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The snow must go on: Can snowmaking keep ski resorts profitable in a changing climate?

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Abstract

Climate change threatens the economic performance of ski resorts, and therefore the economies of mountain regions. Increased snowmaking is the leading adaptation strategy, but its economic contribution remains unclear. To fill this gap, we used dynamic panel data modelling to analyse the economic performance of 56 French Alpine ski lift operators over a 15-year period (2004/05 to 2018/19). Economic performance remains strongly linked to ski lift capacity and shows a high degree of persistence over time, all other things being equal. No evidence has been found that increased investment in snowmaking improves resort sales or profits, even in the worst natural snow seasons. These results strongly challenge the idea that increased snowmaking is an effective economic adaptation to climate change.

Keywords: Ski area; Ski lift operators; Winter tourism; Snowmaking; Climate change adaptation; French Alps

Introduction

Ski tourism is an important industry in mountain regions, with the development of ski resorts having profoundly changed the economy and landscape of the Alps (Denning, 2014). In France, 50 million skier visits per year are registered at ski resorts (Vanat, 2022), directly or indirectly supporting the employment of about 120,000 people (DSF, 2022). Public authorities have promoted the development of the ski tourism industry to revitalise declining mountain economies, transitioning them to winter tourism in the context of the expanding Fordist economic model after the Second World War (Pröbstl-Haider et al., 2019). With their sectoral and geographical spillover effects, ski resorts are the driving force behind these mountain economies. Ski lift operators play a central role at the resorts by providing the transport infrastructure and the slopes. They are one of the most significant contributors to the mountain tourism economy (George-Marcelpoil & François, 2012).

Natural snowfall varies from year to year and is decreasing worldwide as a consequence of climate change, especially in low-lying and mid-elevation areas (Hock et al., 2019). The duration of natural snow cover has already decreased below 2,000 m above sea level (m.a.s.l.) in the Alps (Matiu et al., 2021), undermining the operation of ski resorts at lower altitudes. The future will be even more precarious under various greenhouse gas emission scenarios (François et al., 2023; Spandre et al., 2019). In the 1990s, ski resorts started snowmaking activities to ensure skiability despite inter-annual variability in natural snow conditions. It is now considered the most widespread climate change adaptation strategy (Steiger et al., 2022). In France, the average snowmaking coverage of ski slopes was about 14% in 2004 and 39% in 2018 (Berard-Chenu, François, George, et al., 2022; Spandre et al., 2015) and this will most likely increase.

Several studies have elaborated on the conditions under which snowmaking can improve ski resorts' snow reliability (Scott et al., 2019; Spandre et al., 2017; Steiger et al., 2017). A recent study by François et al. (2023) found that even with 50% snowmaking coverage, 71% of European ski resorts would be at very high risk of snow supply for ski tourism in a world with a global warming level of +4°C. This would be accompanied by an increase in environmental impacts (water demand, electricity consumption and GHG emissions). Even the current ability of snowmaking to support local economies is uncertain. There are ongoing discussions on the physical feasibility of snowmaking, with a notable gap in the literature regarding the impact of snowmaking on the economic performance of ski resort operators and the sustainability of mountain economies (Steiger et al., 2019).

These economic aspects of snowmaking have long been of concern. For example, Scott et al. (2003) and Pickering & Buckley (2010) warned that with

climate change snowmaking could become “uneconomic”. A few studies have quantitatively examined the economic impacts of snowmaking, with mixed results. Falk & Vanat (2016) and Gonseth (2013) found that snowmaking is associated with more skier visits, but this effect tends to diminish as snowmaking use intensifies. Skier visits are furthermore only a proxy and do not reflect the resorts’ financial viability. Gonseth (2008) highlighted a positive but marginally decreasing effect of snowmaking on operator profitability, while Moreno-Gené et al. (2020) observed no evidence of this relationship.

It is currently unclear whether increased snowmaking is an economically sustainable adaptation strategy. With climate change, addressing this question is crucial for the future of mountain regions. As ski lift operators are the main drivers of the ski tourism industry, their profitability is a critical factor in assessing the economic sustainability of mountain regions. It is therefore necessary to determine whether investing in snowmaking systems contributes positively to lift operators’ profitability and long-term survival. These results will have implications beyond the lift operator, since continued investment in snowmaking also raises environmental issues (e.g. water demand, energy and GHG; (François et al., 2023; Knowles et al., 2024), as well as the issue of the efficient allocation of available water resources and public funding.

This study aims to contribute to the debate on the economic impact of snowmaking by overcoming the methodological limitations of previous studies (static econometric model specifications, absence or rudimentary controls for ski lift size and natural snow conditions, imprecise proxy for snowmaking growth, performance not measured at ski lift operator as well as ski resort levels, or study period too long ago; see Table 1). We develop a dynamic panel data modelling approach that extends the existing literature and answers the question of whether additional investment in snowmaking increases the turnover and profitability of ski lift operators, on which the economies of many mountain regions depend. Our results suggest that ski resort operators and public funders should shift their focus away from overreliance on snowmaking as a climate change adaptation strategy.

The following section presents the literature review and the theoretical background, and proposes a conceptual model of ski resorts’ economic performance. The materials and method section presents the data collected and the econometric methodology used for the analysis, followed by the results of the econometric analysis. The discussion section examines the results, whereafter the study concludes.

Literature review, theoretical background and conceptual model

This section first presents the limited literature that has quantitatively examined the effect of snowmaking on ski resorts’ economic performance, as measured by

indicators such as skier visits and profitability. It then presents the theoretical background of this work, followed by our conceptual model that captures the interaction between snowmaking and other factors that influence ski lift operators' economic performance.

Literature review

Table 1 summarises the literature that has quantitatively assessed the economic impact of snowmaking and illustrates the originality of this research. In particular, we present the limitations of these studies, which we aim to overcome in this study.

Study/ characteristics	<i>Gonseth (2008)</i>	<i>Gonseth (2013)</i>	<i>Falk and Vanat (2016)</i>	<i>Moreno-Gené et al. (2020)</i>	<i>This research</i>
Panel data analysis	X	✓ (not a dynamic specification)	✓	✓ (not a dynamic specification)	✓
Adequate sample	✓	✓	✓	X	✓ (less representative for small ski resorts)
Control for ski lift size	✓	✓	✓ (with dichotomous variable)	✓	✓
Control for natural snow conditions	X	✓	✓ (same measurement for all ski resorts)	X	✓
Measure economic performance at ski lift operator and ski resort level	X	X	X	X	✓
Precise proxy for snowmaking growth	X	X	✓	X	✓
Recent research (less than 10 years)	X	X	✓	✓	✓

Table 1: Key characteristics of studies that quantified the economic impact of snowmaking

Gonseth (2008) examined the relationship between profitability as measured by EBITDA (earnings before interest, tax, depreciation and amortisation)

and snowmaking coverage for 87 Swiss ski resorts over the 2003/04 and 2004/05 seasons. The author showed that snowmaking positively affects EBITDA and that this effect decreases as the degree of coverage increases. For the 2003/04 season, the author found that 69.5% of the resorts would have improved their EBITDA if their snowmaking coverage rate had been higher. He noted that the results were difficult to generalise, particularly in the context of climate change, due to the limited time of observation (two seasons). He also pointed out that past EBITDA values were important in determining current EBITDA, that his model did not take this effect into account and that it could alter the calculated coefficients.

In a subsequent study, Gonseth (2013) found that the partial effect of snowmaking on skier visits was positive, but showed a diminishing trend. The methodology consisted of static panel data models applied to a sample of 74 Swiss ski resorts for the 2005/06 to 2008/09 seasons. The time period (four seasons) as well as the lack of previous values in the panel data analysis of the explained variable were study limitations. As pioneering studies, the Gonseth (2008, 2013) results should be treated with caution today, as the data is from 2005 and the snowmaking coverage in Switzerland has increased significantly from around 14% in 2004 to 53% of all slopes in 2020 (Vorkauf et al., 2022).

Falk & Vanat (2016) analysed skier visits for 109 French resorts for the 2006/07 to 2013/14 seasons. They found a positive effect of snowmaking investment on skier visits for high altitude resorts (≥ 1770 m.a.s.l.), but this positive effect decreased as investment increased. For lower altitude resorts, they found that the effect was significant and positive only in extremely dry or low snow winter conditions. They mentioned that their model was quite modest. For example, the variation in resort size was controlled by dichotomous variables, and the reliability of natural snow cover was common to all resorts.

Using a sample of 18 Spanish ski resorts over the 2012/13 to 2017/18 seasons, Moreno-Gené et al. (2020) used a random effects regression estimator to show that snowmaking did not affect profitability (measured by either return on assets or earnings before interest and taxes). The authors acknowledged that the number of resorts analysed and the time period (six seasons) were limitations of their study. Another was the lack of natural snow conditions variables in the model, and they also did not specify a dynamic panel data model.

Theoretical background

In economics, the production function initially integrated capital and labour (Cobb & Douglas, 1928), but ignored the crucial role of nature in economic processes, as Costanza et al. (1997) emphasised. In contrast, Dasgupta & Mäler (2000) considered a production function:

$$Y = f(K, L, R)$$

with K for human-made capital, L for labour, R for natural resources and Y for the economic output.

Applied to the ski industry, Falk & Vanat (2016) derived an econometric model from a production function to study the effect of investments in snowmaking on skier visits, including natural snow conditions as a control variable. Although not mentioned in these terms, it is equivalent to considering a form of natural capital (R = natural snow cover) in a production process (Y = skier visits).

The role of nature in economic activity has also been considered in the field of economic geography, by making a distinction between first-nature and second-nature factors to explain the determinants of firm location. First-nature refers to the physical characteristics of a location, such as climate, topography and natural resources. Second-nature refers to the social and economic structures created by human activity, such as transport networks, urban development and local interdependencies in the goods, land and labour markets (Brakman et al., 2019).

In the context of ski resorts in mountain areas, both altitude and slope are first-nature factors. The former determines the amount of natural snowfall and the duration of the snow season, while the latter provides the topographical conditions for skiing. In contrast, ski lifts and snowmaking are second-nature factors – human-made technologies used to eliminate the need to climb the slopes and to artificially supplement natural snowfall. It should be noted that labour is less important in ski tourism, as the industry is capital-intensive and makes large investments in buildings and equipment (Berard-Chenu et al., 2021).

In the context of a weather-sensitive tourism industry (de Freitas, 2003), it is therefore important to consider whether investing in a second-nature or human-made factor, such as snowmaking, can maintain ski resort operators' profitability when climate change threatens natural snowfall as a critical first-nature factor. This question is aligned to a major debate in the environmental and ecological economics community regarding the possibility of substituting human-made capital for natural capital. Proponents of a “weak” vision of sustainability believe that natural capital can be substituted with other forms of capital, while those with a “strong” vision of sustainability emphasise the unique and irreplaceable value of natural resources (Neumayer, 2003).

Conceptual model

To examine the relationship between snowmaking and ski lift operators' economic performance, we propose a conceptual model that incorporates key factors highlighted in the literature. The model aims to highlight the complex dynamics be-

tween snowmaking, natural snow conditions, resort size, past economic performance and altitude that influence ski lift operators' economic performance (Figure 1).

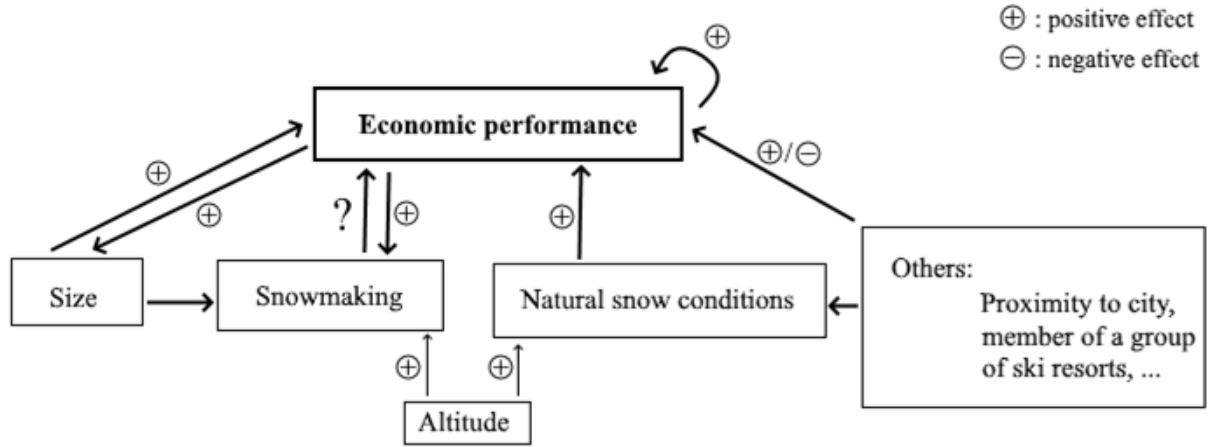


Figure 1: Theoretical framework on the drivers of ski lift operators' economic performance.

As a human-made production factor, snowmaking is expected to improve ski lift operators' economic performance by ensuring reliable skiing conditions, particularly during the opening and closing seasons (Steiger & Mayer, 2008). Based on the law of diminishing returns (Shephard & Färe, 1974), and in line with the findings of Falk & Vanat (2016) and Gonseth (2008, 2013), we expect the marginal return to snowmaking to decrease, all other things being equal. In addition, there may be an inverse relationship between profitability and snowmaking use, as the most profitable resorts often have greater financial capacity to invest in snowmaking infrastructure.

Ski resort size is also a human-made production factor that can influence economic performance through economies of scale (Falk & Steiger, 2020). Larger resorts often have more extensive infrastructure, a greater number of slopes and the ability to offer a wider range of services, which can increase customer satisfaction and attract more visitors. Ski resort size may also be related to the intensity of snowmaking investment, as the expense is likely to be related to the volume of slopes.

Natural snow conditions may influence ski resorts' economic performance, since resorts with better natural snow conditions will probably attract more customers and generate higher revenues. This natural factor is also close to the altitude, which may facilitate economic performance, as ski resorts at higher altitudes have better natural snow conditions as well as more cold slots to produce snow.

Past economic performance may have an impact on current economic performance, as other investments, reputation, word of mouth and business practices (e.g. early bookings by tour operators) are likely to maintain a certain level of

economic performance by retaining customers. Other factors will also affect economic performance, such as proximity to a large city or whether the resort is part of a ski resort group. This kind of data is difficult to collect.

Materials and method

This section presents the data collected to analyse the relationship highlighted in the conceptual model (Figure 1). We present descriptive statistics and the econometric methodology used to estimate these relationships.

Materials

In France, skier transport is legally a public service, and ski lifts are managed by the public authorities. The smallest resorts, with limited economic perspectives, are generally managed directly by the local authorities, while the management of the largest resorts is delegated to private (sometimes semi-public) companies. Because they are larger, private ski lift operators are also more important to the regional economy. Those that are not privately managed do not have private accounts, therefore no data is available. In addition, because they are supported by public authorities, they do not have to achieve financial equilibrium and can afford to make unprofitable investments.

For these two reasons, we excluded publicly managed ski lift operators from our sample and decided to focus on 56 (often larger) private ski resorts in the French Alps that we were able to follow for 15 consecutive seasons, from 2004/05 to 2018/19. Figure 2 shows a map of the ski resorts studied in terms of size and altitude.

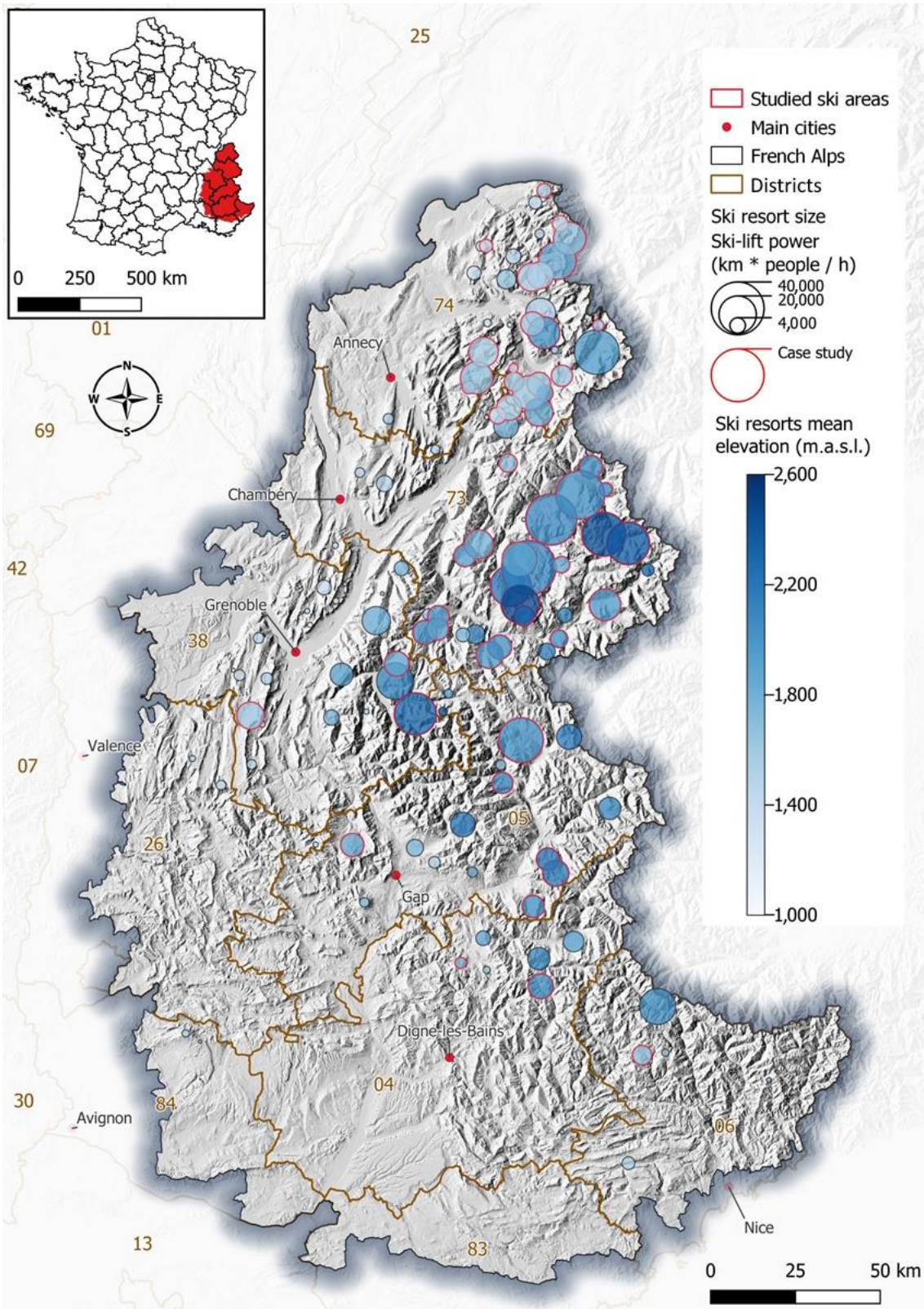


Figure 2: Sample of ski resorts and their altitude.

We collected information about the characteristics, economics and snow cover of the ski resorts. All data is measured at the ski resort level and comes from several sources:

- Two key indicators measure economic performance: turnover and gross operating surplus (GOS). We have extracted both from the Diane database collected by Bureau Van Dijk¹. This database aggregates the balance sheets of French private companies over many years. Turnover is a proxy for skier visits, as it is roughly equivalent to multiplying the price of a ski pass by the number of skier visits, so it also relates to the number of tourists present in the area and participating in the regional economy. GOS measures a company's profitability independently of its investment and financing strategies. GOS is "equal to value added minus payroll and other taxes on production and plus operating subsidies"². This indicator is one of the most widely used measures of a company's financial health and is a better indicator of the profitability of lift companies than turnover or skier visits. Profits are necessary for long-term survival in a competitive environment (Foreman-Peck et al., 2006). In other words, this indicator provides information about the economic sustainability of the ski lift activity in the resort and its ability to secure its role as a local economic driver in mountain regions. It should be noted that the financial year of ski lift operators does not follow the calendar year, but usually ends at the end of autumn, so that each winter season is covered by the same financial year. Unlike ski resorts in other European countries, French ski resorts do not have income from restaurants or accommodation. Berard-Chenu et al., (2022) explained how French ski resort operators have undergone a "specialisation turn", focusing on their core business by, among other things, abandoning certain activities such as real estate development or activities in the ski tourism supply chain.
- The information on snowmaking is taken from a dataset of snowmaking investments for 100 ski resorts in the French Alps from 1997 to 2018. The dataset comes from the journal *Montagne Leaders*, which manages an annual investment survey filled in by ski lift operators in a declarative manner. The investment figures cover all investments related to the development of snowmaking facilities, such as snow guns, water reservoirs or civil engineering investments. Although this data is collected by an unofficial organisation, it is of considerable value. For example, Berard-Chenu et al.

¹ <https://www.bvdinfo.com>

² <https://www.insee.fr/fr/metadonnees/definition/c1538>

(2021) and Falk & Vanat (2016) used this data source for academic research purposes.

- The snow reliability index is calculated according to Spandre et al. (2019), based on the SAFRAN-Crocus Resort modelling chain, adapted to the snow management practices in ski resorts (Spandre et al., 2016). The simulations provide a monthly or annual snow condition index for each ski resort, according to natural snow conditions, and another index for managed snow (including grooming and snowmaking effect on snow cover). We use these indices to focus on snow conditions across and within seasons, as certain periods are critical for winter sports. We considered the worst snow seasons and the worst December/February months by selecting the three seasons or the three December/February months for each ski resort (out of 15, or the 20th percentile) where its snow reliability indices are lowest. They are used as dichotomous variables (value 1 if the snow season or December/February is one of the three worst for the resort, 0 otherwise).
- The BD Stations database³ provides additional relevant information on ski resorts. This database covers 230 French ski resorts, including 139 resorts in the Alps, representing 84.4% of the total ski lift capacity. From this database, we used the average altitude (m.a.s.l.) of the ski resort and the ski lift power (km. pers. h-1) as a proxy for the size of the ski resort. Our sample covers most of the total ski lift power, excluding the often smaller publicly managed ski lift operators (Appendix 1.1 and 1.2).

Descriptive statistics

Table 2 presents the descriptive statistics of the data we collected. Turnover is always positive. GOS is positive on average, but some values are negative, indicating that some resorts are unprofitable in some seasons. For both, the variation in the sample is important and the difference between the median and the mean indicates the presence of strong economic performance values. Each resort has invested in snowmaking during the study period. Snowmaking investments are cumulated over the period, starting at 0 for each resort in 2004. The statistics on ski lift power show the large gap between the smallest and largest resorts. The natural snow reliability index shows that, on average, the resorts have a relatively high natural snow cover (85.95%), with a zero value for a single resort during the winter of 2011. Half of the resorts studied have an average altitude below 1,834

³ <https://www.observatoire-stations.fr>

m.a.s.l., with a range of 1,315 to 2,501 m.a.s.l. This justifies that an important part of the studied resorts is already facing the declining natural snow cover (pronounced below 2,000 m in the French Alps according to Matiu et al., 2021). Appendix 1.2 indicates the distribution of our sample according to altitude and size of the ski resort, and shows that our sample is not representative of the very small ski resorts located at very low altitudes.

Variable	mean	p50	sd	min	max
Turnover (k€)	13,958.32	7,943.34	14,684.57	2.57	62,717.35
Gross operating surplus (k€)	4,740.91	2,448.56	6,042.70	-1,286.91	26,513.50
Cumulated snowmaking investments (k€)	4,931.83	3,415.54	4,968.47	0	29,507.04
Ski lift power (km pers. h-1)	13,324.42	9605	11,111.91	368	52,859
Natural snow cover reliability (%)	85.95	90.95	17.67	0	100
Altitude (m.a.s.l.)	1,834.52	1834	292.64	1315	2,501

Note: Descriptive statistics for the 56 stations over 15 years. Number of observations: 759

Table 2: Summary statistics

Table 3 shows the results of the Pearson correlations. It shows a very strong correlation between turnover, gross operating surplus and ski lift power. There is a strong correlation between both turnover and gross operating surplus, with cumulated investment in snowmaking, and between ski lift power and cumulated investment in snowmaking. Altitude is also strongly correlated with turnover, gross operating surplus and ski lift power. The natural snow reliability indexes show weak correlations with turnover, gross operating surplus and other variables. An appropriate methodology is needed to further investigate the relationships between the variables.

	Turnover	Gross operating surplus	Cumulated snowmaking investments	Ski lift power	Natural snow cover reliability	Altitude
Turnover	1.0000					
Gross operating surplus	0.9637*	1.0000				
Cumulated snowmaking investments	0.6667*	0.6296*	1.0000			
Ski lift power	0.9645*	0.9186*	0.6862*	1.0000		
Natural snow cover reliability	0.2430*	0.2309*	0.1142*	0.2410*	1.0000	
Altitude	0.5516*	0.5703*	0.3523*	0.5336*	0.1903*	1.0000

* Coefficients significant at the 5% level. Please note that significant correlation is not causation.

Table 3: Matrix of Pearson's correlation coefficients for pooled data

Method

Panel data econometric methods were used to analyse the effect of snowmaking on the ski resorts' economic performance. For an introduction to panel data econometrics, see for example (Baltagi, 2021). The focus here is on dynamic specification, according to which one or more lags of the dependent variable are included in the model. Since GOS and turnover are likely to be persistent over time, this will ensure that the residuals do not exhibit autocorrelation.

The usual dynamic panel data econometric model is expressed in this way:

$$Y_{it} = \phi Y_{it-1} + \beta X'_{it} + \lambda_t + \eta_i + \varepsilon_{it} \quad (1)$$

where Y represents the dependent variable, Y_{-1} the lagged dependent variable, X the regressors, λ_t the time effects that are common to all individuals, η_i the individual time-invariant effects and ε the idiosyncratic error, which is assumed to be independent and identically distributed with mean zero. The subscript i stands for individual and t for time periods.

Based on equation 1, the conceptual model and the material collected, we can specify the two models to be estimated by replacing Y with our explained variable and X with our explanatory variables:

$$\begin{aligned} Turnover_{it} = & \phi_1 Turnover_{it-1} + \phi_2 Turnover_{it-2} + \\ & \beta_1 Ski_lift_power_{it} + \beta_2 Snow_cover_reliability_{it} + \\ & \beta_3 Cumulated_snowmaking_investments_{it} + \\ & \lambda_t + \eta_i + \varepsilon_{it} \quad (2) \end{aligned}$$

$$\begin{aligned} GOS_{it} = & \phi_1 GOS_{it-1} + \phi_2 GOS_{it-2} + \\ & \beta_1 Ski_lift_power_{it} + \beta_2 Snow_cover_reliability_{it} + \\ & \beta_3 Cumulated_snowmaking_investments_{it} + \\ & \lambda_t + \eta_i + \varepsilon_{it} \quad (3) \end{aligned}$$

where η_i denotes the fixed effects, which capture all time-invariant factors such as proximity to a large city and λ_t denotes the time effects, which capture all variables that change over time but are common to all ski resorts, such as macroeconomic conditions (e.g. an economic crisis). Temporal dummy variables are introduced in our model to capture these effects. We are interested in estimating β and ϕ in equations 2 and 3 to measure the sign, strength and significance of the relationship between the regressors and the dependent variable.

The most common consistent estimators for the dynamic specification of panel data models are based on the Generalised Method of Moments (GMM). The GMM model provides consistent results in the presence of different sources of endogeneity, namely “unobserved heterogeneity, simultaneity and dynamic endogeneity” (Wintoki et al., 2012). They are particularly suitable for our case because our panel is “short”, meaning that n is large and T is relatively small. This

also implies that non-stationarity is not a significant concern in our case (Baltagi, 2021). In addition, they use instrumental variable techniques, which allow us to treat the lagged dependent variables as predetermined/weakly exogenous (they are correlated with past errors but not with present or future ones).

This also allows us to account for the effect of snowmaking investment on profitability, as it raises the issue of simultaneity, since investment in snowmaking will probably increase ski lift operators' profitability, and profitable ski lift operators are more likely to invest in snowmaking. This suggests that investment in snowmaking should be considered endogenous rather than exogenous in our profitability equation. Note, however, that GOS excludes expenses related to the company's investment and depreciation policies. This means that, by definition, current values of resort profitability are not linked to current investment in snowmaking, although the former may influence the latter.

In addition, it cannot be ruled out that part of the investment in snowmaking will be decided and carried out during the season on the basis of the partial realisation of profits. However, we believe that most investments are decided on the basis of past profits and carried out during the summer. Furthermore, our variable is cumulative snowmaking investment and not current investment, which suggests a dilution of simultaneity and can therefore be considered as a weakly endogenous (predetermined) regressor.

For the predetermined regressors (lagged economic performance, ski lift power and cumulated snowmaking investment), lagged values of the variables are used as instruments to control for their endogenous relationship with the dependent variable.

Four static and four dynamic estimators for panel data model were considered. We focus on the dynamic system GMM estimator developed by Arellano & Bover (1995) and Blundell & Bond (1998). It consists of solving a system with two models: the initial (in levels) and the transformed (in a first difference with levels as instruments). It has the advantage of not removing time-invariant variables, unlike the dynamic Difference-GMM (Arellano & Bond, 1991). By introducing more instruments, it avoids the poor performance of dynamic Difference-GMM due to weak instruments, especially when Y is persistent. We perform this estimator in two steps, to gain efficiency and robustness to autocorrelation and heteroscedasticity.

The estimations were performed using Stata software, and the `xtabond2` package (Roodman, 2009b) was used for the dynamic estimators. We used the `collapse` option, which limits the number of instruments used so that it does not exceed the number of groups. This respects the rule of thumb so that the problem of too many instruments does not affect the estimation (Roodman, 2009a).

Results

This section presents the results of panel data estimations used to analyse the effect of snowmaking on ski resorts' economic performance. The regressors used for each specification are summarised in Appendix 2 and the full results of all static and dynamic estimations are available in the online supplementary materials. The results obtained with turnover as the explained variable are very similar to those obtained with GOS as the explained variable.

The main result is that cumulative investment in snowmaking has no significant effect on either the turnover or the gross operating surplus of ski lift operators, regardless of the specification and the estimator used.

Tables 4 and 5 summarise the estimates with either Turnover or GOS as the dependent variable. We obtained these estimates using the dynamic two-step System-GMM estimator. This estimator is the most efficient and consistent given the specificities of our data (method section). The four specifications displayed include control variables for ski lift power and time effects, as well as the dependent variable lagged by one and two periods.

The first lagged dependent variable always has a significant effect, indicating quite a strong inertia in the dependent variable. This implies that changes in the variable tend to persist over time. For example, if the turnover of the current year increases by one euro, it is expected to increase by 0.695 euro in the following year. Similarly, if the GOS of the current year increases by one euro, it is expected to increase by 0.81 euro in the following year, all other things being equal.

The second lagged dependent variable is not statistically significant, but it is included to control for the autocorrelation of the residuals. Ski lift power is always significant, indicating the importance of resort size for economic performance. A one-point increase in ski lift power results in an increase of 386 in turnover and 137 euros in GOS, all other things being equal. With an increase of 10,530 passenger km. h⁻¹, corresponding to the interquartile range, turnover and GOS increase by 4.065 and 1.442 million euro, respectively.

We henceforth focus on the variables linked to each specification (Appendix 2 contains a description). Column 1 of Tables 4 and 5 introduces our main variable of interest (cumulated snowmaking investment) and the seasonal snow reliability index as an additional control variable. Cumulated snowmaking investment has no significant effect on the dependent variable (either the turnover or the gross operating surplus of ski lift operators), nor does the natural snow cover reliability index.

Model specification n°	[1]	[2]	[3]	[4]
Turnover	0.473***	0.477**	0.533***	0.695***
<i>(First lag)</i>	(0.173)	(0.221)	(0.166)	(0.184)
Turnover	-0.00426	-0.0351	-0.135	0.00809
<i>(Second lag)</i>	(0.0895)	(0.113)	(0.134)	(0.0967)
Cumulated snowmaking investments	0.257			
	(0.162)			
Cumulated snowmaking investments		-0.0681		
<i>(for the worst natural snow seasons)</i>		(0.0617)		
Cumulated snowmaking investments			-0.0822	
<i>(for the worst natural snow in December)</i>			(0.148)	
Cumulated snowmaking investments			-0.00540	
<i>(for the worst natural snow in February)</i>			(0.0337)	
Ski lift power	0.546**	0.876**	0.755***	0.386***
	(0.221)	(0.353)	(0.222)	(0.129)
Snow cover reliability index	15.76			
<i>(Natural snow season)</i>	(21.09)			
Altitude				0.941**
<i>(for the worst-managed snow in December)</i>				(0.463)
Altitude				-0.300
<i>(for the worst-managed snow in February)</i>				(0.450)
Year dummies	Yes	Yes	Yes	Yes
No. of observations	612	612	612	612
Instruments/Groups	38/56	45/56	55/56	52/56
AR(1) test p-value	0.0267	0.0383	0.0219	0.0255
AR(2) test p-value	0.249	0.373	0.993	0.119
Hansen test p-value	0.388	0.223	0.174	0.431

Note : Turnover and cumulated snowmaking investments are expressed in thousands of euros.

Robust option was used for each estimation.

Robust standard errors of two-step GMM estimates use the Windmeijer's finite-sample correction.

The worst snow seasons dummies identify, for each resort, the years where the snow cover reliability indices – computed either based on the natural or managed snow – are among the three lowest (out of 15), either for the whole season or for December/February only. The managed snow cover reliability index is the natural snow cover reliability index adjusted for the effect of grooming and snowmaking on the snow cover.

Standard errors in parentheses

* $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$

Table 4: Modelling ski lift operator's turnover – estimates by the dynamic two-step System-GMM estimator for each model specification

Model specification n°	[1]	[2]	[3]	[4]
Gross operating surplus (<i>First lag</i>)	0.606*** (0.149)	0.540*** (0.199)	0.681*** (0.182)	0.810*** (0.208)
Gross operating surplus (<i>Second lag</i>)	-0.199 (0.122)	-0.132 (0.143)	-0.221 (0.148)	-0.0549 (0.161)
Cumulated snowmaking investments	0.0253 (0.0906)			
Cumulated snowmaking investments (<i>for the three worst natural snow seasons</i>)		-0.0125 (0.0536)		
Cumulated snowmaking investments (<i>for the three worst natural snow Decem- bers</i>)			-0.0551 (0.0626)	
Cumulated snowmaking investments (<i>for the three worst natural snow Febru- arys</i>)			-0.0143 (0.0217)	
Ski lift power	0.285*** (0.0728)	0.342** (0.147)	0.277*** (0.0749)	0.137*** (0.0429)
Snow cover reliability index (<i>Natural snow season</i>)	2.230 (10.52)			
Altitude (<i>for the three worst-managed snow Decem- bers</i>)				0.818** (0.335)
Altitude (<i>for the three worst-managed snow Febru- arys</i>)				-0.0260 (0.385)
Year dummies	Yes	Yes	Yes	Yes
No. of observations	611	611	611	611
Instruments/Groups	47/56	42/56	51/56	47/56
AR(1) test p-value	0.00288	0.0220	0.00844	0.0263
AR(2) test p-value	0.625	0.465	0.730	0.118
Hansen test p-value	0.384	0.296	0.142	0.358

Note: GOS and cumulated snowmaking investments are expressed in thousands of euros.

Robust standard errors of two-step GMM estimates use the Windmeijer's finite-sample correction.

The worst snow seasons dummies identify, for each resort, the years where the snow cover reliability indices – computed either based on the natural or managed snow – are among the three lowest (out of 15), either for the whole season or for December/February only. The managed snow cover reliability index is the natural snow cover reliability index adjusted for the effect of grooming and snowmaking on the snow cover.

Standard errors in parentheses

* $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$

Table 5: Modelling ski lift operators' GOS – estimates by the dynamic two-step System-GMM estimator for each model specification

The second specification (column 2) interacts snowmaking investment with time dummies for the three worst natural snow seasons for each resort, based on its individual natural snow reliability index. The effect of cumulated snowmaking investment on profitability is also insignificant. The third specification (column

3) interacts snowmaking investment with time dummies for the three worst months of December and the three worst months of February regarding natural snow conditions. Snowmaking investment is still insignificant. The fourth specification focuses on the effect of altitude in the three worst months of December and the three worst months of February on managed snow conditions.

The results show that altitude plays a significant and positive role in determining economic performance in December, but its effect is not significant in February. For seasons with low snow cover in December, an elevation of the ski area by 1 metre increases turnover by 0.941 euro and GOS by 0.818 euros, all other things being equal. With an increase of 467 m.a.s.l., corresponding to the interquartile range, turnover and GOS increased by 0.439 and 0.382 million euro respectively.

The coefficients were estimated using logarithms for several variables, and the results were similar. Online supplementary material 1.1 and 1.2 contain synthetic tables with cumulative snowmaking investments, lift capacity and snow cover reliability index in logarithm. The coefficients were also estimated by splitting the observation period in two (from the 2004/05 season to 2011/12 and from the 2012/13 season to 2018/19), and the results were similar. Other estimators produced results very similar to those just described (supplementary material 2.1.1 to 2.2.4). We noticed a lower significance of the ski lift capacity variable with the static fixed effects estimator (within) and with the dynamic difference GMM estimator. This is not surprising, as these estimators perform poorly with regressors that vary slightly over time.

Finally, we can comment on the diagnostic tests. For the GMM to produce consistent estimates, the errors must not be autocorrelated (AR(2) test) and the instruments must be valid (Hansen test). The p-value of the second-order autocorrelation test (AR(2)) is always greater than the 0.05 significance level. We can therefore not reject the null hypothesis of no autocorrelation at the 5% significance level. This indicates that the instruments are robust to serial correlation. The p-value of the Hansen test never indicates the rejection of the null hypothesis of a correct model specification, which means that our instrument set is valid.

Discussion

The finding that investment in snowmaking does not affect turnover and profitability may seem surprising. Snow cover is after all a necessary condition for the ski resort industry and for ski lift revenues and at some times of the season, there may be a deficit. As snowmaking improves snow reliability, we initially expected a positive effect of snowmaking growth on economic performance. However, these insignificant results can be explained as follows.

Early investments in snowmaking are particularly useful, as they are made in key sectors of the ski area. The benefits of further investment however tend to diminish as snowmaking coverage increases (Falk & Vanat, 2016; Gonseth, 2008). This implies that investment in snowmaking may reach an economic limit, where its marginal return is zero. Our results show that, on average, the ski lift operators in our sample have already reached this threshold.

On the demand side, the insignificance of snowmaking investments could be partially explained by the fact that skiers may be more critical of the environmental impact of ski resorts. For example, (Malasevska et al., 2023) showed that alpine skiers are generally willing to pay more for a day pass if the resort is either environmentally certified, carbon-neutral or uses only natural snow. On the supply side, contextual factors may reduce the return on investment in snowmaking, including rising temperatures, decreasing efficiency or potentially rising energy prices (Damm et al., 2014).

Snowmaking requires negative temperatures, and in the context of global warming, cold periods are becoming rarer. During certain periods of natural snow deficit, snow could not be produced (or not in sufficient quantities), therefore snowmaking growth could not reduce economic losses. Increased snowmaking creates additional financial difficulties that may lead to the closure of the most at-risk ski resorts (Rice et al., 2022), and rising operating costs may make the operation of low-altitude resorts unviable in the near future (Dannevig et al., 2021). In the same vein, Hock et al. (2019) and François et al. (2023) have already argued that adaptation to climate change for ski tourism through snowmaking is unlikely to significantly reduce the long-term risks at most locations.

Why would ski lift operators continue to invest in snowmaking despite the lack of impact on their economic performance? We suggest that ski lift operators may not be aware of this lack of impact, or may have a different rationale for their investment decisions than turnover or profitability. Firstly, ski lift operators are in an economic race against each other, where they must constantly invest in order to remain competitive, maintain their reputation and attract skiers, all in a mature European ski tourism market. There may be an upward spiral of investment in snowmaking, with ski lift operators mimicking their competitors and investing regardless of profitability. This could be a lose-lose situation for all involved: investment in snowmaking has an opportunity cost, meaning that the financial resources used for this investment could have been used in other ways that might have generated a better return for the ski lift operator.

Secondly, we suggest that the relationship with tour operators is potentially explanatory. The latter provide large numbers of skiers and are keen to

ensure good skiing conditions for their customers. They can exert pressure on ski lift operators to invest.

Thirdly, the strong involvement of public authorities in the management of ski resorts in France provides another explanation: public financial support encourages investment in snowmaking. They provide an incentive for ski lift operators to invest in snowmaking, even if this investment does not directly improve their profitability. The total subsidies granted by regional authorities in the French Alps for the period 2016-2019 amount to almost 60 million euro, with some windfall profits for ski lift operators (Berard-Chenu et al., 2022).

Fourthly, a path dependency effect may also explain continued investment in snowmaking (Berard-Chenu et al., 2022): resorts may be locked into their past choice and be unable to switch to alternative strategies once they have invested in snowmaking. Path dependency mechanisms should not be ignored when understanding unprofitable decisions by ski lift operators, as they may lead to maladaptation (Scott et al., 2022).

Finally, it can be considered that investment in snowmaking infrastructure for ski lift operators secures all the assets of the operator, including investment in new ski lifts. Investment in snowmaking can therefore be compared to a sunk cost, similar to paying a premium for insurance. An investment in snowmaking is a cost that cannot be recouped and is made to cope with winters with little snow. The lack of significance, even in the worst snow seasons, suggests that the role of snowmaking as an operational hedge (Tang & Jang, 2011) may not have been achieved. Due to climate change, the worst is yet to come for many ski lift operators in terms of snow reliability.

Let's take a broader view of our econometric results: in addition to suggesting that a higher investment in snowmaking does not significantly improve ski lift operators' profitability and turnover, our results show that economic performance is strongly enhanced by economies of scale (ski lift capacity), with altitude also playing a role, especially during winters with limited snowfall.

From an economic geography perspective, our results stress the complementarity between first-nature and second-nature factors in the ski tourism industry. Obviously, ski lift infrastructures cannot be operated without suitable snow conditions. But under average known climate conditions, differences in snow cover do not explain differences observed in operational profits between resorts and years (meaning that snow reliability has a non-significant effect on profitability and turnover).

Yet, under particularly "defavourable" meteorological conditions (e.g. the three worst snow seasons of our study period), a higher altitude – as a proxy for more reliable natural snow conditions for skiing – provides a significant economic advantage. Our results demonstrate that this first-nature advantage is not offset by investments in snowmaking facilities. Altitude and snowmaking facilities are

not substitutes, but complementary: altitude not only provides better natural snow cover and reduced melting speed, but also allows for low temperatures that make snowmaking more feasible and less costly.

The importance of altitude is likely to become increasingly critical in the context of climate change. Human-made snow is expected to become more important in offering suitable ski conditions, but snowmaking is expected to become less efficient due to the depletion of snowmaking slots. It may therefore be futile to think of snowmaking as a magic “second-nature” bullet to solving the problem of climate change at ski resorts. Our results rather suggest that winter sports activity is likely to become even more concentrated in areas with the most favourable first-nature conditions.

This study has limitations that need to be mentioned. The results are less representative of small resorts, which are often publicly owned in France. Their importance to the regional economy is smaller. In addition, the cumulated investments we use to describe snowmaking capital start from 0 at the beginning of our observation period, which ignores possible investments ski resorts made before 2004. As a robustness test, we carried out comparable analyses using cumulated investment starting from 0 in 1997, with similar results.

It should also be stressed that although our analysis considers individual characteristics, the results should be interpreted as a trend and not as a statement that applies to every ski resort. It is plausible that a few ski resorts with underdeveloped snowmaking facilities could still benefit from an additional investment in snowmaking. Further investments in snowmaking should be considered on a case-by-case basis rather than as a generic solution to deteriorating snow conditions in the context of climate change.

Additionally, it is important to note that our results are based on an analysis of a past period. It is therefore necessary to interpret them with caution, as past gains do not prejudice future gains. For instance, in the coming decades we might expect resorts at higher altitudes to benefit from past investments in snowmaking. Despite having better natural snow cover due to their higher altitude, the larger high-altitude resorts have invested the most in snowmaking. In the future, these resorts may be able to offer a service that resorts at lower altitudes cannot provide due to climate change and deteriorating natural snow cover. This is consistent with the spatial shifts phenomenon in tourism flows between specific ski resorts that Soboll & Dingeldey (2012) highlighted.

Although we have begun to analyse the effect of altitude, estimating the coefficients of time-invariant variables in a dynamic panel data model specification that does not have a long period of observations can be challenging (see in particular (Kripfganz & Schwarz, 2019)). We believe that more research is needed

to clarify the impact of altitude on ski resorts' economic performance in a changing climate, by taking advantage of the increasing availability of longitudinal data and the recent developments in dynamic panel data econometric methodology.

Conclusion

In this study, we investigated the impact of snowmaking investments on ski lift operators' economic performance. We collected financial, meteorological and characteristic data for 56 ski resorts in the French Alps over a 15-year period, from the 2004/05 season to the 2018/19 one. We analysed the data using dynamic panel data econometric methods, overcoming several limitations of previous studies. The main result is that cumulated investment in snowmaking over the period has no significant effect on either the turnover or the gross operating surplus of ski lift operators, even during unfavourable snow seasons.

This leads us to make a few recommendations to decision-makers of mountain regions about the ongoing growth in snowmaking as an adaptation to climate change. Further investments in snowmaking do not appear to be determinants for the economic sustainability of mountain regions, while this will increase environmental impacts (e.g. water demand, energy and GHG; (François et al., 2023; Knowles et al., 2024)). This implies that ski resort operators and public funders should shift their focus away from overreliance on snowmaking as a climate change adaptation strategy.

Although we have shown that further investment in snowmaking is not economically recommended, the desirability of maintaining current levels of snowmaking is a different question. To provide an answer, environmental sustainability issues should be addressed. In particular, the availability of water resources is a major constraint on snowmaking capacity and at the same time raises the issue of sharing water resources between different users and ecosystems (Reynard, 2020). From this perspective, the current level of snowmaking should be considered more carefully, not only from a company perspective, but also in a local context, taking into account the concurrent need for resources.

Declaration of interest

The authors do not report any relevant financial or non-financial competing interests.

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