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Climate Change Adaptation of Alpine Ski Tourism in Spain

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Abstract: Mountain ecosystems are considered to be vulnerable to climate change, with potential detrimental effects including the reduction of the snow seasons, the gradual retreat of glaciers, and changes in water storage and availability. One vulnerable sector to climate change is winter tourism, with some resorts likely to experience a significant reduction in the length of the skiing seasons and snow recreation areas throughout this century. This study assessed the vulnerability of 31 Spanish alpine ski resorts to climate change and evaluated the potential socio-economic and environmental implications of several adaptation measures. Results show that lower-altitude areas such as the Cantabrian Mountains and the Iberian System could be more vulnerable to climate change than higher-altitude areas of the Catalan Pyrenees or the Penibaetic System. Adaptation initiatives may include, inter alia, the production of artificial snow, the protection and conservation of the snow coverage area, and the diversification of recreation activities offered during the whole year. The study concludes that the design and implementation of adaptation strategies have to be adequate to the level of vulnerability associated with each resort as well as minimize their potential socio-economic and environmental costs.

Keywords: climate change; adaptation; winter tourism; alpine ski; Spain

1. Introduction

Mountain ecosystems are threatened by climate change [1–3]. The projected gradual increase in atmospheric temperatures together with changes in the precipitation patterns may contribute to a decline in snow reserves [4]. According to the Intergovernmental Panel on Climate Change (IPCC), scenarios RCP (representative concentration pathways) 2.6 and RCP 8.5, spring snow coverage could suffer an average reduction of 7% to 25% in the Northern Hemisphere in 2100, respectively [5].

The gradual disappearance of glaciers, perennial snow, and the length reduction of the snow season will affect the runoff from snow, reducing river flows and water storage and availability in the related basins [1,6,7]. The melting of near-surface permafrost could also contribute to an increase in rockfall frequency [8]. Additional consequences of climate change may include, e.g., the potential loss of open habitats for grassland bird species [9], and the increase in runoff erosion led by the higher frequency of forest fires [10].

One particular sector that can be negatively affected by the potential lack of natural snow, insufficient snow depth, and earlier snow melting is winter tourism. [3,11,12]. The degree of impact of climate change on recreation activities such as alpine skiing may depend on several factors associated with the location of the resorts. These comprise, *inter alia*, the type of climate, altitude, and the geographical position of the ski slopes regarding the daily sun exposition [11]. Artificial snow is commonly used by ski resorts to face shortages of natural snow, as well as one important resource to attract visitors in a context of high competitiveness amongst resorts. This involves promoting recreational areas with significant snow coverage for the development of complementary activities to skiing (e.g., snow thematic parks and snowboarding) and winter sport events [11,13,14]. Nevertheless, the future climate conditions may threaten the implementation of artificial snow, especially in low altitude resorts with physical and economic limitations [3]. Resorts may have to deal with an increase in water and energy consumption, and a reduction in the number of days with low temperatures that are suitable for snow production [3,14], threatening the economic viability of ski resorts.

There are various examples of studies assessing the vulnerability of snow tourism to climate change. Abegg et al. [15] focused on the adaptation of this sector, as well as on the management of natural hazards in the region of the European Alps. They found that the winter tourism industry has already started to implement strategies to respond to climate change. Various technological and behavioral adaptation measures have been put into practice, with artificial snowmaking being the main adaptation strategy. Steiger and Abegg [16] presented a sensitivity analysis of the Austrian ski tourism in terms of natural and artificial snow reliability according to different climate scenarios. This study showed that snowmaking is currently a very important adaptive tool to deal with climate variability and change, but also remarks the physical limits of current snowmaking technology. Demiroglu et al. [17] focused on three resorts located in northeast Turkey by making use of a regional climate model to provide projections of changes in natural snow reliability, snowmaking capacity, and wind conditions under IPCC climate scenario RCP 4.5 and between the periods 1917–2000 and 2021–2050. Results indicate an overall decline in the frequencies of naturally snow reliable days and snowmaking capacities. However, they also stated that this particular region seems to be relatively resilient against climate change. Gilaberte-Búrdalo et al. [12] assessed the temporal trends of various climate and snow parameters (e.g., number of days with snow depth higher than 30 cm, and number of rainy days at low elevation areas) for 11 resorts of the Spanish and Andorran Pyrenees in the period 1960–2006. Moreover, they estimated the potential temporal correlation between the studied parameters. The study concludes that the adverse effects on the ski industry of lesser snow availability may have been partially outweighed by the occurrence of fewer days of closure because of high winds, or other adverse meteorological factors. Marty et al. [18] dealt with the impact of future emission scenarios on snow depth in several elevation levels of two catchment areas of the Swiss Alps by modeling temperature and precipitation changes. They showed that, depending on the emission scenario and elevation zone, the winter season will start half a month to one month later and will end one to three months earlier by the end of this century. The most affected elevation zone for climate change is located below 1200 m.

Regarding perceptions, Saarinen and Tervo [19] conducted interviews with nature-based tourism entrepreneurs in Finland. Half of the interviewees did not believe that the phenomenon actually exists and would influence the region's tourism industry in the future, so they found almost no adaptation strategies. However, other adaptation mechanisms were used to cope with the "normal" weather variation and market changes.

More focused on climate change, skiing and adaptation, Elsasser and Bürki [20] analyzed how ski resorts adopted several adaptation strategies in the Swiss Alps from the end of the 1980s. In their view, although adaptation strategies are predominant (e.g., artificial snow production), as an industry that will be severely affected by climate change, tourism will increasingly have to focus on mitigation strategies (e.g., less greenhouse gas emissions by tourism traffic). Regarding studies focused on specific adaptation measures, Scott et al. [21] explored the importance of snowmaking as a technical adaptation. They studied how snowmaking capacity could affect the vulnerability of the ski industry in southern Ontario (Canada) to climate variability and change. The results indicated that ski areas in the region could remain operational in a warmer climate, particularly within existing business planning and investment time horizons (into the 2020s). They pointed out the necessity of including snowmaking and other adaptation strategies in future climate change vulnerability assessments of the ski industry and winter tourism in other regions of the world.

Scott and McBoyle [22] provided an exhaustive inventory of climate adaptation practices currently used by ski industry, including the historical development of certain key adaptations and constraints to wider use. They classified adaptation measures depending on different stakeholders: ski area operators; skiers/riders/tourists; ski industry associations; financial sector; and Government (local, state, and national). The most analyzed (and important) adaptation measures are, however, those for the ski area operators. They organized the range of adaptation practices into two main types: technological (snowmaking systems, slope development and operational practices, and cloud seeding) and business practices (ski conglomerates, revenue diversification, marketing, and indoor ski areas).

Other authors developed classifications of adaptation before the study by Scott and McBoyle [23–25]. Most adaptation studies used variations of the classifications listed by these authors. Becken and Hay [26] developed a risk-based approach to adaptation by the tourism sector, including adaptation measures for the skiing sector. Some other studies focus on a specific adaptation measure, including Hennessy et al. [27], who analyzed the role of snowmaking in adapting to projected changes in snow conditions in Australia.

Alternative methodologies to derive proposals have also been developed: Behringer et al. [28], for instance, used a participatory integrated assessment (PIA) to involve the knowledge, values and experiences of the various social actors in tourism and agriculture (e.g., skiers, tourism managers, and farmers) in the research process. The study tried to show the suitability of this approach to elucidate the interactions between different stakeholders as an alternative way to find adaptation measures. Beyond the analysis of adaptation measures, other studies analyzed radical adaptation measures such as totally transforming the ski activity into another one (e.g., [29]), while others (e.g., Kaján et al. [30]) focused on the costs of adaptation measures on nature-based winter tourism. Mulec and Wise [31] focused on sustainable tourism opportunities respective of local conditions and communities. More focused on real adaptation programs; the National Ski Areas Association (NSAA) in the United States launched a program in 2000 called "Sustainable Slopes" to adapt to and mitigate climate change. During these years, they conducted many activities to adapt to the new conditions (annual reports of their activities and achievements can be found at: http://www.nsaa.org/environment/sustainable-slopes/).

Alpine skiing is a relevant tourism segment in Spain, with 31 winter resorts in operation. Spanish winter resorts, including both alpine and cross-country (or Nordic) ski resorts, had ~5.1 million visitors during 2013/2014 season, representing ~3% of the total demand of European winter resorts. France and Austria were the most visited countries with a total of 55.3 and 50.9 million visitors, respectively [32]. In Spain, the mountain systems of Catalan and Aragon Pyrenees concentrated more than a half of the visitors.

This study aimed at assessing the vulnerability of Spanish alpine ski resorts to climate change by measuring various indicators. These are associated with the availability of natural and artificial snow, climate projections for the provinces where resorts are located, the proximity to relevant nature areas with recreation and tourism potential, and the touristic relevance of each region, here measured in terms of accommodation capacity and levels of visitation. Moreover, the study identified potential adaptation measures for the sector, and evaluated their socio-economic and environmental costs and benefits.

The article is structured as follows: Section 2 characterizes the Spanish alpine ski resorts assessed in the study. Section 3 presents regional climate projections and a vulnerability analysis of the ski resorts to climate change. Section 4 focus on potential adaptation solutions. Section 5 concludes.

2. Characterization of Alpine Ski Tourism in Spain

This study assesses 31 Spanish alpine ski resorts of the following mountain systems: Catalan Pyrenees (10 resorts), Cantabrian Mountains (7), Aragonese Pyrenees (5), Central System (4), Iberian System (4), and Penibaetic System (1). These resorts are located in 11 of 17 Autonomous Communities of Spain, with Catalonia, Aragon, and Castile and León concentrating the majority of the ski sites with 10, 8, and 7 resorts, respectively. The Spanish provinces with the highest representation are Huesca and Lleida, each one with six resorts (Figure 1 and Table A1 in the Appendix A).

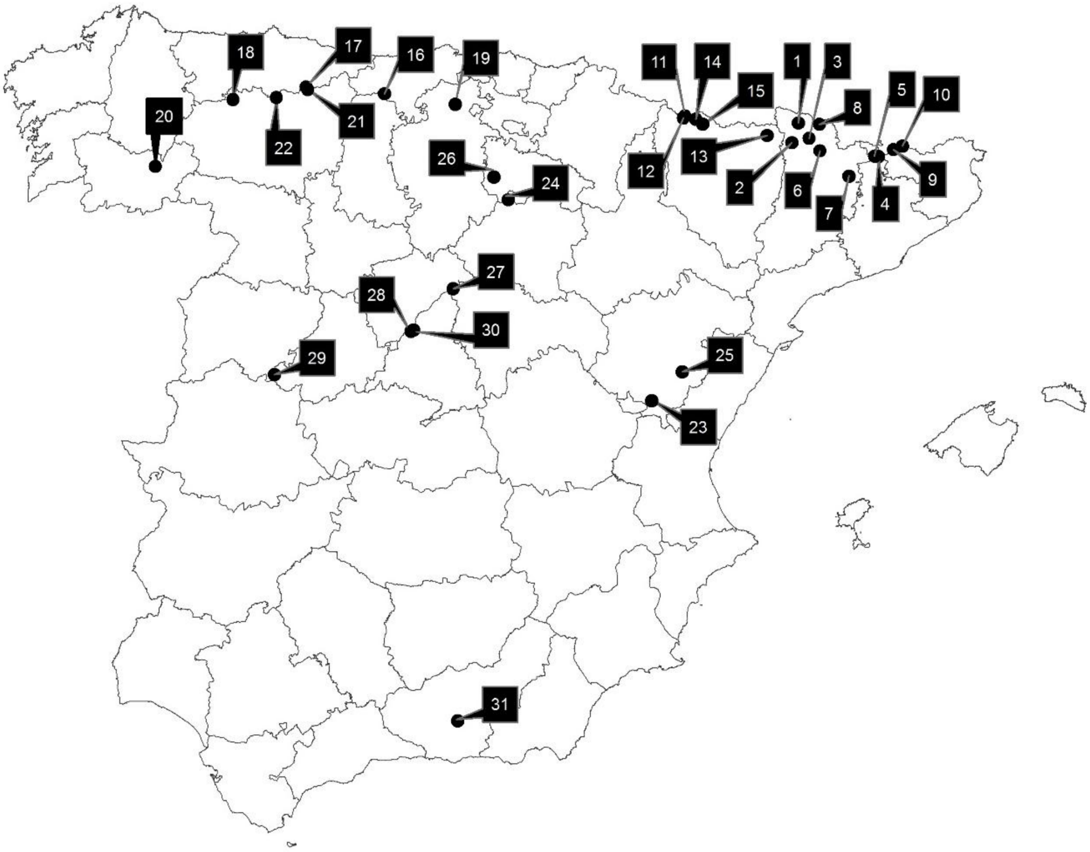

Figure 1. Map of alpine ski resorts of Spain. Legend: *Catalan Pyrenees*: 1. Baqueira Beret; 2. Boí Taüll; 3. Espot Esquí; 4. La Molina; 5. Masella; 6. Port Ainé; 7. Port del Comte; 8. Tavascán; 9. Vall de Núria; 10. Vallter 2000; *Aragonese Pyrenees*: 11. Astún; 12. Candanchú; 13. Cerler; 14. Formigal; 15. Panticosa; *Cantabrian Mountains*: 16. Alto Campoo; 17. Fuentes de Invierno; 18. Leitariegos; 19. Lunada; 20. Manzaneda; 21. San Isidro; 22. Valgrande-Pajares; *Iberian System*: 23. Javalambre; 24. Punto de Nieve Santa Inés; 25. Valdelinares; 26. Valdescaray; *Central System*: 27. La Pinilla; 28. Puerto Navacerrada; 29. Sierra de Béjar; 30. Valdesquí; and *Penibaetic System*: 31. Sierra Nevada.

Table 1 presents the main characteristics of the studied alpine ski resorts. On average, these are located between base and summit altitudes of 1655 and 2257 m. The lowest base altitude corresponds to the resort of Lunada (1300 m), whereas the highest point is located in Sierra Nevada (3300 m). Figure 2 illustrates the altitude range of the studied areas.

Resorts had 1083 ski runs in the 2014/2015 season, representing approximately 1150 km of total length and a global capacity of 470,583 skiers per hour. On average, resorts had about 35 ski runs and 37 km available for skiing. Sierra Nevada presented the highest number of ski runs (120), and Baqueira Beret had the total largest length of ski runs (153 km). In addition, the former resort presented the highest number of sold tickets in 2013/2014 (781,210), whereas the latter observed the highest number of skiers per hour (60,883). Regarding the accommodation sector, 158,252 beds were available in all resorts as well as in their surrounding areas, ranging from a minimum of 490 beds in Javalambre to a maximum of 26,663 beds in Sierra Nevada.

In terms of production of artificial snow, 4791 snow cannons were available at the beginning of 2014/2015. This represented an average of 44.5% potential coverage of artificial snow over the total ski run length, with maximum and minimum values of 100% and 3.9% for Valdelinares and Manzaneda, respectively (Figure 3).

Figure 4 presents the mean values of the maximum snow depth (including both natural and artificial snow) observed in the resorts between the winter seasons of 2009/2010 and 2014/2015. Regarding this indicator, it is expectable to observe a higher predominance of artificial snow over the total amount of snow in the beginning of each season, and a gradual decrease of its relative weight as the most important snow precipitation periods occur in the winter season (information provided by Infonieve.es in August 2015). Values ranged from 42 cm for Manzaneda to 258 cm for Sierra Nevada, with an average of 127 cm for all the resorts.

Table 1. Descriptive analysis of ski resorts of Spain, winter season 2014/2015.

Indicator	Observations (n)	Mean	Min.	Max.	SD	Total
Base elevation (m)	31	1655.1	1300	2100	199.1	-
Summit elevation (m)	31	2257.5	1500	3300	339.5	-
Ski runs (N°)	31	34.9	2	120	29.3	1083
Length of runs (km)	31	37.1	1.8	153	37.9	1150.2
Lifts (Skiers/hour)	30	15,686	1700	60,883	13,639	470,583
Sold tickets (N°; 2013/2014) [1]	25	186,670	4800	781,210	219,339	4,666,753
Snow canons (N°)	26	184.3	1	611	169.4	4791
Artificial snow (km)	25	15.8	0.6	41	12.7	394.8
Artificial snow over total length of runs (%)	25	44.5	3.9	100	26.6	-
Available beds in the resort (N°)	22	1038.5	26	4883	1315	22,847
Available beds in surrounding area (N°)	28	4835.9	410	21,780	5083.8	135,405
Total available beds (N°)	28	5651.9	490	26,663	6074.7	158,252

Source: own elaboration from ATUDEM [33] with the exception of the data corresponding to "Sold tickets", which was based on information available in the website http://www.nevasport.com/noticias/art/43268/Ranking-de-estaciones-de-la-peninsula-por-forfaits-vendidos-2013-2014 (accessed in July 2017), and to "Artificial snow", which counted with ATUDEM [33] and with the information obtained from the website http://www.lugaresdenieve.com/?q=es/estacion/valdesqui (accessed in July 2017) as sources for the Ski resort of Valdesquí. Note: [1] Information referring to the sold tickets corresponds to the season of 2013/2014.

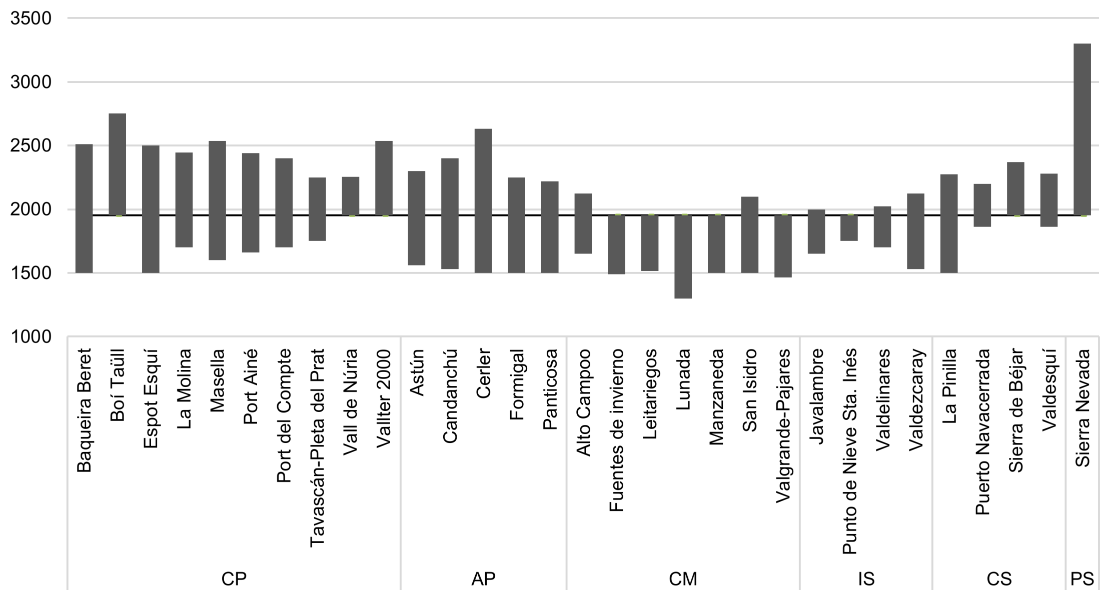

Figure 2. Elevation range of alpine ski resorts of Spain (meters). Source: ATUDEM [33]. The abbreviations stand for: CP (Catalan Pyrenees); AP (Aragonese Pyrenees); CM (Cantabrian Mountains); IS (Iberian System); CS (Central System); and PS (Penibaetic System). The horizontal line corresponds to the average altitude of 1953.3 m.

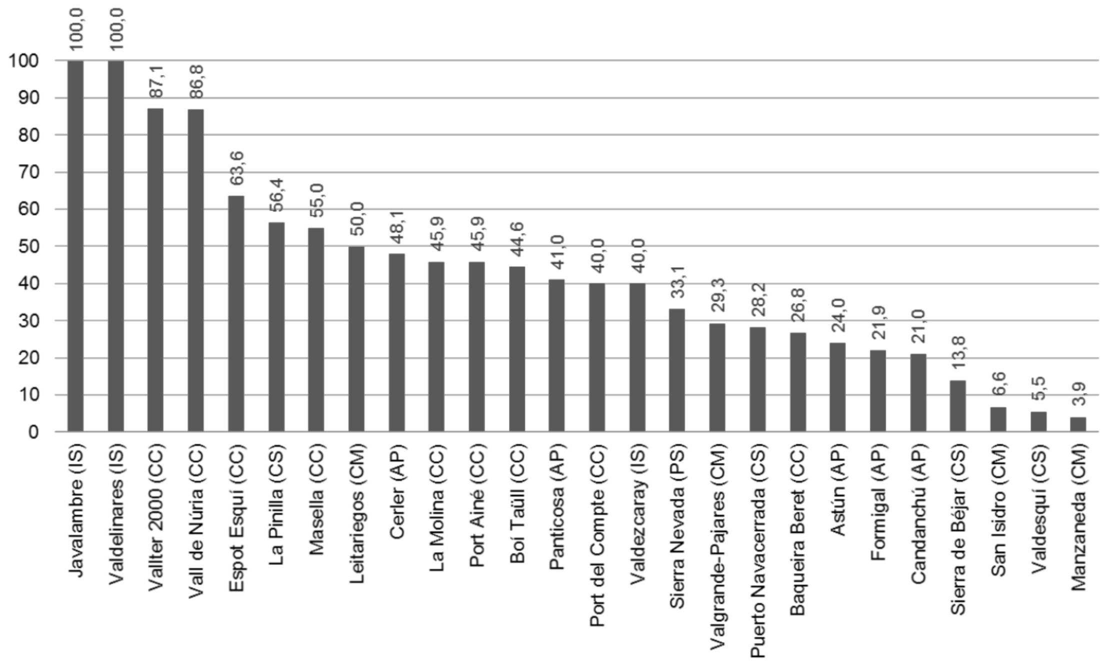

Figure 3. Artificial snow over total length of runs, winter season 2014/2015 (%). Source: ATUDEM [33]; http://www.lugaresdenieve.com/?q=es/estacion/valdesqui (accessed in July 2017). Abbreviations stand for: CP (Catalan Pyrenees); AP (Aragonese Pyrenees); CM (Cantabrian Mountains); IS (Iberian System); CS (Central System); and PS (Penibaetic System). Note: Information for the resorts of Tavascán-Pleta del Prat, Alto Campoo, Fuentes de invieno, Lunada, and Punto de Nieve Sta. Inés is not available.

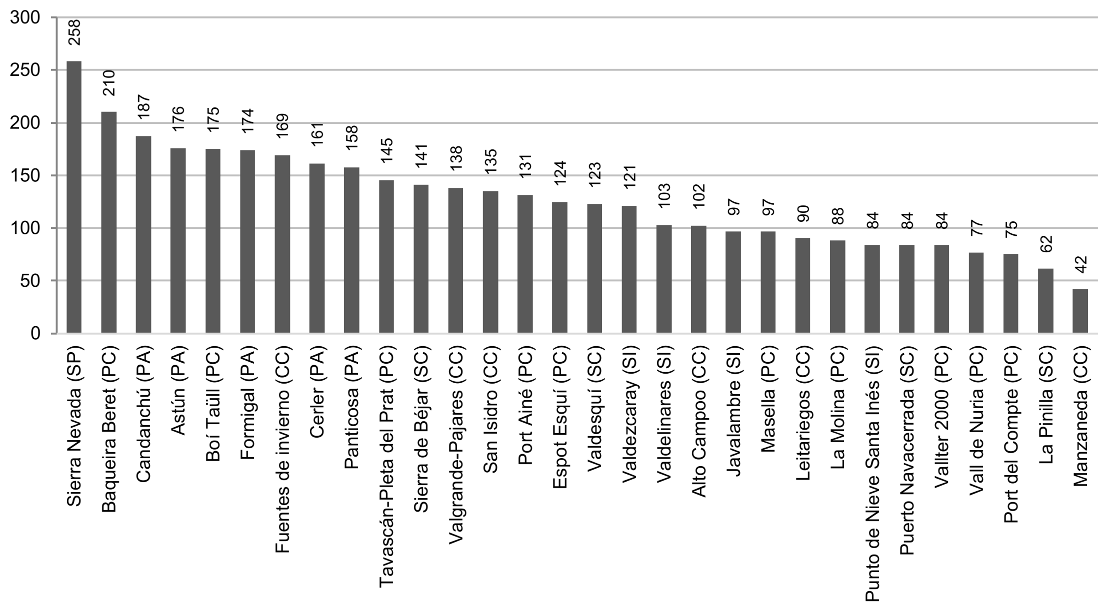

Figure 4. Mean values of the maximum snow depth, winter seasons 2009/2010 to 2014/2015 (cm). Source: Information provided by Infonieve.es in June 2015. Abbreviations stand for: CP (Catalan Pyrenees); AP (Aragonese Pyrenees); CM (Cantabrian Mountains); IS (Iberian System); CS (Central System); and PS (Penibaetic System). Note: Information for the resort of Lunada not available.

3. Climate Change Impact on Winter Tourism in Spain

The first part of this section presents climate projections for the Spanish provinces where the ski resorts are located, followed by an analysis of natural snow-reliability scenarios, and a vulnerability assessment of all ski resorts to climate change.

3.1. Regional Climate Projections

The Spanish Meteorological Agency [34] provides climate projections for the provinces where resorts are located. This section presents the potential changes on mean values of minimum winter temperatures, number of days per annum with minimum temperature lower than 0 °C, and winter precipitation levels. These projections are based on the IPCC climate scenarios RCP 4.5 (538 ppm in 2100), 6.0 (670 ppm in 2100), and 8.5 (936 ppm in 2100), and are presented for 2040, 2070, and 2100, in comparison with the reference period of 1961–2000 [35] (Table A2 in the Appendix A).

The analysis of the previous scenarios shows an expected increase of the minimum winter temperatures in all provinces. Girona presents the highest increase, notably of 4 °C by 2100 for the more extreme scenario (RCP 8.5), followed by Granada and Lleida with a projected increase of 3.7 °C for the same scenario. The lowest increase corresponds to Granada, Madrid, Segovia, and Soria with 1 °C for the scenario RCP 4.5 and the period corresponding to 2040.

All provinces show a likely decrease in the annual number of days below 0 °C. The most pronounced change was associated with Soria with a potential reduction of 70.9 days by 2100 (RCP 8.5), whereas the minimum projected change refers to Ourense for the period referring to 2040 and scenario RCP 4.5 (reduction of 5.2 days).

Finally, a potential reduction in winter precipitation levels throughout the current century is perceivable, except for some results that show a possible increase in precipitation, notably in scenarios RCP 6.0 and RCP 4.5, and provinces of Ourense, Salamanca, and León.

3.2. Natural Snow-Reliability Altitude Limits

An important factor influencing the presence of natural snow is the altitude range of ski resorts. Abegg et al. [15] estimated the natural snow-reliability altitude limits for the alpine ski regions of Austria, Switzerland, Germany, France, and Italy, considering the commonly used 100-day rule [11,20,36]. This establishes that a ski resort needs to have a snow pack depth equal or higher than 30 cm over a total period of 100 days per season to develop winter recreation activities and to be potentially profitable. Accordingly, as indicated in Table 2, the level of altitude that is necessary to guarantee the practice of alpine ski varies according to the type of climate of the different regions. It is assumed that a ski resort is considered profitable if the higher half of its altitude range stays above the altitude limit defined for each type of climate. Results show that the altitude limits rise by 150 m per 1 °C increase in temperature. Steiger and Abegg [16] updated the latter results through the development of a sensitivity assessment of Austrian ski areas to climate change, estimating a shift in the altitude limit of 250 m per 1 °C increase.

Table 2. Natural snow-reliability altitudes according to climate type and climatic scenarios.

Type of Climate	Natural Snow-Reliability Altitude Limit (in Meters)				
	Present	+1 °C	+2 °C	+3 °C	+4 °C
Alpine (Continental)	1050	1200–1300	1350–1550	1500–1800	1650–2050
Alpine (Atlantic-maritime)	1200	1350–1450	1500–1700	1650–1950	1800–2200
Alpine (Mediterranean)	1500	1650–1750	1800–2000	1950–2250	2100–2500

Source: The lower and upper bounds of the natural snow-reliability altitude limits correspond to Abegg et al. (2007) and Steiger and Mayer (2008), respectively.

Figure 5 applies the previous natural snow-reliability limits for the studied resorts, presenting the results for the current period and for three climate scenarios considered in [15,16], respectively.

This analysis followed the assumption that all Spanish mountain areas addressed in this study fit under the category of alpine climate with Mediterranean influence. The higher halves of the altitude ranges are presented for all resorts, meaning that these are only to be considered viable when the altitude range stays above the reliability limits for each scenario. Results obtained with the first simulation indicate that Sierra Nevada, Boí Taull, Vallter 2000, and Sierra de Béjar are considered viable for all scenarios, while Lunada is considered non-viable in all cases. The mountain systems of Catalan Pyrenees and Penibaetic System are associated with a higher level of viability, whereas Cantabrian Mountains reveal the lowest level of viability. When performed the second simulation, only Sierra Nevada is pointed as viable for all scenarios, and more resorts fall into the category of non-viable for the scenario of 1 °C increase, namely Fuentes de Invierno, Leitariegos, Manzaneda, and Valgrande-Pajares. The different results obtained from the two simulations are explained by the assumptions taken in [15]. These included accepting the fulfilment of the 100-day rule without integrating small-scale differences in snow conditions (e.g., at the province level), and considering that the snow-reliability altitude limit will increase 150 m per additional 1 °C [16].

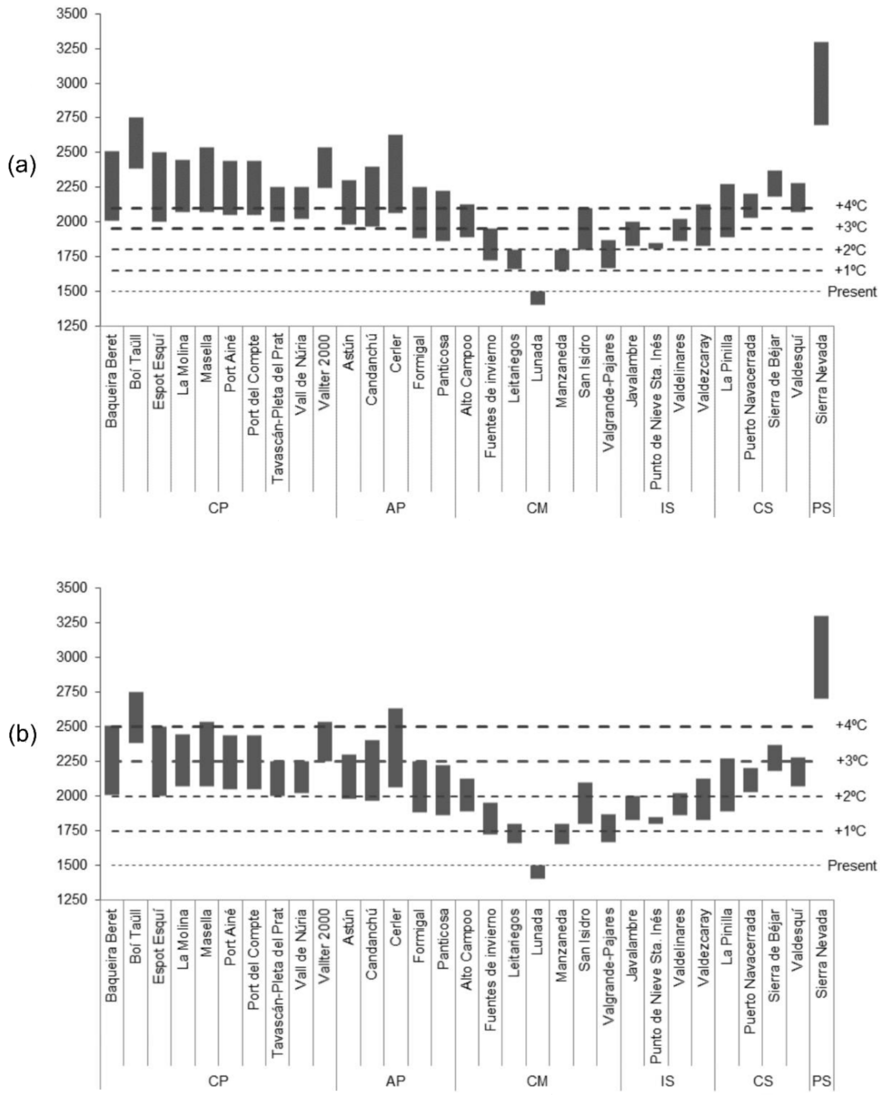

Figure 5. Natural snow-reliability altitudes of alpine ski resorts in Spain according to various climatic scenarios (meters). Sources: Own elaboration based on: Abegg et al. [15] (**a**); and Steiger and Abegg [16] (**b**). The abbreviations stand for: CP (Catalan Pyrenees); AP (Aragonese Pyrenees); CM (Cantabrian Mountains); IS (Iberian System); CS (Central System); and PS (Penibaetic System).

The results obtained with the two previous simulations need to be interpreted with caution due to the differences between the sites figuring in the original studies and the Spanish ski areas. Moreover, the analysis did not consider various potential differences amongst the studied resorts (e.g., climate characteristics and geographical orientation). Nevertheless, the previous projections provide an indication of vulnerability of the studied resorts. Results are consistent with other studies applied for the Autonomous Community of Catalonia (Spain). As examples, Llebot [37,38] considered that only those areas located above 2000 m will be viable for skiing under increases of 1.8 °C–2 °C.

3.3. Vulnerability Analysis of Ski Resorts to Climate Change

This subsection presents a classification of the studied areas in terms of their level of vulnerability to climate change, using the categories of low, medium, and high vulnerability (Table 3).

The analysis included three indicators aiming at capturing the snow conditions of ski resorts: the maximum snow depth, which characterizes their current snow condition (including both natural and artificial snow) based on data associated with the winter seasons comprised between 2009/2010 and 2014/2015; and two indicators corresponding to the future natural snow-reliability, aiming at capturing the potential vulnerability associated with their altitude ranges. The first indicator corresponds to the information presented in Figure 3, equally divided into three levels of snow depth. The indicators referring to natural snow-reliability are based on [15,18], notably on the analysis presented in Tables 2 and 3 and Figure 5. The viability to a maximum of 2 °C increase corresponds to the medium level, which represents a realistic climate scenario where the natural snow-reliability altitude limit is between 1800 m and 2000 m. The definitions of high and low vulnerability levels are based on the previous level and adopt the threshold of a minimum of 3 °C, and maximum of 1 °C increase, respectively.

In addition, the touristic relevance of the resorts was assessed through the following indicators. First, a group of three indicators was used to measure the regional potential for the development of non-snow based recreation activities (e.g., birdwatching and trekking). For that purpose, various proximity ranges to natural parks, special protection areas (SPA) for birds, and sites of community importance (SCI) were defined. The selected ranges were different in the case of natural parks in comparison with SPA and SCI sites, as the two latter sites are more frequently found in the national territory (Figures A1–A3 in the Appendix A). Second, an indicator of tourism offer in terms of the total number of beds available in the surrounding area of the resorts according to information obtained from [33] was used (Table A3 in the Appendix A). Third, the number of visitors entering the provinces where the resorts are located was selected to assess the general touristic demand (Table A3).

Table 3. Criteria for the definition of the vulnerability levels.

Indicators	Low	Medium	High
Maximum snow depth (cm)	173–258 cm	87–172 cm	0–86 cm
Natural snow-reliability (m) based on [15,16] [1]	Viable to a minimum of 3 °C increase	Viable to a maximum of 2 °C increase	Viable to a maximum of 1 °C increase
Proximity to natural parks (km)	<10 km	10–20 km	>20 km
Proximity to special protection areas for birds (SPA) (km)	<5 km	5–10 km	>10 km
Proximity to sites of community importance (SCI) (km)	<5 km	5–10 km	>10 km
Available beds in the surrounding area (n°)	>6000	3000–6000	<3000
Travelers entering the Province (n°)	>1 million	0.5–1 million	<0.5 million

Note: [1] Corresponds to two indicators that share the same criteria for the definition of the vulnerability levels.

Table 4 presents the results of the vulnerability analysis. The higher levels of vulnerability are associated with the resorts located in the Cantabrian Mountains and the Iberian System. On the contrary, the Penibaetic System, where the resort of Sierra Nevada is located, presents very low or low levels of vulnerability for all categories. Ski resorts present higher levels of vulnerability for the indicators referring to the natural snow-reliability (based on [16]) and the proximity to natural parks, and lower levels regarding the proximity to SPA and SCI sites.

Table 4. Vulnerability analysis of alpine ski resorts to climate change.

Mountain System	Ski Resort	Maximum Snow Depth [1]	Line of Natural Snow-Reliability [2]	Line of Natural Snow-Reliability [3]	Proximity to Natural Parks [4]	Proximity to SPA Sites [5]	Proximity to SCI Sites [5]	Available Beds in the Surrounding Area [6]	Travelers Entering the Province [7]
CP	Baqueira Beret								
	Boí Taüll								
	Espot Esquí								
	La Molina								
	Masella								
	Port Ainé								
	Port del Comte							NA	
	Tavascán-Pleta del Prat								
	Vall de Núria								
	Vallter 2000								
AP	Astún								
	Candanchú								
	Cerler								
	Formigal								
	Panticosa								
CM	Alto Campoo								
	Fuentes de invierno								
	Leitariegos								
	Lunada	NA						NA	
	Manzaneda								
	San Isidro								
	Valgrande-Pajares								
IS	Javalambre								
	Punto de Nieve Santa Inés							NA	
	Valdelinares								
	Valdezcaray								
CS	La Pinilla								
	Puerto Navacerrada								
	Sierra de Béjar								
	Valdesquí								
PS	Sierra Nevada								

Source: Own elaboration based on: [1] Infonieve.es; [2] [15]; [3] Steiger and Abegg [16]; [4] http://www.redeuroparc.org (accessed in March 2018); [5] http://www.magrama.gob.es/es/biodiversidad/servicios/banco-datos-naturaleza/informacion-disponible/rednatura_2000_zepa_descargas.aspx (accessed in March 2018); [6] ATUDEM [33]; [7] INE [39]. Legend: black = high vulnerability; dark grey = medium vulnerability; light grey = low vulnerability. Notes: The abbreviations stand for: CP (Catalan Pyrenees), AP (Aragonese Pyrenees), CM (Cantabrian Mountains), IS (Iberian System), CS (Central System), and PS (Penibaetic System); NA (not available).

4. Adaptation to Climate Change by the Winter Tourism Sector

The first part of this section describes potential adaptation measures for the winter tourism sector, counting with a literature analysis and open-ended interviews to eight representatives of some Spanish ski resorts and climate change experts between April and October of 2015 as main sources of information. The interviewed organizations included: the Institute for Prospective Technological Studies-Joint Research Centre, IPTS-JRC (Seville); BC3 Basque Centre for Climate Change; Sustainability Measurement and Modeling (SUMMLAB—Polytechnic University of Catalonia); Aramon Group, responsible for the management of the resorts of Cerler, Formigal, Panticosa, Javalambre and Valdelinares; Catalan Office for Climate Change; resort of Valdesquí; Cetursa, the company responsible for the management of the resort of Sierra Nevada; and the Department of Tourism and Mountains of the Ferrocarrills de la Generalitat de Catalunya (FGC), which manages the Catalan resorts of Espot Esquí, La Molina, Port Ainé, Vall de Núria, and Vallter 2000. The interviews made to the representatives of the previous organizations were mainly focused on their perceptions on the impact of climate change on the winter tourism sector, as well as on potential adaptation measures.

The second part presents an evaluation of the socio-economic and environmental costs and benefits that can be associated with the selected measures.

4.1. Identification and Characterization of Adaptation Measures

4.1.1. Artificial Snow Production

Spanish resorts have made significant investments in snowmaking systems in the past decades. La Molina, in the Catalan Pyrenees, was the first resort to implement snow cannons in Spain in 1985 [40], and since that period, the development of artificial snow systems increased substantially.

Snowmaking may represent a high cost for the resorts because of the need of implementing various costly operations, inter alia, the development of water supply systems, and the purchase and installation of snow cannons [41]. Estimates obtained for La Molina show an average artificial snow production and cost from 2006/2007 to 2014/2015 seasons of 625,305 m^3 and 553,773 € (0.9 € per m^3), respectively Cost categories include energy consumption, maintenance, salaries, the operation of snow grooming machines, and water consumption (personal information provided by a representative of the ski resort La Molina on June 2015).

Various socio-economic and environmental costs may occur as a result of the development of snow production systems: a negative impact on local and regional water resources, associated with an increase in water consumption, and the potential deviation of water resources from local basins. This impact could be more pronounced if used water is captured from natural sources on shortage periods, as well as if potable water is used in snow cannons; an increase in the consumption of fossil fuel energy sources, thus rising CO_2 emissions; changes in natural soil and land uses; impact on local fauna and flora; and the slower recuperation of grasslands and shrublands due to the slow melting of artificial snow [42].

4.1.2. Technological Innovation

This measure can be associated with improvements in snowmaking technology. This may involve the possibility to produce artificial snow under higher atmospheric temperatures with less water and energy consumption. There was a significant progress in snowmaking technology in the past decades. Currently, cannons can produce snow at temperatures equal to or higher than −1.5 °C in comparison with temperatures of −4 °C in the 1990s. Another type of innovation already in use in some resorts is the application of automated snowmaking systems, which allows taking advantage of the most favorable weather conditions to produce snow (personal information provided by a representative of Sierra Nevada resort on April 2015).

4.1.3. Nocturnal Skiing

Spanish resorts currently implementing nocturnal skiing include Masella, Vall de Núria, Valgrande-Pajares, and Sierra Nevada (personal information provided by representatives of the resorts on October 2015). Estimates for the latter resort indicate an approximate cost of 156€ per hour and km of ski runs opened during nocturnal skiing periods. Cost categories include energy consumption, the operation of snow grooming machines, personal transport, and salaries In: http://premsa.gencat.cat/pres_fsvp/docs/2010/11/02/16/53/3d19d69e-c362-4c9f-aa15-a83557582e21.pdf, accessed in July 2017).

This measure could help compensating potential revenue losses associated with the reduction of snow days due to climate change. Nevertheless, the implementation of nocturnal activities will have to consider potential adverse weather conditions during the nocturnal period, as well as the risk of higher occurrence of accidents (personal information provided by a representative of the ski resort La Molina in June 2015).

4.1.4. Protection and Conservation of the Snowpack

Several techniques can be used for the maintenance of snow areas. Some examples include: the protection of the snowpack from crosswinds; water drainage operations as a way to delay snow melting (from: www.nevasport.com/noticias/art/10115/Valgrande-Pajares-Mas-nieve-y-nuevo-telesilla-de-cuatro-plazas, accessed in March 2018); modification of the ski runs slopes, which may reduce the effect of solar radiation on snow melting [43]; protection from avalanches; protection or storage of snow during the non-ski seasons (an illustrative example was the storage of 450,000 cubic meters of snow in Russia with the purpose of preparing the Olympic Winter Games of Sochi 2014 from: www.nevasport.com/noticias/art/38951/Rusia-comienza-a-almacenar-450000-m3-de-nieve, accessed in March 2018); the reduction of the number of skiers per hour, allowing a better use of snow areas and reducing the pressure over the snow areas; and monitoring and improving snow resistance (from: www.nevasport.com/noticias/art/21074/Espot-Esqui-contrata-un-servicio-para-rentabilizar-la-innivacion-artificial, accessed in March 2018). High variability of snowpack from year to year will also increase vulnerability from a business perspective, as tourist numbers decrease greatly in low snow years.

4.1.5. Diversification of Snow-Based Activities

Despite the popularity of alpine ski amongst the visitors of the study areas, there are currently other snow-based activities that are available in some resorts. These include cross-country (or Nordic) skiing, snowboarding, ice karting, sledding, thematic parks, or ice rinks [33].

The resorts tend to promote different activities as a way to attract a more diverse group of visitors, with good results. As an example, Sierra Nevada's snow park for snowboarding and freestyling has already exceed the number of entrances in the main ski slope in the past seasons (personal information provided by a representative of Sierra Nevada resort on April 2015) (In: http://premsa.gencat.cat/pres_fsvp/docs/2010/11/02/16/53/3d19d69e-c362-4c9f-aa15-a83557582e21.pdf, accessed in March 2018).

4.1.6. Expansion of Skiable Area

Some resorts might have the possibility to expand their ski runs length in selective areas where there is a high availability of natural snow or it is feasible to produce snow [37]. Nevertheless, it is important to assess the potential impact associated with this measure, including: the land-use conflicts [44]; the impact of construction works on natural areas; the impact on the landscape quality; and the increase in the consumption of water and energy resources. Other limitations associated with this type of measure include the need of substantial investments, the availability of free areas in higher altitudes, as well as other orographic constraints [38].

4.1.7. Public and Private Economic Assistance and Management Solutions

Resorts may experience significant revenue losses as a result of the lower availability of natural snow and the reduction of visitors with climate change. Some resorts may have to rely on financial assistance as a way to maintain their activity. Examples of assistance measures comprise subsidies, tax incentives or insurances [37]. There are already some cases of Spanish resorts that were subsidized in order to renovate their snowmaking systems (In: http://premsa.gencat.cat/pres_fsvp/docs/2010/11/02/16/53/3d19d69e-c362-4c9f-aa15-a83557582e21.pdf, accessed in March 2018), or that have requested public assistance to compensate revenue losses associated with less visitors in periods of natural snow shortage (from: www.nevasport.com/noticias/art/21393/El-sector-de-la-nieve-solicita-ayudas-para-salvar-la-temporada, accessed in March 2018).

Because of the difficulty to cover operational costs, various ski resorts were already intervened by the State in the past and are currently being managed by public entities (e.g., Port Ainé or Espot Esquí). It can be expected that more resorts will follow this solution in the future, which raises a discussion on the use of public funds for the management of ski resorts.

Another management option that can be adopted refers to the grouping of various ski resorts, which allows to share resources, and reduce future economic risks, while benefiting from the potentialities of each area. An example is the Aramon Group, a holding company responsible for the management of various ski resorts in Spain.

4.1.8. Transformation of Ski Resorts into Multi-Recreational Mountain Resorts

Several resorts are currently offering alternative recreational activities to snow-based products. This allows maintaining these areas opened during the whole year, capturing the attention of other type of customers, and reducing the dependency of snow activities. Some examples of activities include thematic parks, bike tours, trekking, mountain climbing, cultural events, and spa and hotel services. According to [33], 70% of Spanish ski resorts are open during the summer season. Vall de Núria is an example of one resort strong relying on non-snow recreational activities. Estimates from the past years show that there is an approximate ratio of one skier per seven visitors in this resort (personal information provided by a representative of this ski resort on June 2015).

4.1.9. Redefinition of the Local Economic Model

The difficulty to guarantee a regular availability of snow (both natural and artificial), and a potential lack of competitiveness of some resorts regarding the supply of non-snow recreational activities, may force some areas to adapt under a different local economic model. This may lead to the promotion of other economic activities, inter alia, agriculture, pasturage, forestry, restoration of traditional practices, and eco-tourism. This strategy may require significant investments.

In addition, some resorts may be located in mountain areas facing demographic challenges associated with migration, low birth rates, and population ageing. These factors need to be considered in the redefinition of the local economic model together with the potential impact of climate change.

4.1.10. Marketing Strategies

Resorts may have to develop new marketing strategies for the purpose of attracting customers in the context of climate change. This will require the analysis of the visitor's behavior regarding potential changes in the snow-based recreation products. The promotion of a more diverse set of activities offered by the resorts has to integrate the competitiveness context associated with both the ski resorts and the surrounding area. Moreover, it is important to consider that higher operational costs associated with the need to adopt adaptation measures may lead to an increase in recreation activities prices, which may rebound negatively on the demand. This situation may impel resorts to develop new products and promotions to attract customers. Nevertheless, it is also relevant to consider that the existing competiveness in this sector may force the resorts to internalize costs without passing them to consumers via prices of product and services.

4.2. Evaluation of Adaptation Costs and Benefits

Table 5 presents a qualitative evaluation of the socio-economic and environmental costs and benefits associated with the types of adaptation identified in the previous section. Moreover, it includes a classification of the potential magnitude of economic costs resulting from the application of each type of adaptation. This analysis considers the magnitude levels of low, medium, and high cost and it is based on the information presented in the previous section, which was based on a literature analysis and interviews with representatives of some Spanish ski resorts and climate change experts. The results show that potentially costlier measures include artificial snow production, diversification of snow-based activities, expansion of skiable area, transformation of ski resorts into multi-recreational mountain resorts, and the redefinition of the local economic model. On the contrary, less expensive measures include nocturnal skiing, and marketing strategies.

Table 5. Socio-economic and environmental costs and benefits associated with adaptation measures.

Adaptation Measures	Benefits	Costs	Magnitude of Economic Costs
Artificial snow production	- Recreational and economic benefits - Use of artificial water reservoirs to fight forest fires and for other recreational purposes	- Impact on local and regional water balance - Increase in CO_2 emissions - Impact on natural soil - Impact on local fauna and flora - Landscape degradation - Opportunity costs - Risk of no return on investment - Increase in construction waste associated with the development of snow production systems	++/+++ (depending on the need to fully develop snow making systems, and on the changes in the conditions for snow production in the resorts)
Technological innovation	- CO_2 emissions savings - Lower pressure on water resources - Costs savings	- Opportunity costs - Technological obsolescence with potential environmental costs (e.g., increase of waste) - Increase in material and energy consumption associated with technology manufacturing - Insufficient return on investment as a result of the difficulty to produce snow in future climate conditions	++
Nocturnal skiing	- Better distribution of the carrying capacity - Recreational and economic benefits	- Increase in energy consumption - Noise and visual pollution with potential impact on nocturnal species - Higher risk of accidents	+/++ (depending on the capacity of the resorts to attract customers for this activity)
Protection and conservation of the snowpack	- Guarantee income - Supporting a sustainable carrying capacity - Increase security of ski runs and skiers	- Impact on local fauna and flora - Landscape degradation	++
Diversification of snow-based activities	- Reduction of the environmental pressure caused by other activities - Reduction of the economic dependency from other activities	- Higher consumption of material, water and energy resources - Impact on local fauna and flora - Landscape degradation - Land-use conflicts	++/+++ (depending on factors such as the response of the demand, and the type of activities implemented)
Expansion of skiable area	- Recreational and economic benefits	- Increase consumption of water and energy resources - Land-use conflicts - Increase in construction waste as a result of construction works - Increase in the emissions of dust, noise and contaminants as an outcome of oil combustion related with machinery activity - Impact over natural soils - Impact on local fauna and flora - Landscape degradation	++/+++ (depending on the construction cost per square meter)

Table 5. *Cont.*

Adaptation Measures	Benefits	Costs	Magnitude of Economic Costs
Public and private-economic assistance and management solutions	- Economic benefits and promotion of recreational activities	- Opportunity costs associated with the diversion of economic resources from other uses - Positive tax discrimination	+++
Transformation of ski resorts into multi-recreational mountain resorts	- Recreational and economic benefits - Support the sustainability of the local economy - Adjustment of recreational activities to the natural environment with a lower environmental impact - Adjustment of the recreational opportunities to the climate scenarios	- Higher consumption of material, water and energy resources as a result of potential construction works - Increase of waste as a result of construction works to convert resorts	++/+++ (depending on factors such as the response of the demand, and the type of activities implemented)
Redefinition of the local economic model	- Preference for the promotion of the sectors that are more adapted to climate change and to the regional characteristics - Contribution to economic and local demographic sustainability	- Loss and degradation of physical capital - Soil degradation - Higher consumption of material, water and energy resources in the short-term as a result of potential construction works - Increase of waste as a result of construction works to convert resorts - Potentially high investment required	++/+++ (depending on the current state, and the potentialities of the territory for the development of alternative sectors)
Marketing strategies	- Support recreational and economic benefits	- Higher consumption of material and energy resources as a result of marketing strategies	+/++ (depending on the response of the demand)

Legend: Levels of magnitude for the potential economic costs have the following meaning: +++, high; ++ medium; and +, low. Source: Literature analysis and interviews with representatives of some Spanish ski resorts.

5. Conclusions

Winter tourism is a relevant sector in Spain. The 2013/2014 season counted approximately five million visitors, distributed through more than thirty resorts located in six mountain systems of the mainland territory. This sector is particularly vulnerable to climate change, with a significant impact being associated with the degradation of the snow conditions for the practice of recreational activities.

This study assessed the vulnerability to climate change of 31 alpine ski resorts in Spain. Moreover, it evaluated the potential socio-economic and ecological effects of several adaptation measures. The studied resorts present some heterogeneity in terms of features such as altitude range, length of ski runs, accommodation capacity, maximum snow depth, and number of visitors. Artificial snow is a common resource used by the Spanish resorts, with more than 4700 cannons operating in 2014/2015.

Climate projections for the provinces where the resorts are located showed a likely increase in winter minimum temperatures and a decrease in the annual number of days with minimum temperature below 0 °C. Moreover, projections indicated a likely reduction of the winter precipitation levels, notwithstanding a potential increase in precipitation for some scenarios and provinces. Despite the uncertainty inherent in climate projections and the variability in the results provided by different models, these changes may contribute to the lower availability of natural snow and worsen the conditions for the production of artificial snow. Both aspects have negative implications for the duration of the ski seasons and the availability of suitable areas for ski practicing.

The vulnerability analysis of the ski resorts to climate change shown in this study addressed the following indicators: maximum snow depth (including both natural and artificial snow); natural snow-reliability; proximity to natural parks; proximity to special protection areas for birds (SPA); proximity to sites of community importance (SCI); available beds in the surrounding area; and number of travelers entering the provinces of the ski resorts. Results showed potential signs of a higher vulnerability for the majority of the resorts of the Cantabrian Mountains (e.g., Leitariegos, Lunada, Manzaneda), and the Iberian System (e.g., Javalambre, Valdelinares). Resorts presenting lower levels of vulnerability included Sierra Nevada from the Penibaetic mountain system, followed by Baqueira Beret and Boí Taüll, located in the Catalan Pyrenees, and Valdesquí in the Central System. One of the limitations of this analysis relies on the application of the results of a natural snow-reliability assessment of other EU mountain areas with Alpine Mediterranean climate on to the Spanish ski resorts. Moreover, the analysis did not consider potential differences among these resorts in terms of aspects such as climate conditions and geographical orientation of the ski slopes. Accordingly, the study has space for improvement, notably by working with climate models fitted to a spatial scale closer to those of the resorts, leading to a better assessment of both natural and artificial snowmaking potential.

One of the main contributions of this study was obtaining empirical evidence by assessing the Spanish case. Following a literature analysis focused on the adaptation to climate change by the winter tourism sector of various world regions, the study characterized various adaptation measures for the context of Spain with the support of real data and opinions from key stakeholders. Ten adaptation measures were assessed: artificial snow production, technological innovation, implementation of nocturnal skiing, protection and conservation of the snowpack, diversification of snow-based activities, expansion of skiable area, public and private economic assistance and management solutions, transformation of the ski resorts into multi-recreational mountain resorts, redefinition of the local economic model, and marketing strategies. Similar to the inventory provided by Scott and McBoyle [22], these measures are more intended for ski area operators, despite also including other stakeholders (e.g., local government, financial sector). The knowledge about the potential level of vulnerability of ski resorts to climate change may contribute to the definition of the most adequate adaptation measures [11]. Resorts with higher levels of vulnerability would need to better assess the potential use and feasibility of snowmaking technology as the main adaptation option in the medium and long term. This type of strategy is very well documented in the consulted literature (e.g., [15–17,20,21,42]), which also remarks its potential socio-economic and environmental impact and physical limitations. Taking the example of the resort of Leitariegos, where the artificial snow coverage over total length of runs reaches only 3.9%, the decision on whether invest in snowmaking equipment will benefit from the analysis of climate change impact. Resorts classified with this level may have to consider adopting structural adaptation strategies such as the transformation of ski resorts into multi-recreational mountain resorts, or the redefinition of the local economic model.

On the contrary, resorts with lower levels of vulnerability may rely on a combination of technical (e.g., production of artificial snow, and conservation of the snowpack) and structural solutions (e.g., diversification of snow-based activities).

The design and implementation of adaptation strategies must aim to minimize their potential socio-economic and environmental costs. Measures adopted with the purpose of exclusively maintaining the operation of resorts as winter tourism destinations, inter alia, the production of artificial snow, expansion of skiable areas, or the public economic assistance to resorts, raise various environmental and social aspects of concern. Some examples include the degradation of water resources, and local fauna and flora, as well as the misuse of public funds. Moreover, this study considered that resorts located in areas experiencing—out migration and population ageing have to integrate these factors in the definition of structural adaptation strategies aimed at redefining the local economic model. This issue has to be considered not only at the level of regional and national policies but also at the EU-level (e.g., under the scope of Community Strategic Guidelines for Rural Development and Cohesion Policy) [45].

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Appendix A

Table A1. List of mountain systems, ski resorts, Autonomous Communities, and provinces.

Mountain System	Ski Resort	Autonomous Community	Province
Catalan Pyrenees	Baqueira Beret	Catalonia	Lleida
	Boí Taüll	Catalonia	Lleida
	Espot Esquí	Catalonia	Lleida
	La Molina	Catalonia	Girona
	Masella	Catalonia	Girona
	Port Ainé	Catalonia	Lleida
	Port del Compte	Catalonia	Lleida
	Tavascán	Catalonia	Lleida
	Vall de Núria	Catalonia	Girona
	Vallter 2000	Catalonia	Girona
Aragonese Pyrenees	Astún	Aragon	Huesca
	Candanchú	Aragon	Huesca
	Cerler	Aragon	Huesca
	Formigal	Aragon	Huesca
	Panticosa	Aragon	Huesca
	Llanos del Hospital	Aragon	Huesca
Cantabrian Mountains	Alto Campoo	Cantabria	Cantabria
	Fuentes de invierno	Asturias	Asturias
	Leitariegos	Castile and Leon	León
	Lunada	Castile and Leon	Burgos
	Manzaneda	Galicia	Ourense
	San Isidro	Castile and Leon	León
	Valgrande-Pajares	Asturias	Asturias
Iberian System	Javalambre	Aragon	Teruel
	Punto de Nieve Santa Inés	Castile and Leon	Soria
	Valdelinares	Aragon	Teruel
	Valdezcaray	Rioja	Rioja
Central System	La Pinilla	Castile and Leon	Segovia
	Puerto Navacerrada	Community of Madrid	Madrid
	Sierra de Béjar	Castile and Leon	Salamanca
	Valdesquí	Community of Madrid	Madrid
Penibaetic system	Sierra Nevada	Andalucía	Granada

Table A2. Projected climate changes for the provinces of the ski resorts.

Province	RCP 4.5			RCP 6.0			RCP 8.5		
	2040	2070	2100	2040	2070	2100	2040	2070	2100
Asturias									
Minimum winter temperatures (°C)	+1.1 (0.4)	+1.3 (0.6)	+1.7 (0.8)	+1.1 (0.3)	+1.3 (0.4)	+2.2 (0.4)	+1.2 (0.6)	+2.4 (0.6)	+3.3 (1.0)
Annual days below 0 °C (N°)	−7.6 (4.0)	−8.5 (5.0)	−9.7 (5.7)	−6.3 (1.8)	−8.8 (3.3)	−10.9 (4.5)	−8.8 (3.7)	−12.0 (5.4)	−14.1 (6.5)
Winter precipitation levels (%)	−2.5 (19.0)	−9.5 (21.9)	−4.6 (25.9)	+11.9 (32.5)	−7.4 (22.6)	−8.6 (27.2)	−7.6 (27.0)	−13.8 (13.8)	−8.0 (36.4)
Burgos									
Minimum winter temperatures (°C)	+1.2 (0.6)	+1.3 (0.7)	+1.8 (0.8)	+1.3 (0.4)	+1.4 (0.7)	+2.4 (0.3)	+1.3 (0.6)	+2.4 (0.6)	+3.4 (1.1)
Annual days below 0 °C (N°)	−23.7 (6.3)	−26.9 (11.8)	−29.0 (14.5)	−20.3 (6.0)	−29.2 (7.0)	−33.8 (5.5)	−26.7 (11.8)	−41.2 (9.5)	−49.6 (15.3)
Winter precipitation levels (%)	+0.5 (24.4)	−13.5 (23.0)	−2.8 (26.6)	−13.0 (23.3)	−2.6 (32.9)	−3.5 (14.9)	−5.6 (27.2)	−17.5 (19.6)	−4.5 (40.9)
Cantabria									
Minimum winter temperatures (°C)	+1.1 (0.6)	+1.3 (0.6)	+1.7 (0.7)	+1.2 (0.4)	+1.4 (0.4)	+2.3 (0.4)	+1.3 (0.5)	+2.4 (0.6)	+3.3 (1.1)
Annual days below 0 °C (N°)	−6.1 (3.1)	−6.0 (4.0)	−6.5 (4.5)	−4.6 (2.5)	−6.5 (2.3)	−8.2 (3.3)	−6.7 (2.7)	−8.4 (3.8)	−10.0 (4.7)
Winter precipitation levels (%)	−5.1 (25.4)	−10.0 (22.6)	−9.4 (30.4)	−11.7 (31.8)	−9.3 (23.3)	−15.5 (32.9)	−13.2 (25.6)	−12.7 (20.4)	−12.0 (31.4)
Girona									
Minimum winter temperatures (°C)	+1.2 (0.5)	+1.6 (0.8)	+1.8 (0.7)	+1.4 (0.4)	+1.6 (0.4)	+2.8 (0.4)	+1.6 (0.6)	+2.8 (0.7)	+4.0 (1.2)
Annual days below 0 °C (N°)	−11.9 (5.6)	−13.6 (7.9)	−15.3 (7.3)	−9.0 (3.5)	−13.9 (5.3)	−19.6 (9.0)	−15.5 (7.8)	−22.4 (9.9)	−26.6 (10.4)
Winter precipitation levels (%)	−16.7 (19.6)	−10.1 (30.8)	−6.4 (24.2)	+4.8 (51.3)	+0.5 (43.5)	−5.7 (39.2)	+1.5 (38.1)	−19.0 (24.1)	−12.9 (34.6)
Granada									
Minimum winter temperatures (°C)	+1.0 (0.6)	+1.4 (0.7)	+1.9 (0.7)	+1.4 (0.4)	+1.6 (0.6)	+2.4 (0.4)	+1.5 (0.9)	+2.5 (0.7)	+3.7 (1.1)
Annual days below 0 °C (N°)	−5.4 (2.4)	−6.8 (3.4)	−7.3 (3.9)	−6.1 (3.8)	−8.4 (4.0)	−9.0 (4.4)	−7.1 (2.8)	−9.2 (3.8)	−10.3 (5.0)
Winter precipitation levels (%)	−15.2 (35.8)	−19.0 (35.4)	−10.0 (48.7)	+9.9 (58.9)	−10.0 (48.3)	−20.4 (28.9)	−5.8 (50.7)	−37.7 (38.3)	−14.1 (52.2)
Huesca									
Minimum winter temperatures (°C)	+1.1 (0.6)	+1.5 (0.7)	+1.9 (0.7)	+1.3 (0.5)	+1.5 (0.4)	+2.5 (0.5)	+1.4 (0.6)	+2.6 (0.6)	+3.6 (1.3)
Annual days below 0 °C (N°)	−26.6 (7.8)	−33.6 (12.1)	−36.6 (11.7)	−25.0 (6.8)	−35.7 (8.5)	−42.2 (6.3)	−29.3 (10.3)	−52.0 (10.3)	−61.8 (15.7)
Winter precipitation levels (%)	−0.5 (22.3)	−11.0 (21.3)	−2.1 (25.7)	+10.8 (36.5)	+1.8 (41.2)	−6.6 (19.7)	−3.1 (28.0)	−19.1 (16.1)	−7.6 (36.9)
León									
Minimum winter temperatures (°C)	+1.1 (0.5)	+1.3 (0.6)	+1.7 (0.7)	+1.3 (0.4)	+1.3 (0.5)	+2.2 (0.4)	+1.2 (0.6)	+2.3 (0.6)	+3.3 (1.0)
Annual days below 0 °C (N°)	−25.7 (7.4)	−31.2 (12.6)	−36.5 (15.2)	−26.1 (5.9)	−37.7 (7.5)	−40.5 (7.5)	−29.8 (11.5)	−49.7 (10.2)	−61.5 (17.1)
Winter precipitation levels (%)	+4.4 (30.6)	−13.1 (23.1)	+2.2 (34.0)	+17.9 (27.8)	+1.1 (43.8)	+2.9 (21.8)	−3.0 (32.6)	−17.2 (28.5)	−1.5 (48.7)
Lleida									
Minimum winter temperatures (°C)	+1.1 (0.6)	+1.4 (0.7)	+1.8 (0.7)	+1.3 (0.5)	+1.5 (0.4)	+2.5 (0.3)	+1.4 (0.6)	+2.6 (0.6)	+3.7 (1.2)
Annual days below 0 °C (N°)	−23.1 (7.5)	−30.3 (9.6)	−33.9 (9.2)	−23.1 (5.7)	−33.0 (6.2)	−40.2 (6.0)	−27.1 (10.0)	−48.3 (8.8)	−60.9 (12.7)
Winter precipitation levels (%)	−5.6 (27.0)	−8.9 (26.8)	−6.3 (31.6)	+12.1 (50.0)	+5.2 (47.2)	−2.6 (24.4)	−0.5 (36.4)	−22.1 (25.3)	−4.9 (43.8)
Madrid									
Minimum winter temperatures (°C)	+1.0 (0.6)	+1.4 (0.8)	+1.8 (0.7)	+1.3 (0.5)	+1.5 (0.7)	+2.2 (0.5)	+1.4 (0.8)	+2.3 (0.7)	+3.5 (1.1)
Annual days below 0 °C (N°)	−14.2 (5.9)	−17.0 (6.8)	−17.8 (8.9)	−13.2 (5.5)	−18.9 (3.8)	−21.0 (6.2)	−16.4 (7.3)	−23.4 (6.1)	−27.8 (9.1)
Winter precipitation levels (%)	−4.0 (35.1)	−13.6 (31.1)	−1.8 (43.0)	+14.9 (30.5)	−2.8 (47.1)	−5.3 (21.6)	−3.5 (40.7)	−27.3 (30.1)	−3.3 (54.2)

Table A2. *Cont.*

Province	RCP 4.5			RCP 6.0			RCP 8.5		
	2040	2070	2100	2040	2070	2100	2040	2070	2100
Ourense									
Minimum winter temperatures (°C)	+1.1 (0.6)	+1.1 (0.6)	+1.6 (0.8)	+1.1 (0.4)	+1.4 (0.6)	+2.1 (0.3)	+1.2 (0.7)	+2.3 (0.6)	+3.3 (1.0)
Annual days below 0 °C (N°)	−5.2 (4.5)	−5.9 (5.1)	−7.5 (5.2)	−5.3 (2.8)	−6.7 (3.6)	−8.3 (4.3)	−7.1 (3.0)	−9.0 (5.7)	−10.2 (5.3)
Winter precipitation levels (%)	+5.3 (29.5)	−10.9 (22.5)	+2.8 (32.3)	+13.7 (26.8)	+1.6 (40.7)	+0.4 (15.8)	1.7 (33.1)	−15.5 (23.9)	−0.7 (44.1)
Rioja									
Minimum winter temperatures (°C)	+1.2 (0.5)	+1.3 (0.7)	+1.7 (0.8)	+1.3 (0.3)	+1.3 (0.6)	+2.2 (0.4)	+1.3 (0.6)	+2.3 (0.6)	+3.4 (1.1)
Annual days below 0 °C (N°)	−16.7 (5.6)	−18.3 (9.5)	−21.3 (9.8)	−12.2 (4.2)	−21.6 (5.8)	−22.9 (3.1)	−19.6 (8.6)	−28.5 (8.6)	−35.2 (12.6)
Winter precipitation levels (%)	−4.3 (19.2)	−12.9 (21.2)	−3.8 (23.2)	+12.1 (26.2)	−1.7 (24.7)	−4.5 (20.1)	−7.3 (26.2)	−15.7 (17.2)	−8.5 (33.9)
Salamanca									
Minimum winter temperatures (°C)	+1.1 (0.7)	+1.3 (0.7)	+1.8 (1.0)	+1.4 (0.6)	+1.6 (1.0)	+2.2 (0.4)	+1.4 (0.9)	+2.3 (0.7)	+3.5 (1.1)
Annual days below 0 °C (N°)	−19.8 (6.6)	−19.0 (10.8)	−24.3 (14.0)	−15.2 (7.0)	−22.9 (6.9)	−24.1 (6.9)	−22.1 (9.9)	−30.0 (9.5)	−37.2 (13.5)
Winter precipitation levels (%)	+4.5 (36.0)	−11.8 (28.2)	+1.8 (40.5)	+17.4 (27.3)	+0.7 (47.7)	+2.9 (23.9)	−1.3 (38.3)	−21.4 (31.3)	0.0 (56.3)
Segovia									
Minimum winter temperatures (°C)	+1.0 (0.6)	+1.2 (0.8)	+1.7 (1.0)	+1.3 (0.4)	+1.4 (1.0)	+2.1 (0.5)	+1.3 (0.9)	+2.3 (0.7)	+3.5 (1.2)
Annual days below 0°C (N°)	−20.7 (7.3)	−21.6 (12.5)	−25.4 (15.6)	−17.5 (8.4)	−26.0 (8.6)	−28.4 (9.9)	−23.7 (12.1)	−33.0 (13.7)	−42.7 (16.9)
Winter precipitation levels (%)	−1.0 (26.0)	−12.2 (24.2)	−1.3 (29.3)	+11.7 (23.6)	−1.7 (39.5)	−2.7 (15.7)	−3.1 (28.4)	−18.9 (21.5)	−2.6 (42.5)
Soria									
Minimum winter temperatures (°C)	+1.0 (0.5)	+1.2 (0.7)	+1.7 (0.8)	+1.2 (0.4)	+1.3 (0.7)	+2.1 (0.3)	+1.2 (0.7)	+2.2 (0.6)	+3.3 (1.1)
Annual days below 0 °C (N°)	−27.2 (8.7)	−35.0 (15.1)	−40.2 (15.4)	−28.8 (6.1)	−43.5 (8.6)	−45.3 /7.8)	−33.2 (12.6)	−56.8 (10.5)	−70.9 (19.3)
Winter precipitation levels (%)	−1.2 (27.4)	−13.3 (24.9)	−1.4 (31.2)	+11.5 (27.4)	0.0 (39.5)	−4.7 (17.0)	−2.5 (31.3)	−20.7 (21.8)	−4.0 (44.1)
Teruel									
Minimum winter temperatures (°C)	+1.1 (0.4)	+1.4 (0.7)	+1.8 (0.7)	+1.4 (0.3)	+1.4 (0.5)	+2.2 (0.3)	+1.3 (0.8)	+2.4 (0.7)	+3.4 (1.0)
Annual days below 0 °C (N°)	−16.2 (3.9)	−20.2 (8.2)	−22.8 (8.4)	−14.7 (3.9)	−22.9 (5.6)	−26.2 (3.0)	−19.1 (7.2)	−30.5 (7.3)	−36.5 (9.7)
Winter precipitation levels (%)	−16.6 (19.2)	−13.9 (21.6)	−2.7 (32.2)	+7.9 (50.4)	+4.4 (51.5)	−5.4 (33.5)	−2.7 (30.7)	−24.1 (25.6)	−16.3 (36.5)

Source: Own elaboration based on AEMET.es. Notes: Results correspond to the mean values of the projected changes obtained from 13 models in the case of RCP 4.5, 6 models for RCP 6.0, and 14 models for RCP 8.5. Results establish a comparison with the reference period of 1961–2000. The first indicator refers to changes in the minimum winter temperatures (in °C), the second indicator addresses changes in the number of annual days with minimum temperature lower than 0 °C, and the third indicator presents changes in winter precipitation (in %). Standard deviations (SD) are presented within brackets.

Table A3. Touristic offer and demand of the ski resorts.

Ski Resort	Number of Available Beds in the Surrounding Area [1]	Number of Travellers Entering the Province [2]
Baqueira Beret	11,000	733,222
Boí Taüll	4724	733,222
Espot Esquí	1837	733,222
La Molina	16,541	3,231,098
Masella	14,924	3,231,098
Port Ainé	2260	733,222
Port del Compte	NA	733,222
Tavascán	550	733,222
Vall de Núria	3519	3,231,098
Vallter 2000	2397	3,231,098
Astún	6134	686,718
Candanchú	11,753	686,718
Cerler	6112	686,718
Formigal	10,060	686,718
Panticosa	10,452	686,718
Alto Campoo	2301	1,493,707
Fuentes de invierno	681	1,493,707
Leitariegos	1460	716,152
Lunada	NA	769,789
Manzaneda	837	262,772
San Isidro	2593	716,152
Valgrande-Pajares	1734	1,493,707
Javalambre	490	350,033
Punto de Nieve Santa Inés	NA	190,879
Valdelinares	1300	350,033
Valdezcaray	3001	539,092
La Pinilla	1894	385,287
Puerto Navacerrada	3928	10,283,425
Sierra de Béjar	4553	863,486
Valdesquí	4554	10,283,425
Sierra Nevada	26,663	2,525,956

Source: [1] [33]; [2] [40].

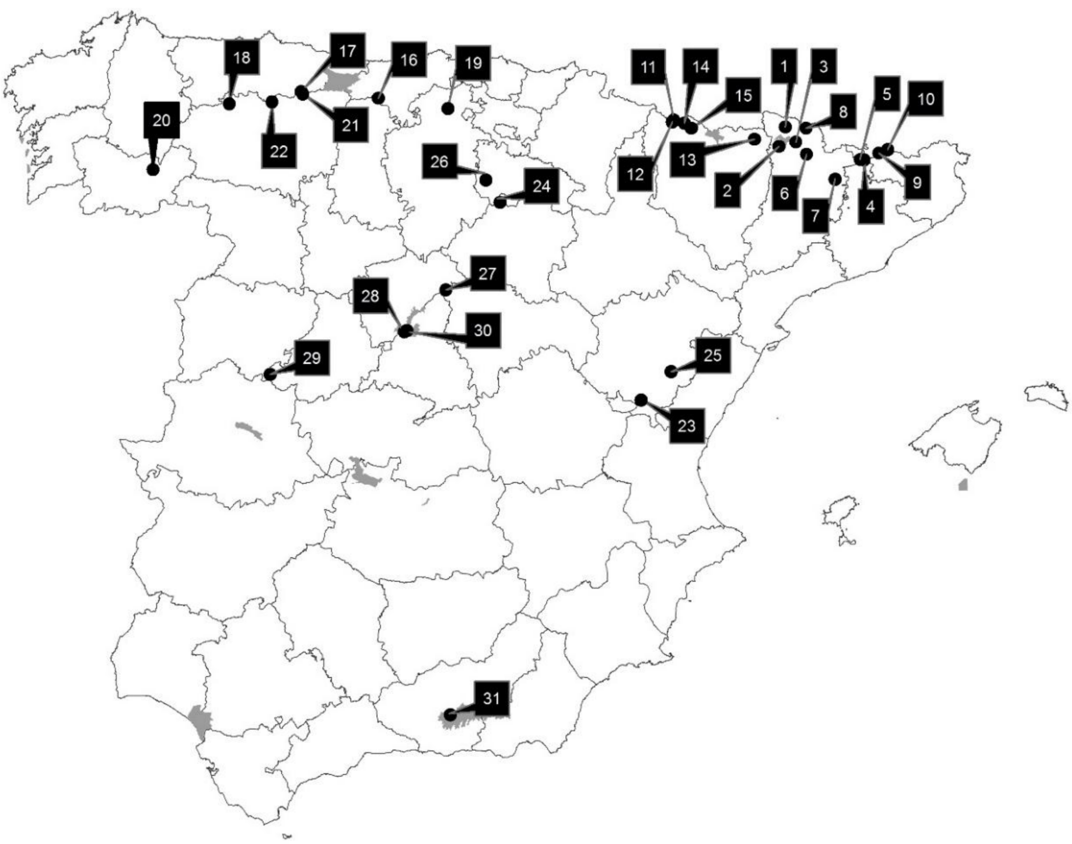

Figure A1. Map of alpine ski resorts and Natural Parks in Spain. Source: Based on http://www.redeuroparc.org/descargasmapas.jsp (accessed in December 2015). Legend: Same information as Figure 1.

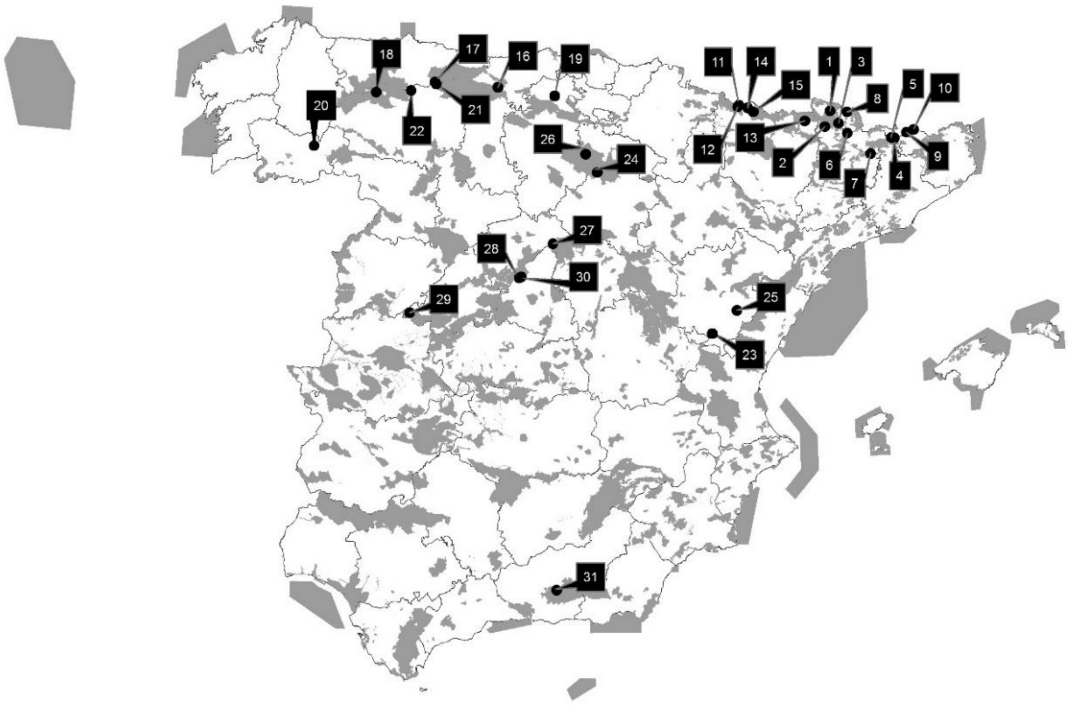

Figure A2. Map of alpine ski resorts and ZEPA sites in Spain. Source: Based on http://www.magrama.gob.es/es/biodiversidad/servicios/banco-datos-naturaleza/informacion-disponible/rednatura_2000_zepa_descargas.aspx (accessed in December 2015). Legend: Same information as Figure 1.

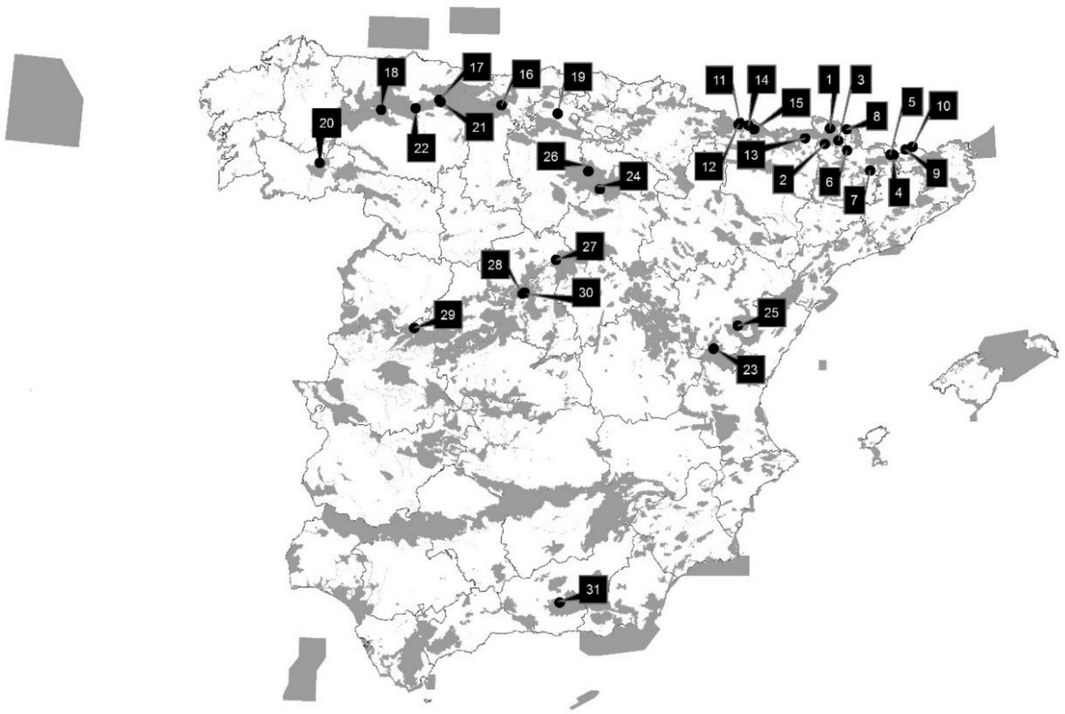

Figure A3. Map of alpine ski resorts and LIC sites in Spain. Source: Based on http://www.magrama.gob.es/es/biodiversidad/servicios/banco-datos-naturaleza/informacion-disponible/rednatura_2000_zepa_descargas.aspx (accessed in December 2015). Legend: Same information as Figure 1.

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