Saas-Fee temporarily closes its cable cars for maintenance in May and reopens in June (e.g., April 23 to June 3, 2023). The rationale behind Saas-Fee's closure period is based on a perceived decline in demand after the competitive skiing season, typically around the month of May; the decline in demand during this period is attributed to a collective waning interest in skiing as the spring progresses despite favorable snow conditions, which can sometimes extend into June. Zermatt, which is known for its year-round skiing experience, uses its skiing capacity as a strategic marketing tool, emphasising the guarantee of snow 365 days a year. Moreover, Zermatt's glacier skiing infrastructure is situated several hundred meters higher than Saas-Fee's,[1] further supporting its year-round appeal.

In addition, Zermatt offers easier and longer slopes that are open to recreational skiers, while Saas-Fee has more graded slopes designed primarily for ski athletes. In Zermatt, alpine skiing is the main focus; in contrast, Saas-Fee is characterized by its multi-disciplinary emphasis on alpine skiing, ski cross, and freestyle. Freestyle skiing training takes place mainly within the confines of the designated snow park, also known as the Stomping Ground.

4.2. Linear relationship of vulnerabilities and adaptation strategies

Figs. 2–7 are spatially organized, depicting three different geographical locations where vulnerability factors and adaptation strategies take place. The innermost circle (blue) comprises variables associated with glaciers and skiing slopes; the intermediate circle (green) shows variables pertaining to the destination itself; and the outermost circle (white) represents variables that occur outside the destination and are considered external factors.

[1] The minimum–maximum range of altitudes of the ski area of Zermatt is 1620–3899 m, compared to 1500–3600 m for Saas-Fee.

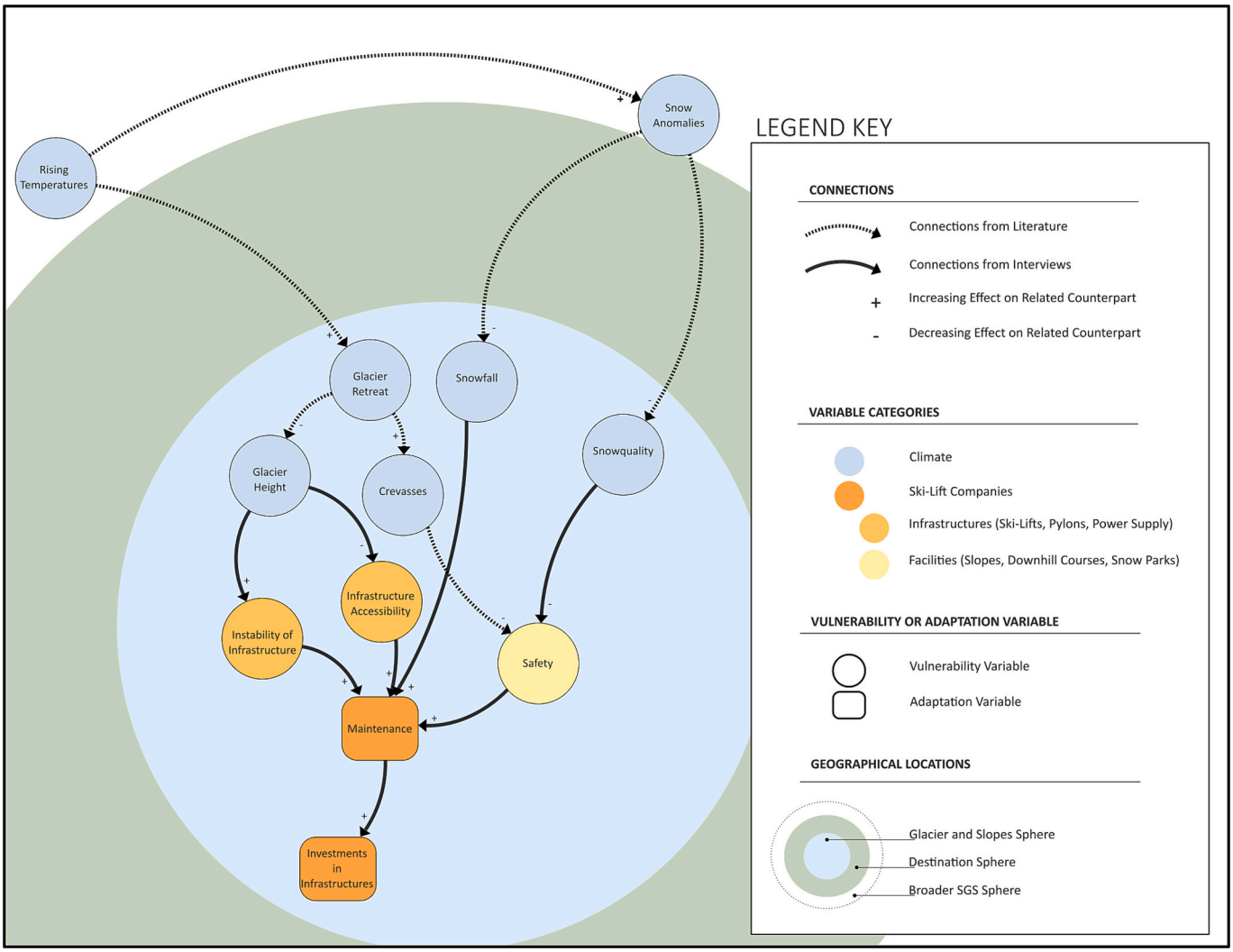

Fig. 2. Influences of rising temperatures and the influences thereof on infrastructure.

All the variables in these diagrams are directly or indirectly interrelated. Positive influences are marked with a "+" and negative influences with a "-". The relationships derived from the interviews are marked with solid lines, while relationships inferred from the literature are marked with small-dashed lines. Other relationships have been hypothesized (larger dashed lines), meaning that the relationship was suggested in the interviews or in the literature but should be validated through further research.

4.2.1. Rising temperatures and the influences thereof on infrastructure

To start with climatic variables, *rising temperatures*—which lead to *glacier retreat* and *snow anomalies*—present notable challenges for infrastructure and *safety*, ultimately necessitating increased *maintenance* and new *investments in infrastructure.* Specifically, *glacial retreat* reduces *glacier height* and increases the development of *crevasses*, leading to *safety* issues that must be managed by the cable-car company filling them with snow. Additionally, the reduction of *glacier height* increases the *instability of infrastructure* and decreases the *infrastructure accessibility*.

Instability of infrastructure is exemplified by ski lifts being situated on the glacier, which necessitates significant labor inputs. Ski-lift pylons and the lower terminus are normally set in ice, floating on the glacier, while the upper terminus is set on firm ground. The ice is moving down toward the valley, which means that, depending on the inclination of the glacier, these installations are descending up to 30 m a year. Consequently, the pylons on the glacier and other installations must be moved up and stabilized to ensure that they operate properly during the summer season—a task that must be undertaken at least once a year. "*Sisyphus sends his regards,*" commented one staff member on such labor. To manage such challenges, cable car companies in Zermatt and Saas-Fee are compelled to undertake extensive *maintenance* work that induces additional costs.

At the same time, the reduction of *glacier height* poses a challenge to the *infrastructure accessibility*, defined as entering and leaving via ski-lifts or cable cars to slopes and vice versa. To access these infrastructures, athletes are required to walk across debris-laden terrain that was formerly covered with ice and snow. To facilitate the *infrastructure accessibility* for skiers and snowboarders, the cable car company has made *investments in infrastructure*, or adaptation measures attributable to *glacier retreat*. Several interviews revealed that skiers could still ski on these "access slopes" in the early 2000s.

In Zermatt, there's the track that crosses over to go to Testa Grigia, where you used to arrive… 20 years ago, you'd arrive flat. Now, you arrive at the bottom of the Testa Grigia lodge and you must climb a 30-degree slope to get to the top, which is 50 m long.

(Ski coach)

Snow anomalies, manifesting in decreased *snowfall*, represent a primary concern and constitute a significantly more serious factor in the maintenance of glacier skiing than *glacier retreat* and a key factor for operation. For example, Zermatt had to close its summer glacier skiing

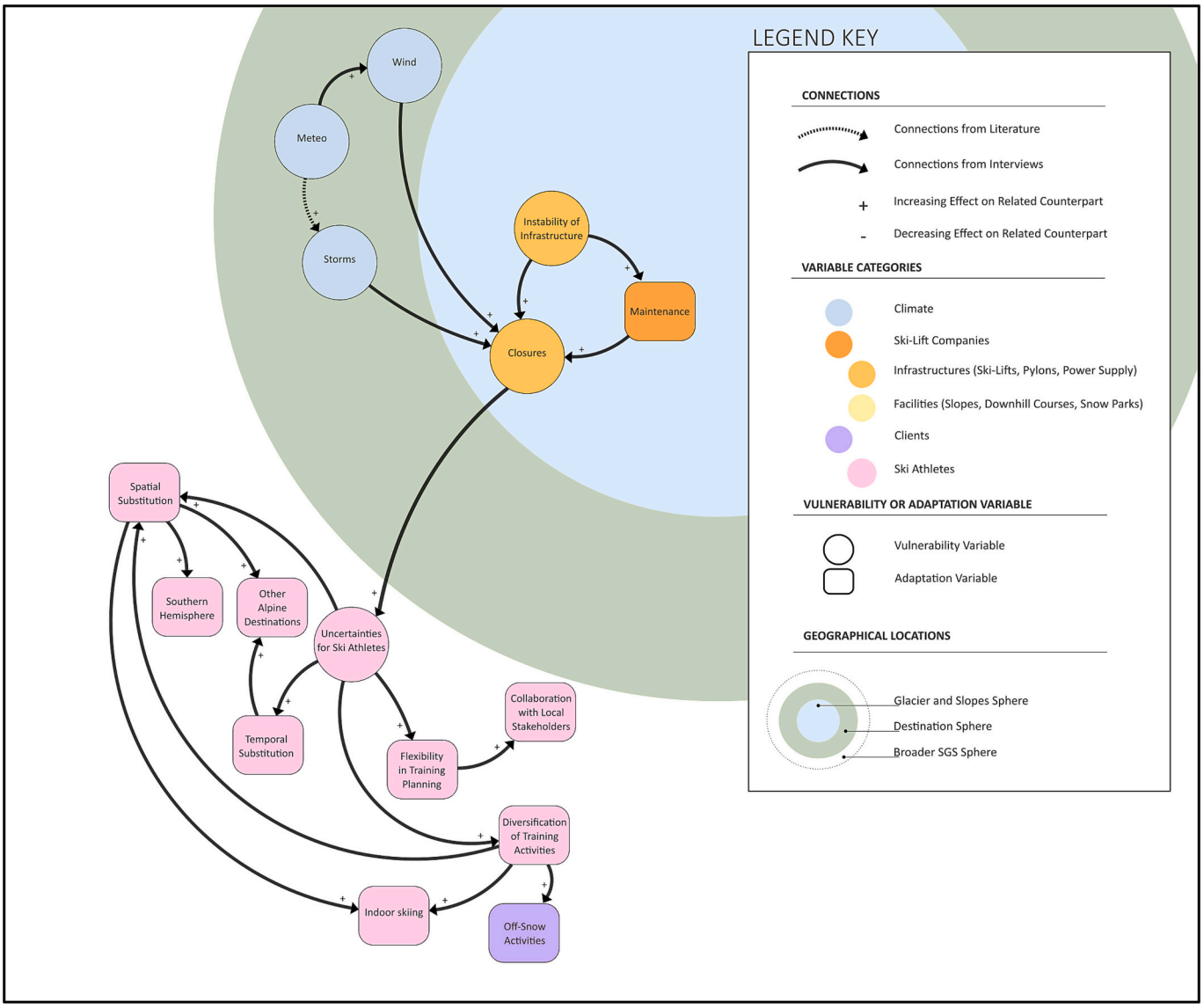

Fig. 3. Influences of closures and their consequences.

infrastructure to recreational skiers in the summer of 2022 and limit access for sports teams, because safety could not be guaranteed as a result of the lack of snow needed to access the infrastructure. Similarly, poor *snow quality* resulting from warm and overcast weather poses a risk to the opening of summer glacier skiing infrastructure; in warm and overcast conditions, there is an increased risk that the snow will not compact properly and will only freeze on the surface, posing a safety risk to skiers and snowboarders since the top layer of snow may be prone to sliding.

The conditions on our glaciers are too bad and less regular. For example, in Saas-Fee, it's very often that out of 5 days of skiing, we lose one, or two, or even three […] on a glacier; what you have to bear in mind is that for the conditions to be right, for the snow to be optimal, and for the facilities to be open for the safety of tourists and athletes alike, […] at night, the sky has to be clear so that there's no reverberation of heat between the clouds and the glacier. When it's overcast, the snow doesn't press down and it doesn't get hard […] Also, there shouldn't be any thunderstorms, nor any rain. If it snows too much, there could be avalanches.

(Ski coach)

In short, whether confronted with the challenges of infrastructure instability, facility accessibility, or safety management, cable car companies are compelled to allocate substantial resources in order to keep their installations open.

4.2.2. *Closures and their consequences*

Climate change increases the risk of unplanned *closures*, as happened during summer 2022. *Closures* can be induced by *instability of infrastructure* and the increased necessity of *maintenance*, as well as by weather related hazards, such as *storms* and *wind*. These potential *closures* during the summer result in *uncertainties for ski athletes,* leading them to find other short-term solutions in order to complete their summer training. Recurrent closures can result in negative publicity, thereby reducing the demand for this activity at the destination.

The ski lifts were starting to fall. It had melted so much that crevasses had formed and the cables holding the lifts had started to move. So, suddenly, out of the blue, they say it's cancelled, and you have one day to think about finding another solution, finding other training runs, finding hotels.

(Ski coach)

Uncertainties lead athletes to adapt rapidly. *Flexibility in training planning* requires teams and particularly coaches to *collaborate with local stakeholders*, such as accommodation facilities and cable car companies, to find solutions to train for the number of days required. Other adaptations include *diversification of training activities*, which involves *off-snow activities* like fitness training or supplemental training taking place

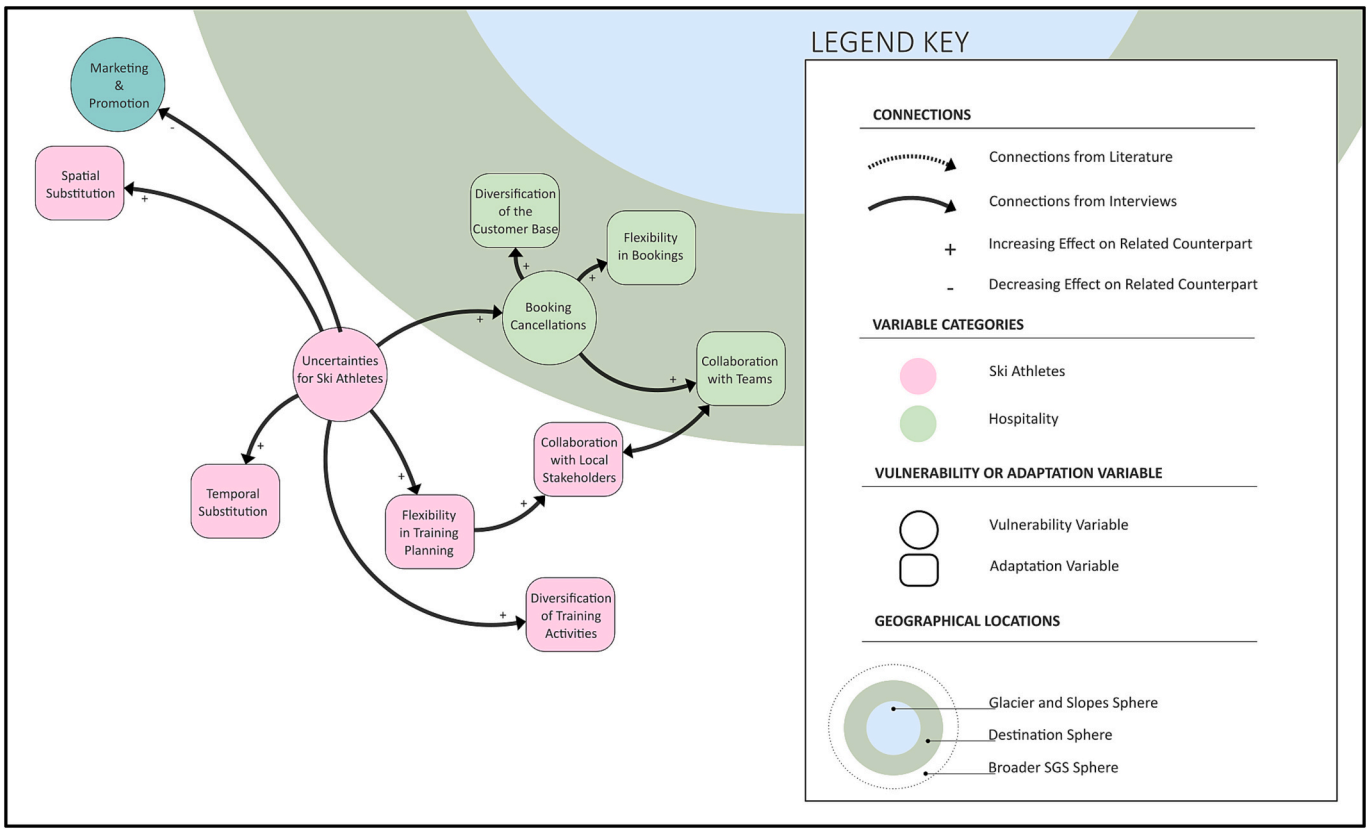

Fig. 4. Consequences of uncertainties for hospitality personnel.

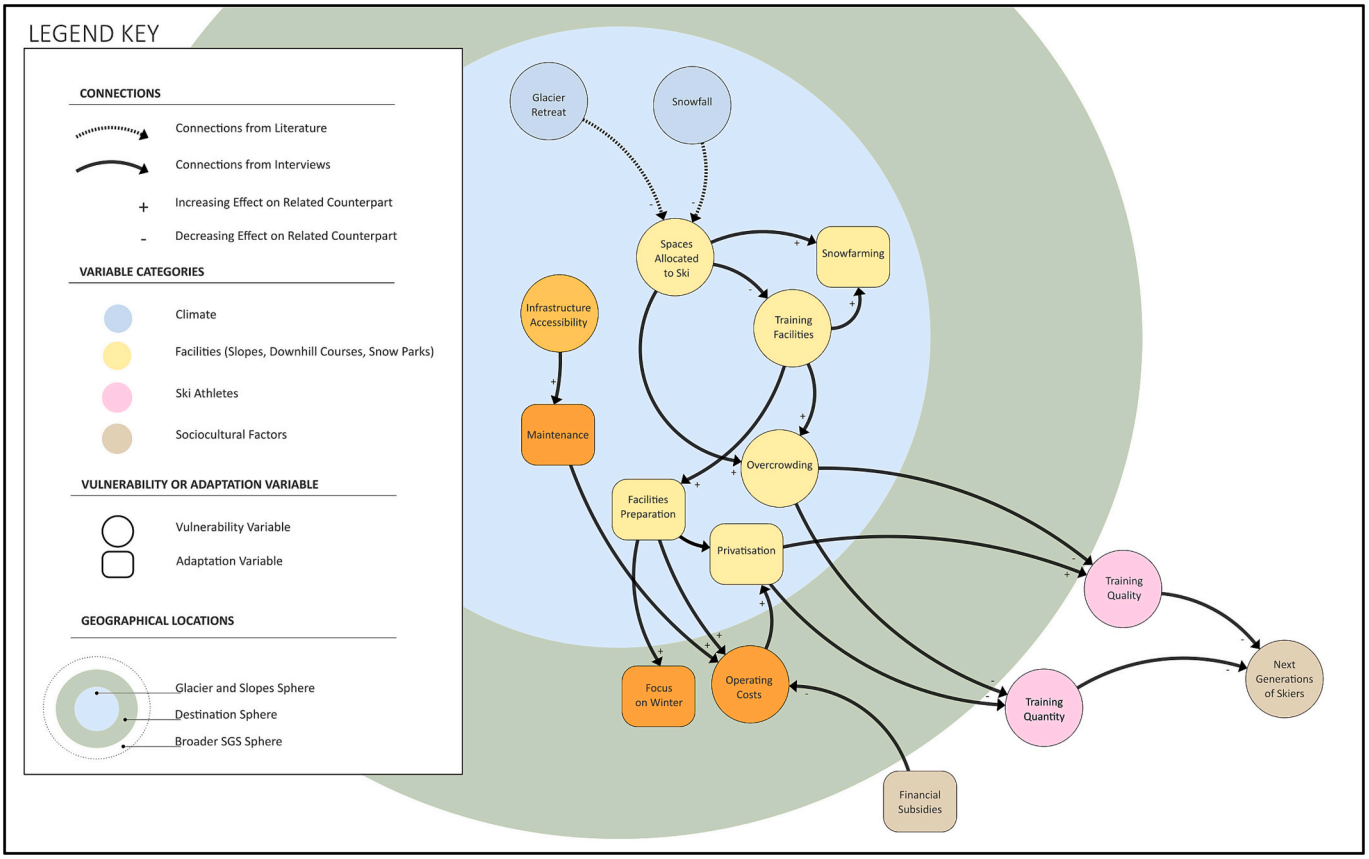

Fig. 5. Influences of reduction in spaces allocated to skiing.

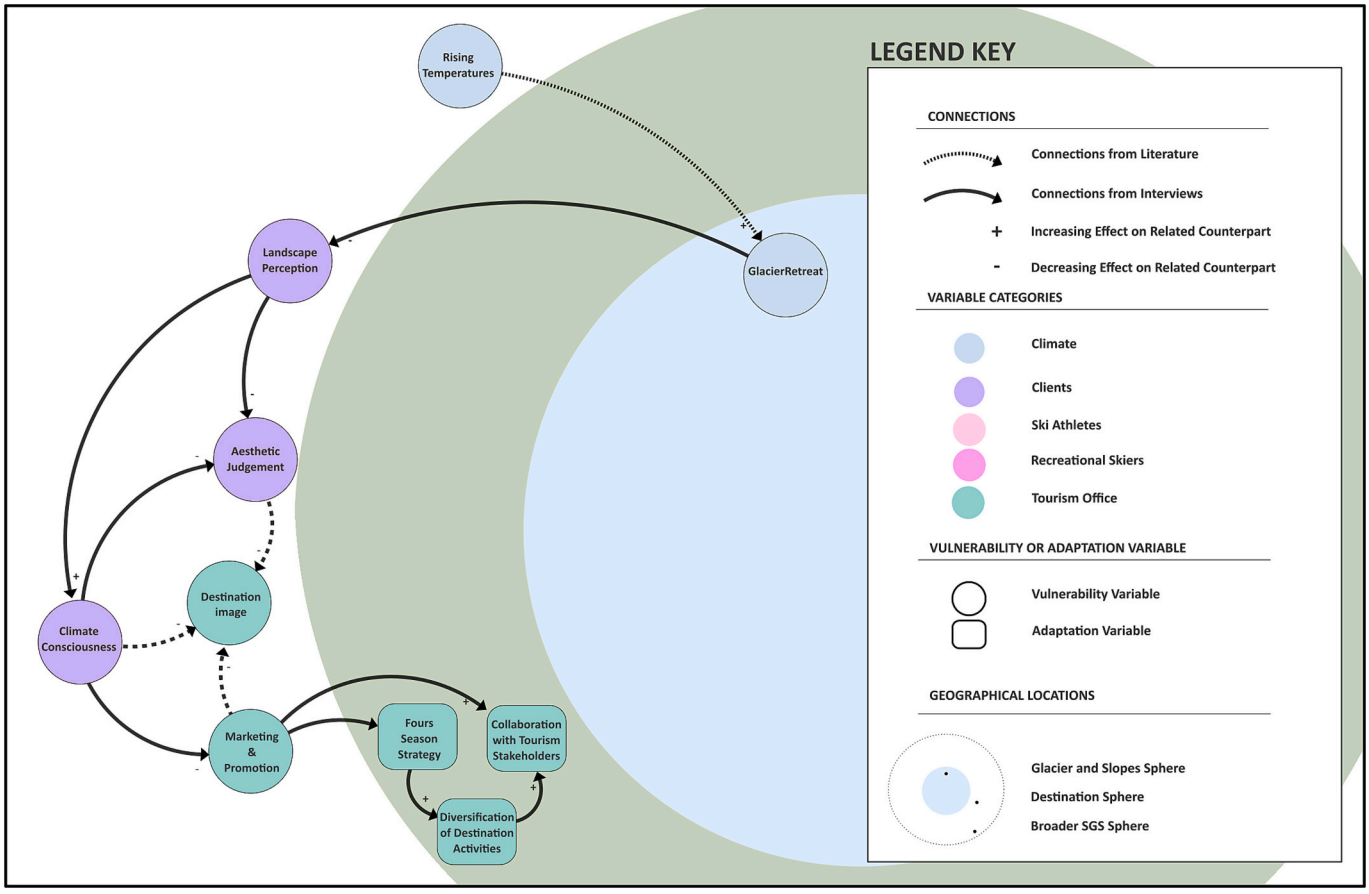

Fig. 6. Influences of climate consciousness and the image of the destination.

at the destination. This is coupled with *spatial substitution*, whereby athletes sometimes replace glacier skiing infrastructure with *indoor skiing* facilities, which offer year-round skiing opportunities on artificial snow in halls that offer permanent and regular snow conditions. The Netherlands, Belgium, and northern Germany are popular destinations among athletes. For skiers with greater financial means and top athletes, *spatial substitution* also involves participation, in training camps located in the *Southern hemisphere*. Locations such as Argentina, Chile, and New Zealand offer ideal winter conditions and serve as alternatives during European summers. Many teams are now looking for other destinations to train.

I think 80 % *of nations used to come. But now there have only been two other nations, two or three other nations. So there are far fewer nations for ski cross. It was the only place in the world where you could train for ski cross in the summer. But now the Canadians, the big nations, are not coming any more, the trip is too expensive for what it is. So, everyone goes to Chile instead.*

(Ski athlete)

Other strategies employed by ski athletes to mitigate uncertainties include *temporal substitution,* whereby athletes—particularly those in foreign junior categories—avoid popular training summer ski areas like Zermatt and Saas-Fee during midsummer (July and August). During this period, advanced skiers and locals frequent such locations, and they often enjoy better conditions due to their greater financial resources. Consequently, junior athletes opt to avoid these destinations and instead choose *other alpine destinations* that offer similar training facilities, which may not be available throughout the entirety of summer but usually are open in May, June, September, and October.

One may question the necessity for athletes to engage in skiing activities during the summer months. Insights garnered from our interviews clarify that ski athletes typically spend 40 days in on-snow training, a prerequisite for optimal readiness before the first International Ski and Snowboard Federation (FIS) Alpine Ski World Cup of the year takes place. Moreover, athletes competing for the FIS Alpine Ski Europa Cup avail themselves of opportunities to accrue supplementary points by participating in events conducted in the southern hemisphere. This strategic endeavor is undertaken with the objective of enhancing their prospects for qualification for the esteemed FIS Alpine Ski World Cup.

4.2.3. *Consequences of uncertainties for hospitality sector*

It is important to understand that summer glacier skiing infrastructures are a financially deficient business within the portfolio of the Zermatt cable car company, with a numerical annual loss of CHF 1.5 million. Nevertheless, this activity brings benefits to the destination. For instance, the establishment of summer glacier skiing infrastructures offers additional value for hospitality establishments. Particularly noteworthy is the strategic focus of Zermatt's hoteliers on recreational skiers, given their substantially greater economic expenditure compared to snow-sport athletes; recreational skiers tend to allocate more resources to food and hospitality services, whereas ski athletes, typically operating within team structures, show a lower propensity for significant spending.

Booking cancellations mean that hospitality stakeholders must demonstrate great *flexibility in bookings* in the face of *uncertainties for ski athletes*; this poses major challenges for local accommodation establishments and requires them to constantly adjust to changing circumstances, affecting their ability to maintain stable reservation levels. In Saas-Fee, ski teams are the primary clientele during summer, meaning they represent a crucial source of income for the stakeholders in the local hospitality sector. *Booking cancellations* entail a potential decline in revenue if these are not substituted with alternative bookings. Some

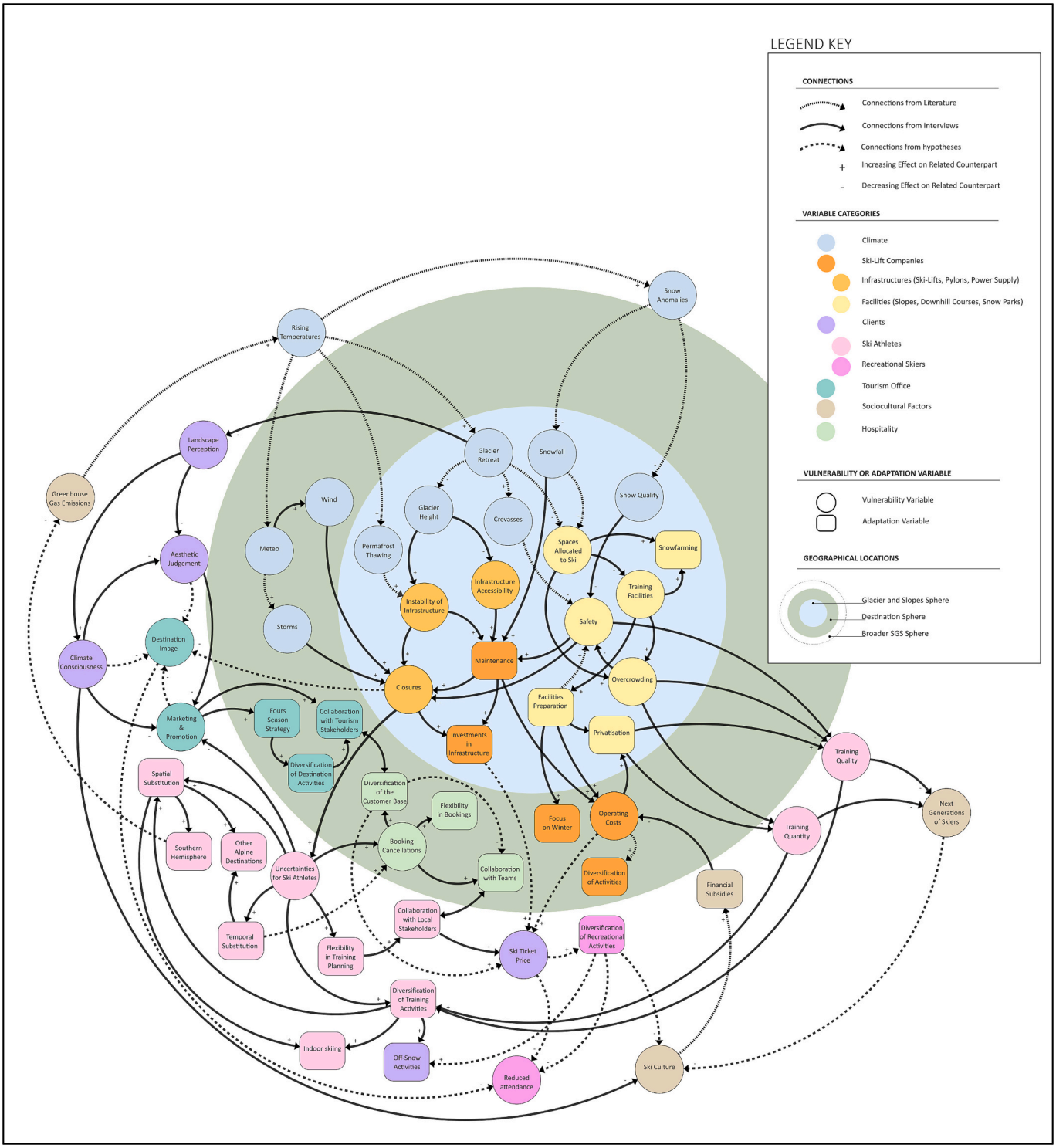

Fig. 7. Systems thinking model of vulnerability and adaptation of summer glacier skiing, visualized through a casual loop diagram with connections from interviews and literature.

accommodation establishments in Zermatt are not willing to host summer glacier skiing clients, due both to their lower economic value compared to other more free-spending customers as well as to potential cancellations. This shift represents a *diversification of the customer base*.

At the same time, hosts established close *collaboration with teams*, as certain accommodation establishments rely heavily on summer glacier skiing clients. Some establishments offer preferential rates to ski teams for lodging and meals. Additionally, these accommodations often organize early morning services (sometimes as early as 4:30 am) that provide breakfast and organize shuttle services to the valley station of the cable car. Hence, flexibility, collaboration, and transparent communication with sports teams emerge as vital elements in mitigating the adverse impacts of uncertainties on the hospitality sector.

4.2.4. *Reduction in spaces allocated to skiing*

Glacier retreat, combined with *snow anomalies* that include decreased *snowfall*, influences the *space allocated to ski*, which has been diminishing over the last 40 years. In that time, several summer glacier skiing

destinations in the European Alps had to shut down due to glacier retreat or had to limit their opening time frame during the summer; this, in turn, has made existing summer glacier skiing destinations like Saas-Fee and Zermatt more attractive for athletes who want to harness such locations for their trainings.

Previously, the Italians used to go to the Stelvio […] and the French used to go to Tignes or Les Deux Alpes, but now they come here a lot more.

(Ski coach)

Glacier closures and capacity restrictions have intensified "competition" for training area reservations, and access is now restricted to a specific number of ski athletes, with a priority-based system. An interview conducted with a coach illustrated the ongoing competition for access to slopes and the high demand for visiting Zermatt and Saas-Fee for training purposes. Typically, coaches secure their training slots in the first four months of the year, and a hierarchical structure governs the reservation process: regional and national ski teams are accorded precedence, due to their potential involvement in subsidizing glacier skiing infrastructure, and further stratification exists within the various squads, whereby World Cup racers enjoy the highest priority while juniors are allocated comparatively lesser precedence.

But, for example, I was coaching a U16 team at the time, and because of the problem of priority, we lost skiing days, because they gave priority to the European Cup/World Cup.

(Ski coach)

Due to changing snow conditions and the retreat of glaciers, some training facilities, such as snow parks and ski crosses, are disappearing: there is no longer enough snow available to build the modules, and the lower parts are no longer covered in ice and are becoming soil. This change has led to a decrease in attendance, particularly among less skilled athletes, while simultaneously making the facility more exclusive for top athletes.

Moreover, the infrastructure is not only expensive for customers but also for cable car companies, who maintain these infrastructures. Despite both cable car companies receiving federal subsidies (contingent on their provision of skiable facilities for SwissSki association skiers), they continue to face economic challenges related to summer glacier skiing. As a result, these companies are increasingly considering abandoning this type of investment in favor of more profitable ventures, such as focusing on winter skiing.

Direct observations at the cable-car stations revealed a busy influx of ski athletes in the early hours of the morning, from around 6 am to 9 am. Saas-Fee has set up a slot system, and athletes can learn of their time-slot the previous day, either online or at the counter. During peak periods at Saas-Fee, the slopes accommodate more than a thousand skiers and snowboarders, highlighting the significant demand for glacier skiing opportunities. The heightened demand for *spaces allocated to ski* coupled with the limited supply require cable car companies to maximise the use of the available spaces. Consequently, slopes are closely situated next to one another, and in instances in Saas-Fee—where the allocated zones are sometimes less than six meters apart—this leads to overcrowding.

The area where you can still ski during summer is getting smaller and smaller.

(Tourism Office)

Maintaining sufficient *spaces allocated to ski* requires meticulous *preparation* and maintenance to ensure optimal conditions. The intricate preparation and maintenance of features such as half-pipes and ski-jump hills are paramount, given that freestyle athletes rely heavily on the architectural integrity of these elements for both safety and performance. However, the expertise required for such endeavors is relatively rare. Saas-Fee has chosen to address this challenge by outsourcing the management of its snow park to an external organization known as *Stomping Ground*. This *privatization* initiative has resulted in an enhancement of *training quality* accompanied by a reduction in *training quantity*. At the same time, *overcrowding* on glacier slopes leads to a decrease in *training quality* due to long waiting times, narrow downhill courses, and busy slopes. Reductions in the quantity and the quality of training is more likely to affect younger generations and athletes who cannot afford the price of a private slope, leading to a reduction in training during the summer; this may affect the *next generation of skiers*. Nevertheless, *privatization* of certain ski facilities brings an increase in *training quality* for the top athletes who can afford it.

Stomping Ground is the best snow park for training before the winter season.

(Ski athlete)

Access to the Stomping Ground is far too expensive […] the national teams pay that, but which national teams can afford that? The Swiss, the Norwegians, sometimes the Swedes, the Canadians and the Americans, and the Japanese. But nobody else.

(Ski athlete)

4.2.5. Climate consciousness and the image of the destinations

Glacier retreat also influences the *landscape perception* of individuals who engage in summer glacier skiing. Senior ski coaches are particularly adept at discerning the effects of climate change, due to their ability to juxtapose the current conditions with those of previous periods, but even 20-year-old skiers could share perceptions of climate change. The visual manifestation of climate change in the form of glacier retreat and snow conditions raises skiers' awareness of environmental realities through *aesthetic judgments* and *climate consciousness*. The former refers to the visible retreat of glaciers and the associated debris, while the latter involves an increased awareness of the ongoing rise in temperatures.

Yeah, it's clearly climate change. So, for example, I even see a difference in two years. I can see a big difference on the glacier […] so the glacier is very gray […] and then, with all that dirt and dust […] there are bits of plastic sticking out.

(Ski coach)

Glacier retreat affects the destination's image itself, with the loss of scenic appeal inevitably diminishing the destination's attractiveness for ski athletes and other visitors alike. The deterioration of summer glacier skiing as an experience—which is more and more perceived as a working and training activity and not as a recreational activity per se—prompts tourism offices to shift their *marketing & promotion* strategies toward *diversification of destination activities*, turning more to alternatives such as mountain biking or hiking during the summer season. The indirect influence of *rising temperatures* on the seasonality of a destination prompts tourism offices to respond with a four-season strategy, which in turn necessitates the establishment of new synergies and *collaborations with tourism stakeholders*.

> *We are aware that there is simply too much pressure from outside to focus fully on [summer glacier skiing] […] also because of sustainability […] there is a consensus that biking has great potential and that it will replace [summer glacier skiing] more and more.*
>
> *(Tourism Office)*

4.3. System dynamics of vulnerability and adaptation

The complex interdependencies that define this system's vulnerabilities and adaptation pathways are highlighted by the analysis of the stakeholders involved in summer glacier skiing (Fig. 7). A prominent feedback loop emerges from the progressive shrinking of skiing areas, driven primarily by glacier retreat and snow anomalies. This spatial contraction increases uncertainty for both stakeholders and visitors, leading to shifts in consumer behavior, including spatial substitution in particular. Ski athletes increasingly favor alternative destinations with higher altitudes or more reliable snow conditions. However, such adaptive behavior often requires long-distance travel, mainly by carbon-intensive modes of transport; the resulting increase in greenhouse gas emissions further accelerates global warming, thereby exacerbating glacier retreat and snow anomalies. This positive feedback loop illustrates how adaptive responses to climate change can paradoxically intensify the very drivers of vulnerability.

From a systems thinking perspective, uncertainty is identified as a leverage point that influences the decisions and resiliencies of multiple stakeholder groups. For example, hoteliers face fluctuating demand, which complicates capacity management and investment planning. Similarly, destination managers must navigate increased uncertainty in order to maintain the attractiveness and operational functionality of their areas. Such cascading effects underscore the systemic nature of vulnerability, wherein the effects of uncertainty are spread across interconnected actors, worsening the challenges of adaptation.

Another critical feedback loop arises from the economic impacts of climate change. Rising operating costs are forcing ski resort operators to privatize facilities in order to mitigate financial losses; however, privatization limits access to facilities, reducing opportunities for athletes and recreational skiers alike. This restriction weakens the supply chain of new participants, decreases visitor numbers, and reduces the amount of financial support from national institutions such as the Swiss Confederation, which traditionally invests in sports and tourism infrastructure. The subsequent reduction in funding places an additional financial burden on ski operators, further increasing their operating costs. This positive feedback loop illustrates how economic and infrastructural constraints can exacerbate systemic vulnerabilities over time.

Finally, the system-wide perspective provided by systems thinking reveals a notable asymmetry in the summer glacier skiing system: unlike other sectors, where feedback loops directly influence the driving variables, summer glacier skiing lacks a direct feedback mechanism targeting its underlying climatic-geomorphological conditions. While rising temperatures, glacier retreat, and snow anomalies drive the feasibility of summer glacier skiing, skiing activities themselves do not exert any direct pressure on these climatic or geomorphological drivers; the only indirect influence comes from the behavior of tourists, whose increased greenhouse gas emissions due to spatial substitution contribute to global warming. This asymmetry highlights the fundamental vulnerability of the summer glacier skiing system, as it remains entirely dependent on external climatic forces with limited capacity to mitigate or reverse these impacts through its operational activities.

5. Discussion

Using a systems thinking approach to summer glacier skiing shows that the consequences of the disappearance of glaciers are far-reaching, impacting not only cable car companies but also the hospitality sector, athletes and—on a more comprehensive scale—the tourism industry in mountain regions. As Knowles & Scott (2024) recently demonstrated for the Canadian ski industry, a number of stakeholders rely on the niche activity of summer glacier skiing. Therefore, addressing the challenges related to the future of it, as well as those related to climate risks more generally, is important not only for the preservation of the activity itself but also for the sustainability of the entire system of destinations in Alpine regions. A systems thinking perspective facilitates a better understanding of the key vulnerability factors that need to be addressed to adapt summer glacier skiing but also to transition to a future without this activity.

Climate change poses significant challenges to summer glacier skiing in both destinations examined in this study. Adaptation strategies mainly focus on glacier management and lift infrastructure, which fall within the domain of reactive and incremental adaptation strategies (Fedele et al., 2019), as already described in the context of glacier tourism (Salim, Ravanel, Bourdeau, & Deline, 2021, Salim, Ravanel, Deline, & Gauchon, 2021; Strong et al., 2023). Despite the importance of this practice to both destinations, adaptation primarily takes the form of reactive responses, with stakeholders not foreseeing a discontinuation of glacier skiing despite projections of glacier retreat (Bosson et al., 2023). On the supply side, reactive measures to sustain the activity include moving infrastructure to higher altitudes where temperatures would allow continued it, technical innovations such as the development of snow-independent skiing (i.e., indoor or snowless skiing, enabling athletes to train throughout the year), and diversification of activities at the studied destinations.

On the demand side, the findings show the profound impact of uncertainty on ski athletes' behavior. The observed adaptations are consistent with the literature with respect to substitution of outdoor recreation (e.g., McCreary et al., 2019; Rutty et al., 2015; Salim et al., 2023), which involves temporal, spatial, and activity substitution. However, climate change is not the only variable influencing athletes' behavior and adaptation strategies: mismatches between athlete planning and summer glacier skiing supply can also be considered. For instance, demand decreases faster than snow cover in May and June but increases faster in October. This mismatch could be triggered and managed by internal ski sport structures (such as the FIS agenda), school holidays, and the media; during our interviews, several ski athletes expressed their views on the rigid timing structure. Such changes require a willingness among stakeholders to find a shared solution by discussing and rethinking the ski training timeframe. This is all the more important given the notable commitment in Switzerland to preserving glacier skiing infrastructures, driven by a desire to maintain a vibrant skiing culture. The Swiss federation supports these areas through junior sports finance programs whereby they mitigate the operational costs of cable cars.

From a more general perspective, the results of this study show the importance of taking a holistic view of the vulnerabilities and adaptations of various tourism stakeholders in addressing the challenge of climate change adaptation. This understanding can be useful to identifying adaptation pathways that lead to maladaptation (Schipper, 2020). For example, our results show that vulnerability caused by climate variables leads cable car companies to increase their maintenance and investment, thereby increasing their vulnerability to increasing ticket prices and visitor numbers. Interestingly, the workshops revealed that most stakeholders were unaware of each other's vulnerabilities, which underscores continued calls for more transdisciplinary research on climate adaptation (Pachoud et al., 2023).

The systems thinking approach used in this study made it possible to identify the vulnerability relationships between the stakeholders of the destinations, as shown in Fig. 8. Climate-related variables have a direct impact on ski-lift companies by affecting the facilities they provide and their costs, which in turn affects customers, for whom uncertainty is a key vulnerability factor. Climate-related variables also have a direct impact on customers: for example, climate awareness, such as awareness of glacial retreat, does not directly impact summer glacier skiing, but it does influence customers' perceptions of the landscape, which may influence their behavior. Climate variables also have an indirect impact on destination management and hospitality, mainly through customer management; changes in climate patterns or lift infrastructure can, e.g., cause fluctuations in clientele, which in turn can affect the hospitality sector. Accordingly, customer behavior plays an important role in shaping the dynamics of the hospitality sector. Customer behavior also shapes other external factors, such as the socialization and cultivation of current and future ski generations. Societal willingness to maintain and invest in skiing in general emerged in several conversations during the interviews and proved to be important through the subsidizing of cable car companies. Finally, human-induced greenhouse gases—a layer of external factors—influence the climate but are themselves influenced by customers' substitution behaviors, namely spatial substitution to the southern hemisphere; this adaptation strategy that increases greenhouse gas emissions can be understood as maladaptation (Schipper, 2020).

6. Conclusion

This research provides a systemic understanding of the impacts of climate change on the niche activity of summer glacier skiing in Saas-Fee and Zermatt, Switzerland. Building on a systems thinking perspective, our findings indicate that the potential discontinuation of summer glacier skiing would trigger wide-reaching impacts, extending beyond

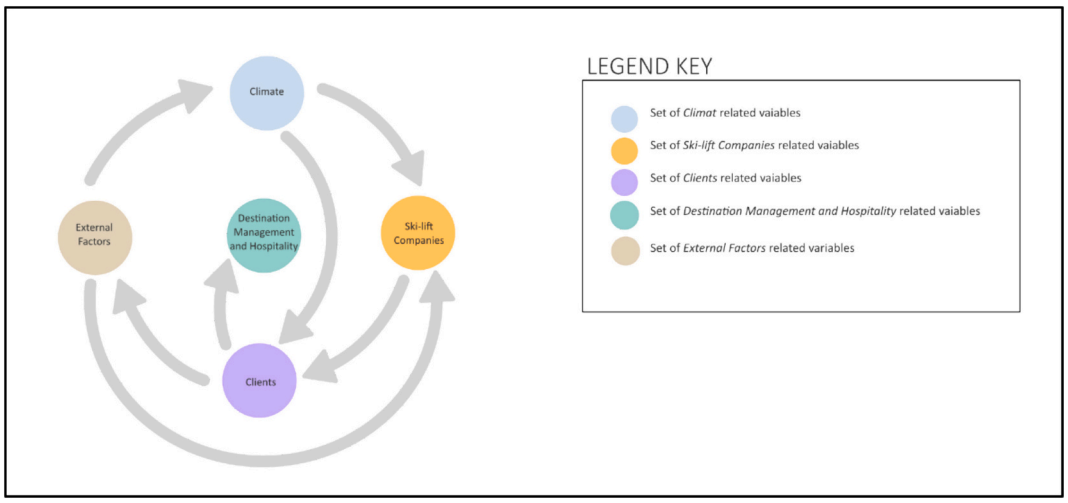

Fig. 8. Synthesized representation of the interrelationships of summer glacier skiing vulnerabilities.

cable car companies to affect the hospitality sector, athletes, and the broader mountain tourism industry. The low level of attention given to transformative adaptation by tourism operators, despite the likelihood of the imminent disappearance of summer glacier skiing, demonstrates the need for a paradigm shift; this entails not only addressing immediate challenges but also considering broader, structural changes in the operational framework. As ski teams shift their focus to alternative destinations and facilities, existing glacier skiing infrastructures are confronted with clear economic concerns, requiring a strategic and forward-thinking approach to ensure its viability or sustain its disappearance in the face of the evolving environmental and economic landscape.

Using a systems thinking approach makes it possible to understand and visualize the vulnerability of different stakeholders, their adaptation strategies, and their interrelationships. Systems thinking enables the identification of feedback loops wherein adaptation strategies increase vulnerability to climate change or lead to decreases in financial subsidies. Potential maladaptation pathways are also identified, with ski price management increasing economic vulnerability. Finally, leverage points, such as uncertainties, were highlighted as important to understanding the behavior of multiple stakeholders. This understanding is a starting point for managing sustainable adaptation strategies and limiting the risk of maladaptation.

This research also allows stakeholders to improve their common understanding of the situation and could potentially be used in the future to develop and test adaptation strategies with the tourism community. Systemic understanding also makes it possible to identify knowledge gaps, in particular with regard to the impact of climate change on the glacial landscape and its effects on the image of such destinations and the behavior of their clientele. The main identified adaptation strategies are reactive measures, but the wider impacts of climate change require a shift toward more transformative adaptation; this involves rethinking not only how summer glacier skiing is managed but also how mountain tourism as a whole can evolve to remain sustainable in the face of climate uncertainty. Future efforts should aim to foster innovation, improve stakeholder collaboration, and develop new models that balance environmental, economic, and cultural sustainability. The way forward requires a concerted effort to build resilience and adaptability, to ensure that mountain destinations can continue to thrive despite a changing climate.

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CRediT authorship contribution statement

Ephraim Gerber: Writing – review & editing, Writing – original draft, Methodology, Investigation, Formal analysis, Data curation. **Jeanne Fournier:** Writing – review & editing, Writing – original draft, Methodology, Investigation, Formal analysis, Data curation. **Emmanuel Salim:** Writing – review & editing, Writing – original draft, Supervision, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Emmanuel Fragnière:** Writing – review & editing, Supervision, Methodology, Funding acquisition, Conceptualization. **Leïla Kebir:** Writing – review & editing, Methodology, Funding acquisition, Conceptualization.

Declaration of competing interest

This manuscript has not been published or presented elsewhere in part or entirety and is not under consideration by another journal. All study participants provided informed consent, and the study design was approved by the appropriate ethics review board. We have read and understood your journal's policies and believe that neither the manuscript nor the study violates any of these. There are no conflicts of interest to declare.

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