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Ski resorts threaten climate refugia for high-elevation biodiversity under current and future conditions in the Alps

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ABSTRACT

Climate and environmental changes are dramatically impacting mountain ecosystems, species and livelihoods. Alpine species are contracting as a response to global change and human impacts. Climate refugia are crucial sites for conservation, because they will preserve suitable conditions for biodiversity in the face of climate change. Outdoor recreational activities (skiing in particular) are threatening mountain ecosystems, leading to conflicts with biodiversity. There is therefore a compelling need to investigate the spatial impact of ski resorts on climate refugia, which we evaluate under current and future conditions in the Alps, where those key conservation sites are exposed to human pressure and are often located outside protected areas. This information is key to prevent/reduce the impacts of ski resorts on climate refugia and increase skiing sustainability. Downhill ski-pistes occupy 489,119 ha in the Alps (average elevation 1792 m) and, if their immediate surroundings are also considered, the current overlap with climate refugia reaches 11 %, leading to additional strong fragmentation of high-elevation habitats, impairing connectivity. One out of three of current ski-pistes is associated with a possible impact on climate refugia and this situation will aggravate in the future. Ski-piste distribution will shift upwards (predicted elevational increase 271–609 m) because of climate change, leading to an increase in the overlap between suitable areas for ski-pistes and climate refugia (from 57 % under current conditions to 69 %–72 %). These results highlight the urgent need to preserve climate refugia and the climate-threatened biodiversity they host from environmental alterations caused by unsustainable development.

1. Introduction

Anthropogenic impacts have altered habitats, ecosystem balance and services (Weiskopf et al., 2020), induced climate change (IPCC, 2013) and severely affected biodiversity (Zalasiewicz et al., 2019). Additional impacts may arise from the adaptation of human activities to the new climates (Bradley et al., 2012; Chapman et al., 2014), which may negatively affect the species' capacity to cope with climate change (Watson, 2014). Mountains are experiencing a higher-than-average rate of warming (Pepin et al., 2022) and drastic landscape changes because of both climate change and variations in land-use (Anselmetto et al., 2024) that are modifying mountain habitats, affecting biodiversity and ecosystem services (Tasser et al., 2024).

Birds are threatened by those ongoing changes, such as direct and indirect effects of climate modifications (Brambilla et al., 2016; O'Connor et al., 2022) and human encroachment on ecosystems (Butchart et al., 2010; Chamberlain et al., 2016b). Birds are sentinels of the pervasive effects of climate change and anthropic alteration, both in general and specifically in mountain ecosystems (Chamberlain et al., 2023).

Alpine species and habitat are shifting their range as a response to global warming (Walther et al., 2002), with strong consequences in high-elevation areas (Chamberlain et al., 2016a, 2016b; Sekercioglu et al., 2008). The direct impact of human activities poses further threats to biodiversity and ecosystems, and may impair species' ability to track suitable climate. Anthropogenic impacts are reshaping mountain areas by for instance the construction of road networks to support the exploitation of ecosystem services like timber, gas and heavy metal (Leu et al., 2008) or tourism and recreation (Geneletti and Dawa, 2009), influencing ecosystems (Rodríguez-Rodríguez and Bomhard, 2012) with effects on both biodiversity (including birds; Caprio et al., 2023) and ecosystem services (Alba et al., 2022; Vigl et al., 2021).

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A major source of threats for many mountain ecosystems is represented by intense recreational activities and the related tourism. Winter sports in particular are altering landscape and habitats, resulting in direct (e.g. collisions, Miquet, 1990) and indirect (e.g. disturbance, Arlettaz et al., 2015) impacts on many species, threatening alpine wildlife (Rolando et al., 2007) in many different ways (Rixen and Rolando, 2013) and leading to conflicts with mountain biodiversity (Caprio et al., 2011) (see Fig. 1 for examples of source of impacts within and around ski-pistes and Fig. S1 for examples of ski-driven alteration of high-elevation habitats). Alpine skiing and ski touring have been frequently reported to exert major and widespread impacts on mountain biodiversity and ecosystems (Rixen and Rolando, 2013; Sato et al., 2013). In alpine habitats, ski pistes have negative effects on grassland bird communities (lower abundance at and around ski pistes; Rolando et al., 2007), seed rain (reduced by 90 % on pistes compared to adjacent natural grasslands; Urbanska et al., 1998), grassland specialists occurrence (Caprio et al., 2011), birds sensitive to collision (Buffet and Dumont-Dayot, 2013), small mammals (Sanecki et al., 2006) and arthropods (Negro et al., 2010; Kessler et al., 2012). Furthermore, ski resorts may increase opportunistic predators with consequences for sensitive species (Watson and Moss, 2004). Taken together, the negative effects of ski pistes on biodiversity extend well beyond the pistes themselves, impacting e.g. on bird populations at a landscape scale (Caprio et al., 2023).

Outdoor snow sports are quickly growing and yet highly vulnerable to climate change (Scott et al., 2012; Wilkins et al., 2021b). They are often practised in fragile alpine ecosystems, where high-elevation species evolved adaptations to survive under harsh and highly seasonal environmental conditions (Marchand, 2014). These species are highly threatened at the same time by both climate change and ski-related impacts (e.g. Bech et al., 2012; Brambilla et al., 2022), and the two may act synergistically, exacerbating each other's effect. Climate change is indeed leading to similar upward contractions of both winter sports and high-elevation biodiversity, which are progressively concentrated in the upper, colder, portions of the valleys (Brambilla et al., 2016; Mitterwallner et al., 2024).

Climate refugia are areas that are suitable now for climate threatened-species, and will continue to be suitable even under future conditions determined by climate change. Climate refugia are therefore crucial for conservation, and represent key areas that can promote the persistence of habitats and species threatened by the changing climate, because they will preserve suitable conditions for them in the face of climate change (Morelli et al., 2020). Recreational activities such as skiing (Arlettaz et al., 2015; Rixen and Rolando, 2013) and climate change (Pearce-Higgins et al., 2015) have negative effects on birds and may exert increasing synergistic impacts on high-elevation species (Brambilla et al., 2016). Therefeore, there is a compelling need to investigate the potential impact of ski resorts on key conservation sites, by analysing the distribution of downhill ski-pistes and infrastructures in relation to climate refugia. Knowing such overlap is crucial to assess and potentially redefine the current management and conservation strategies in relation to winter sports in an era of dramatic climate change. Given that many climate refugia are located just above several ski resorts along the elevational gradients, in view of future climatic conditions (Gilaberte-Búrdalo et al., 2014), a possible future exacerbation of the potential conflict between skiing and biodiversity in the Alps can be expected (Brambilla et al., 2016).

With this work, we evaluate the spatial impact of ski resorts on climate refugia under current and future conditions. We focus on the Alps, where climate refugia are frequently under pressure because of human activities and development, and often occur outside protected areas (Brambilla et al., 2022). We assess the impact of existing ski resorts and, by modelling the future distribution of ski-pistes, we extend the evaluation to future conditions to foresee where potential issues might arise. This information can provide guidance to prevent or reduce the possible impacts of ski resorts on climate refugia and increase the effectiveness of conservation strategies and the sustainability of winter sports.

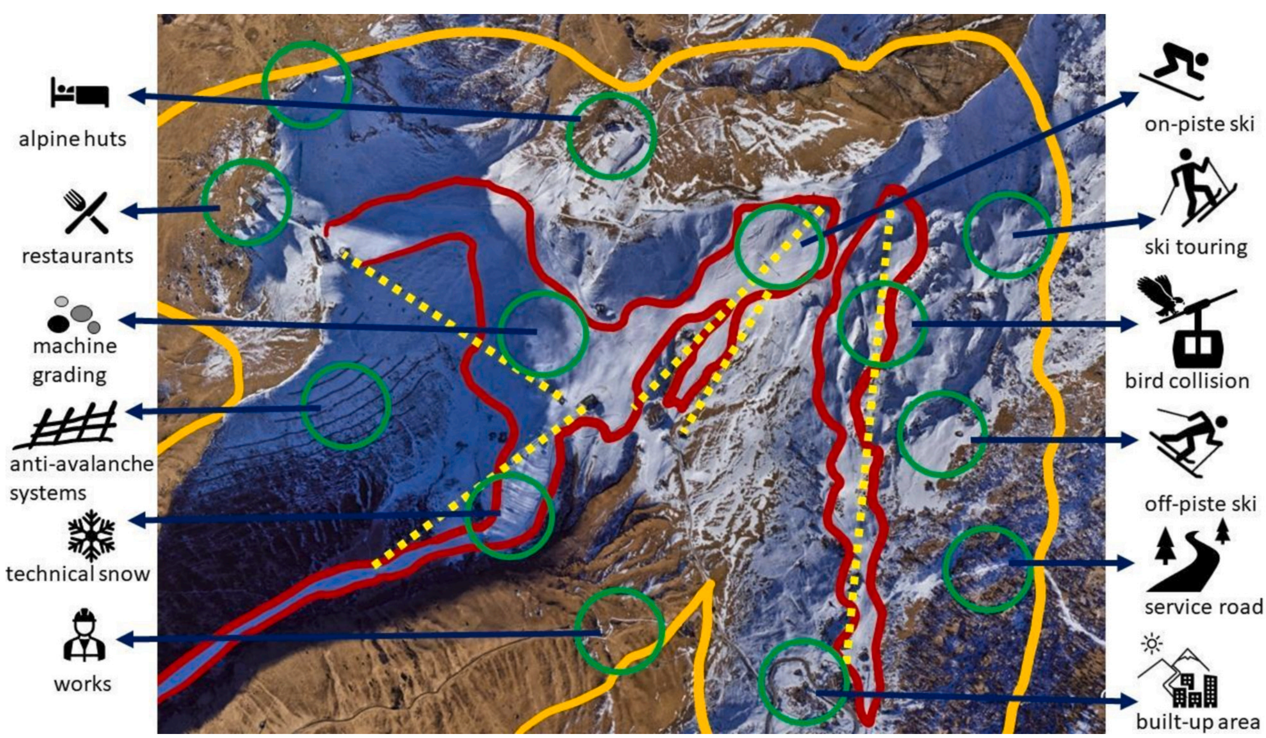

Fig. 1. Examples of possible sources of impacts associated with ski resorts, within and around the ski-pistes. Red lines depict ski-pistes, dashed yellow lines ski-lifts, and the orange line the buffer around the ski-pistes. Green circles represent the possible location of the example impact. Base image: Google Earth (accessed on 4th January 2024); example site: Passo Sella (Italy); symbols: MS PowerPoint icons and original drawings (anti-avalanche systems). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

2. Methods

2.1. Study system

The European Alps, defined as the main area included in the Alpine Convention (Fig. 2), encompass an area of nearly 190,000 km^2 across seven countries in south-central Europe. Characterised by high peaks (up to 4809 m asl), deep valleys and rich biodiversity, the Alps are one of the most densely populated mountain regions in the world (Perlik et al., 2001), showing a gradient of cultural and socio-economic contexts (Tasser et al., 2024), and, with hundreds of millions of tourists each year, stand as one of the most touristic destinations worldwide (Romeo et al., 2021). The Alps play a key role in the conservation of high-elevation species and habitats threatened by climate change: with an unparalleled availability of high-elevation areas at the European level, they offer to cold-adapted mountain species and habitats an irreplaceable opportunity to track suitable climates in the future (Brambilla et al., 2022). Climate refugia have been identified in the European Alps based on current and future distribution of high-elevation avian species, which are sensitive to both climate change (Brambilla et al., 2022) and direct and indirect impacts of ski-resorts (Table S1). In-situ climate refugia for most of the climate-sensitive species offer, and will continue to provide in the future, suitable conditions for high-elevation biodiversity. Such multispecies refugia stretch over an area of 14,865 km^2 and are key to conservation of high-elevation species and habitats in the Alps (Brambilla et al., 2022).

2.2. The possible current and future impact of ski-pistes

To evaluate the potential impact of ski resorts on alpine biodiversity under a changing climate, knowing the distribution of both climate refugia and ski-pistes is essential. The spatial location of in-situ climate refugia for high-elevation birds ('multispecies type 1 refugia') in the Alps was retrieved from Brambilla et al. (2022). A complete map of ski-piste distribution was realised in a GIS environment integrating existing data with new assessments (see Table S2).

To identify the spatial relationship between climate refugia and ski-pistes we overlapped i) the raster of multispecies type 1 refugia (Brambilla et al., 2022) and ii) ski-piste data with a 1 km-buffer drawn around the polygons. The latter was used to incorporate the potential disturbance of existing ski resorts, due to snow grooming, ski-related infrastructures and land management, and off-piste skiing (see Fig. 1).

To evaluate whether the potential impact of ski-pistes on climate refugia will be modulated by climate change, we modelled the potential distribution of ski-pistes under current and future conditions. We considered the exact same scenarios used for the identification of climate refugia and thus modelled the distribution of ski-pistes under current conditions and projected the distribution model over four alternative future climates (Table S3), and evaluated the associated changes in average elevation (Brambilla et al., 2022). The ski-piste distribution was modelled according to slope, solar radiation, average annual temperature and annual amount of precipitation (variables already proved successful in explaining piste distribution in the Alps; Brambilla et al., 2016), using the same procedure (see Table S3) and

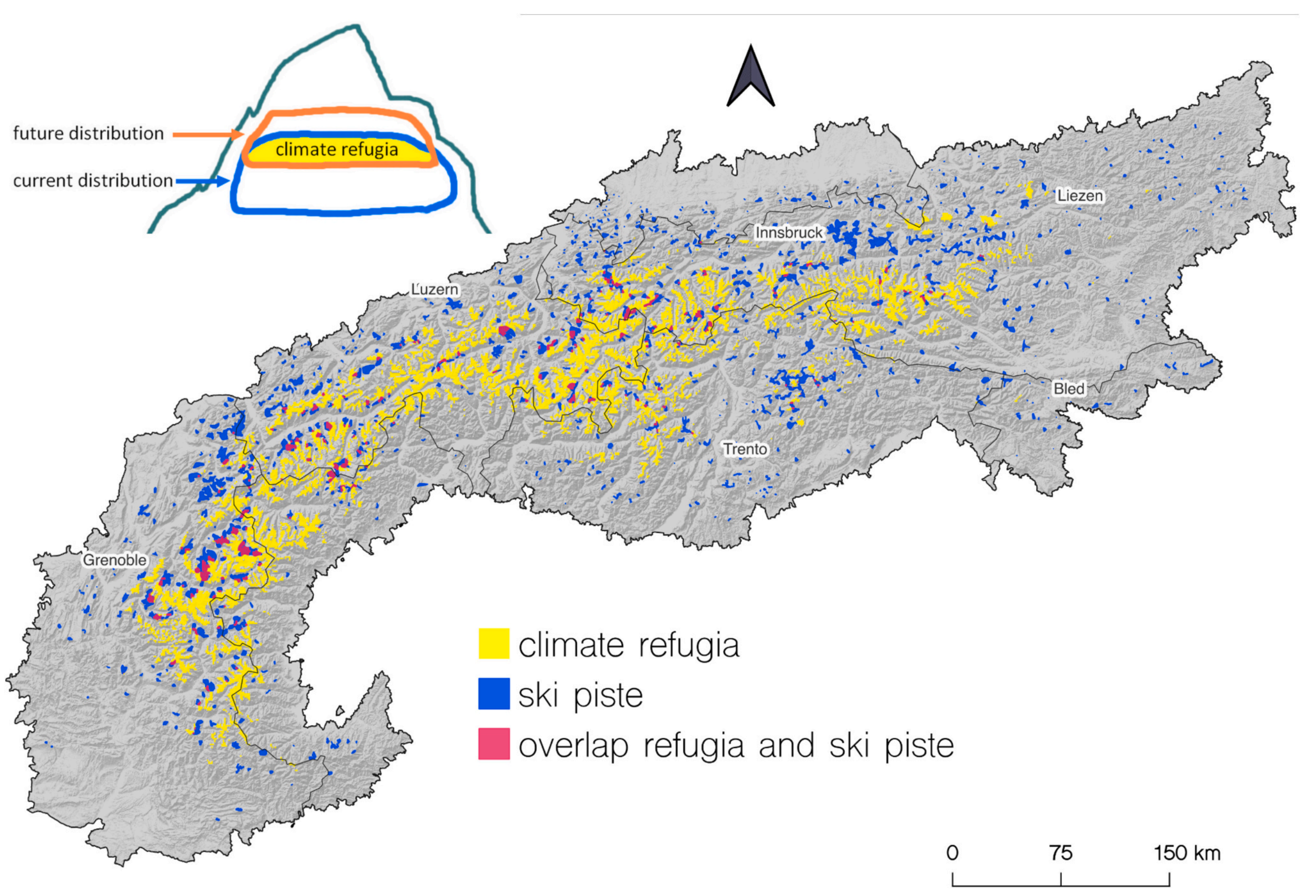

Fig. 2. Distribution of ski pistes (blue polygons) within Alpine Regions, multispecies type 1 refugia (in yellow; Brambilla et al., 2022), and overlapping sites between refugia and ski pistes plus 1 km buffer (magenta). State boundaries and the location of some Alpine towns are also shown. Hillshade derived from EU-DEM v1.0 (publicly provided by the European Environment Agency), Alps' boundaries as Alpine Convention area (Permanent Secretariat of the Alpine Convention, available on https://www.atlas.alpconv.org/). The upper left inset shows the concept of climate refugia of type 1 as areas suitable now and in the future for the target species. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

layers adopted for the species distribution models elaborated for the definition of climate refugia (Brambilla et al., 2022).

Using the 1 km × 1 km raster grid of the climate refugia, ski-piste occurrence sites were defined as the centroids of the raster cells falling within the ski-piste polygons defined by means of the procedure described above ($N = 4863$) (Lamboley and Fourcade, 2024). They were then subdivided into two spatially independent partitions, a larger one ($N = 3653$) for training the model, and the other ($N = 1210$) for testing it, by means of the checkerboard2 command in ENMeval. Background points ($N = 40{,}729$) were located within a buffer zone comprised between 5 and 10 km from existing ski-pistes and outside protected areas. This allowed us to avoid at the same time the overlap of background points with existing ski-resorts and with protected areas (where piste absence could be due to regulatory reasons instead of morphological and/or climatic factors), and to ensure that background points were in Alpine areas potentially exploitable for ski-pistes, being close to the existing ones. All evaluation metrics revealed a good model ability to predict ski-piste occurrence over the spatially independent dataset (Table S3), and the predicted distribution of ski-pistes matched well with the distribution of ski-pistes across Europe, therefore also outside the model's calibration area (see Fig. S2).

To evaluate the possible variation in the potential impact of ski-pistes on climate refugia, we i) defined the areas suitable for ski-pistes as those with a predicted suitability higher than the Maximum Training Sensitivity plus Specificity threshold (Liu et al., 2016), ii) draw a 1 km-buffer around the areas suitable for ski pistes (as done for currently existing ski-pistes) under different scenarios (current climate, and the four different future climates), iii) overlaid the resulting surface (suitable areas plus 1 km-buffer) with the climate refugia and estimated the amount of overlap between potential ski-pistes (plus relative immediate surroundings) and climate refugia under different scenarios. Hereafter, all the overlap evaluations refer to the area occupied by, or suitable for, ski-pistes plus the relative 1 km-buffer and climate refugia.

3. Results

3.1. Current overlap between ski-pistes and climate refugia

We estimate the area covered by downhill ski-pistes in the Alps to be 489,119 ha. The average elevation of (polygonal) current ski resorts is 1792 m asl, and the average elevation of (raster) suitable area for ski-pistes is 1766 m. The extent of climate refugia overlapped by ski-pistes encompasses 160,739 ha (Fig. 2), and the area currently suitable for ski-pistes overlaps with 57 % of climate refugia (Table 1).

3.2. Ski-piste distribution and the future overlap with climate refugia

Ski-piste distribution is affected by (in order of permutation importance) annual temperature, slope, annual precipitation and solar radiation (Fig. S3). The link with climatic parameters –temperature in particular- will lead to an upward shift in the future distribution of ski-resorts. The potential impact of ski-pistes on climate refugia is predicted to increase in the future: the average elevation of suitable extent for ski-pistes in the future is definitely higher than under the current conditions (Table 1, Fig. 3). More precisely, the overlap between suitable areas for ski-pistes and climate refugia will increase from 57 % in current conditions, to 69 % (UKESM1–0-LL, MRI-ESM2–0), 71 % (GFDL-ESM4) or 72 % (IPSL-CM6A-LR) in 2041–2070 (corresponding to an increase of 17–21,000 ha, i.e. 21–25 %).

Table 1
Average elevation of ski-pistes and suitable area under different climate conditions, and relative overlap (suitable areas plus 1 km-buffer) with climate refugia (in terms of interested extent of refugia).

Scenario	Average elevation (m asl)	Extent (ha*1000)	Overlap with refugia
Existing ski-pistes	1792	489	11 %
Currently suitable	1766	5163	57 %
GFDL-ESM4 suitable	2088	3432	71 %
UKESM1-0-LL suitable	2375	1950	69 %
IPSL-CM6A-LR suitable	2175	2952	72 %
MRI-ESM2-0 suitable	2037	3695	69 %

4. Discussion

Climate change is dramatically impacting mountains worldwide, threatening species, disrupting ecosystem processes and balance, eventually leading to alterations, degradation and reductions of key ecosystem services (Adler et al., 2023; Egan and Price, 2017).

High-elevation birds include cold-adapted species inhabiting rigid and cold environments (Chamberlain et al., 2023), currently undergoing significant declines (Scridel et al., 2018), including in the Alpine region (Lehikoinen et al., 2019). Birds are good indicators of general biodiversity, also in mountain regions (e.g. Anderle et al., 2024), and high-elevation birds could act as indicators of the fate of alpine ecosystems (Ahmadi et al., 2024). The areas serving as climate refugia for these species undergoing distribution shrinkage (de Gabriel Hernando et al., 2021) could be regarded as key areas for the conservation of alpine biodiversity and ecosystems under a changing climate (Brambilla et al., 2022).

Within such contexts, leisure activities are adding further concerns to the conservation of such species. Ski-pistes and related infrastructures result in a number of direct and indirect impacts on biodiversity and ecosystems at high elevation, varying from habitat alteration and fragmentation (Caprio et al., 2011) and soil degradation (Casagrande Bacchiocchi et al., 2019), to avian collision with suspended cables (Bech et al., 2012), disturbance (Korňan, 2020), disruption of interspecific interactions (Watson and Moss, 2004), and by causing stress and physiological alteration (Arlettaz et al., 2015). Moreover, due to the decrease of snowfall cover and the increase of temperature (François et al., 2023; Gottlieb and Mankin, 2024), ski resorts will experience a contraction range and elevational shift, stretching towards higher areas (Steiger and Abegg, 2013), with predicted variations similar to those forecast for high-elevation birds (Brambilla et al., 2022), worsening their impact on the latter (Brambilla et al., 2016).

The results of mapping existing ski-pistes and infrastructures show that the former are frequently overlapping with, or next to, the climate refugia that represent key sites for the conservation of high-elevation species. The overlap with areas potentially suitable for ski pistes, including also those sites not exploited because of accessibility or regulation (e.g., protected areas) issues, is even higher. This pattern highlights the potential impact of ski trails and related infrastructures on high-elevation birds and the associated biodiversity and ecosystems. Even in areas where ski-pistes do not overlap or overlap only partially with the climate refugia, there could be a still relevant impact due to strong fragmentation of high-elevation habitats and impairment of the potential connectivity among them, which could strongly affect bird dispersal (Rahbek et al., 2019; Klinga et al., 2019). This is particularly evident when looking at some specific cases (Fig. S4), adding further threats to the populations of species already showing signs of isolation and restricted gene flow across different mountain areas (Ceresa et al., 2023, 2024).

Results show that approximately 11 % of the climate refugia key to high-elevation birds in the Alps is encroached by ski-pistes and their immediate surroundings. Winter tourism and sport industry in past decades increased dramatically in the Alps (Patthey et al., 2008), exacerbating the pressure on alpine ecosystems and wildlife also due to vast and unpredictable free-ranging outdoor activities related to the use of ski-pistes (Rixen and Rolando, 2013). When comparing the current extent of ski-pistes in the Alps and the overlap between ski-pistes and climate refugia, the overlap of the former over the latter corresponds to 33 % of the current ski-pistes, and this means that one out of three ski-

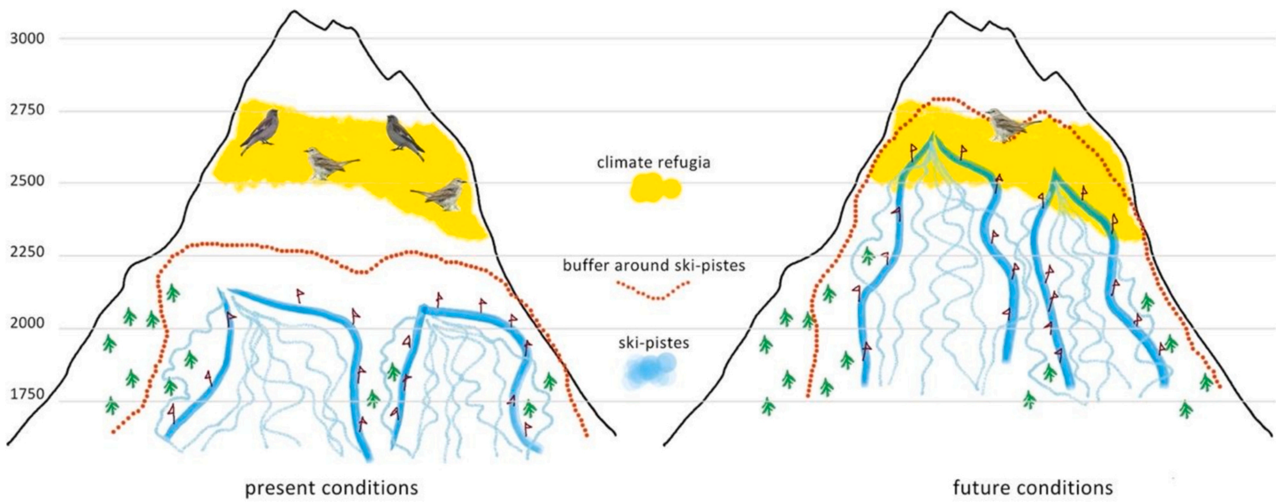

Fig. 3. Visual representation of the elevational shift forecast for ski-pistes and the consequent increase in the overlap with climate refugia. Example species: snowfinch (e.g. first from the left) and water pipit (e.g. first from the right).

pistes is associated with possible impacts on high-elevation biodiversity threatened by climate change. This concerning situation is predicted to aggravate in the future: the ski industry is dramatically affected by climate change, by means of increased temperature, variation in precipitation regimes, and consequent irregular and less reliable snow cover (Gilaberte-Búrdalo et al., 2014; Mitterwallner et al., 2024). Such climatic variations are causing the abandonment of many low-elevation ski-resorts, the use of technical snow when the temperature permits, and the construction of new resorts at higher elevation (Legambiente, 2024; Table S4). This is perfectly matched by the distribution model for ski-pistes and the predicted increase in the average elevation of suitable areas from 271 to 609 m. Moving upwards, ski-resorts will further encroach on climate refugia (see also Fig. 3), with an estimated figure of a 21–25 % increase in the potential overlap, which would lead to an overlap between areas suitable for ski-pistes and climate refugia increasing from an already concerning 57 % to an alarming level of 69–72 %.

Ski industry worldwide is facing the need to adapt to current and future climate conditions (Scott and McBoyle, 2007), with different issues and solutions being raised in Europe (Campos Rodrigues et al., 2018), Japan (Suzuki-Parker et al., 2018), Canada (Rutty et al., 2017), New Zealand (Hendrikx et al., 2013) and North America (Scott and McBoyle, 2007; Wilkins et al., 2021a). The construction of new ski resorts at higher elevation represents a potential mean to sustain the winter tourism economy (Dawson and Scott, 2013), but it could lead to further machine-grading of slopes, habitat fragmentation, alteration of soil properties, with severe impact on the environment (Hudek et al., 2020), heightening the negative impact of downhill skiing on several alpine species (Rolando et al., 2007). Ski pistes are already associated with touristic and popular destinations, where higher visitation rates are increasing impacts (Beza, 2010), negatively affecting relevant cultural ecosystem services and limiting the access to natural resources for residents (Schirpke et al., 2020). In addition, winter sports are responsible for the increasing demand of electricity and water to supply snow scarcity (François et al., 2023).

5. Conclusions

The combined effect of global change and human activities is particularly concerning in mountain systems. Climate refugia are key sites to species and ecosystems threatened by climate change, but they also largely overlap with existing and possible ski-pistes, and will overlap even more in the future (up to almost three quarters of their extent over the Alps). The building and management of Alpine ski resorts are dependent on country- and region-specific regulations. Even if private companies often hold most of resorts, public entities are involved in planning, funding or co-financing initiatives, and providing or denying authorisations for new resorts and pistes. The spatial distribution of climate refugia should be considered in the evaluation of the possible trade-offs between conservation and socio-economic objectives, especially because many refugia lie outside the network of protected areas and hence are not safeguarded by other tools in the current conditions. The concerning situation highlighted by our results and the alarming perspectives raise the need to pay attention to the conservation of climate refugia, irreplaceable sites for high-elevation biodiversity and ecosystems. Hence, there is an urgent need to i) preserve climate refugia from environmental alterations due to unsustainable development (also outside protected areas), and ii) further investigate the spatio-temporal dynamics of these conflicts at finer scales to understand the drivers of species' ecology and population trajectories in sites affected by ski infrastructures and adopt mitigation measures.

CRediT authorship contribution statement

Francesca Roseo: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Validation, Visualization, Writing – original draft, Writing – review & editing. **Claudio Celada:** Conceptualization, Funding acquisition, Methodology, Supervision, Writing – review & editing. **Mattia Brambilla:** Conceptualization, Formal analysis, Investigation, Methodology, Supervision, Validation, Visualization, Writing – original draft, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.biocon.2024.110890.

Data availability

The location of ski-pistes in the Alps obtained by combining the different sources described in the text is available as a geopackage file. The location of ski-piste and control points used for modelling is available as .RDS file. Files can be freely downloaded from https://doi.org/10.13130/RD_UNIMI/HADWPV.

References

Adler, C., Wester, P., Bhatt, I., Huggel, C., Insarov, G.E., Morecroft, M.D., Muccione, V., Prakash, A., 2023. Climate change 2022 – Impacts. In: Adaptation and Vulnerability: Working Group II Contribution to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change, 1st ed. Cambridge University Press. https://doi.org/10.1017/9781009325844.

Ahmadi, M., Nawaz, M.A., Asadi, H., Hemami, M., Naderi, M., Shafapourtehrany, M., Shabani, F., 2024. Protecting alpine biodiversity in the Middle East from climate change: implications for high-elevation birds. Divers. Distrib. e13826. https://doi.org/10.1111/ddi.13826.

Alba, R., Kasoar, T., Chamberlain, D., Buchanan, G., Thompson, D., Pearce-Higgins, J.W., 2022. Drivers of change in mountain and upland bird populations in Europe. Ibis 164, 635–648. https://doi.org/10.1111/ibi.13043.

Anderle, M., Brambilla, M., Angelini, L., Guariento, E., Paniccia, C., Plunger, J., Seeber, J., Stifter, S., Tappeiner, U., Tasser, E., Hilpold, A., 2024. Efficiency of birds as bioindicators for other taxa in mountain farmlands. Ecol. Indic. 158, 111569. https://doi.org/10.1016/j.ecolind.2024.111569.

Anselmetto, N., Weisberg, P.J., Garbarino, M., 2024. Global change in the European Alps: a century of post-abandonment natural reforestation at the landscape scale. Landsc. Urban Plan. 243, 104973. https://doi.org/10.1016/j.landurbplan.2023.104973.

Arlettaz, R., Nusslé, S., Baltic, M., Vogel, P., Palme, R., Jenni-Eiermann, S., Patthey, P., Genoud, M., 2015. Disturbance of wildlife by outdoor winter recreation: allostatic stress response and altered activity–energy budgets. Ecol. Appl. 25, 1197–1212. https://doi.org/10.1890/14-1141.1.

Bech, N., Beltran, S., Boissier, J., Allienne, J.F., Resseguier, J., Novoa, C., 2012. Bird mortality related to collisions with ski–lift cables: do we estimate just the tip of the iceberg? Anim. Biodivers, Conserv.

Beza, B.B., 2010. The aesthetic value of a mountain landscape: a study of the Mt. Everest Trek. Landsc. Urban Plan. 97, 306–317. https://doi.org/10.1016/j.landurbplan.2010.07.003.

Bradley, B.A., Estes, L.D., Hole, D.G., Holness, S., Oppenheimer, M., Turner, W.R., Beukes, H., Schulze, R.E., Tadross, M.A., Wilcove, D.S., 2012. Predicting how adaptation to climate change could affect ecological conservation: secondary impacts of shifting agricultural suitability. Divers. Distrib. 18, 425–437. https://doi.org/10.1111/j.1472-4642.2011.00875.x.

Brambilla, M., Pedrini, P., Rolando, A., Chamberlain, D.E., 2016. Climate change will increase the potential conflict between skiing and high-elevation bird species in the Alps. J. Biogeogr. 43, 2299–2309. https://doi.org/10.1111/jbi.12796.

Brambilla, M., Rubolini, D., Appukuttan, O., Calvi, G., Karger, D.N., Kmecl, P., Mihelič, T., Sattler, T., Seaman, B., Teufelbauer, N., Wahl, J., Celada, C., 2022. Identifying climate refugia for high-elevation alpine birds under current climate warming predictions. Glob. Change Biol. 28, 4276–4291. https://doi.org/10.1111/gcb.16187.

Buffet, N., Dumont-Dayot, E., 2013. Bird collisions with overhead ski-cables: a reducible source of mortality. In: Rixen, C., Rolando, A. (Eds.), The Impacts of Skiing and Related Winter Recreational Activities on Mountain Environments, pp. 123–136. https://doi.org/10.2174/978160805488611301001O.

Butchart, S.H.M., Walpole, M., Collen, B., Van Strien, A., Scharlemann, J.P.W., Almond, R.E.A., Baillie, J.E.M., Bomhard, B., Brown, C., Bruno, J., Carpenter, K.E., Carr, G.M., Chanson, J., Chenery, A.M., Csirke, J., Davidson, N.C., Dentener, F., Foster, M., Galli, A., Galloway, J.N., Genovesi, P., Gregory, R.D., Hockings, M., Kapos, V., Lamarque, J.-F., Leverington, F., Loh, J., McGeoch, M.A., McRae, L., Minasyan, A., Morcillo, M.H., Oldfield, T.E.E., Pauly, D., Quader, S., Revenga, C., Sauer, J.R., Skolnik, B., Spear, D., Stanwell-Smith, D., Stuart, S.N., Symes, A., Tierney, M., Tyrrell, T.D., Vié, J.-C., Watson, R., 2010. Global biodiversity: indicators of recent declines. Science 328, 1164–1168. https://doi.org/10.1126/science.1187512.

Campos Rodrigues, L., Freire-González, J., González Puig, A., Puig-Ventosa, I., 2018. Climate change adaptation of alpine ski tourism in Spain. Climate 6, 29. https://doi.org/10.3390/cli6020029.

Caprio, E., Chamberlain, D.E., Isaia, M., Rolando, A., 2011. Landscape changes caused by high altitude ski-pistes affect bird species richness and distribution in the Alps. Biol. Conserv. 144, 2958–2967. https://doi.org/10.1016/j.biocon.2011.08.021.

Caprio, E., Rolando, A., Arlettaz, R., Chamberlain, D., 2023. 7· anthropogenic activities and mountain birds. In: Chamberlain, D., Lehikoinen, A., Martin, K. (Eds.), Ecology and Conservation of Mountain Birds. Cambridge University Press, Cambridge, UK, pp. 260–295.

Casagrande Bacchiocchi, S., Zerbe, S., Cavieres, L.A., Wellstein, C., 2019. Impact of ski piste management on mountain grassland ecosystems in the Southern Alps. Sci. Total Environ. 665, 959–967. https://doi.org/10.1016/j.scitotenv.2019.02.086.

Ceresa, F., Brambilla, M., Kvist, L., Vitulano, S., Pes, M., Tomasi, L., Pedrini, P., Hilpold, A., Kranebitter, P., 2023. Landscape characteristics influence regional dispersal in a high-elevation specialist migratory bird, the water pipit *Anthus spinoletta*. Mol. Ecol. 32, 1875–1892. https://doi.org/10.1111/mec.16853.

Ceresa, F., Brambilla, M., Kvist, L., Vitulano, S., Pes, M., Tomasi, L., Pedrini, P., Bettega, C., Anderle, M., Hilpold, A., Kranebitter, P., 2024. Restricted dispersal and inbreeding in a high-elevation bird across the 'sky islands' of the European Alps. J. Biogeogr. 51, 853–868. https://doi.org/10.1111/jbi.14787.

Chamberlain, D., Brambilla, M., Caprio, E., Pedrini, P., Rolando, A., 2016a. Alpine bird distributions along elevation gradients: the consistency of climate and habitat effects across geographic regions. Oecologia 181, 1139–1150. https://doi.org/10.1007/s00442-016-3637-y.

Chamberlain, D., Lehikoinen, A., Martin, K. (Eds.), 2023. Ecology and Conservation of Mountain Birds, 1st ed. Cambridge University Press. https://doi.org/10.1017/9781108938570.

Chamberlain, D.E., Pedrini, P., Brambilla, M., Rolando, A., Girardello, M., 2016b. Identifying key conservation threats to Alpine birds through expert knowledge. PeerJ 4, e1723. https://doi.org/10.7717/peerj.1723.

Chapman, S., Mustin, K., Renwick, A.R., Segan, D.B., Hole, D.G., Pearson, R.G., Watson, J.E.M., 2014. Publishing trends on climate change vulnerability in the conservation literature reveal a predominant focus on direct impacts and long time-scales. Divers. Distrib. 20, 1221–1228. https://doi.org/10.1111/ddi.12234.

Dawson, J., Scott, D., 2013. Managing for climate change in the alpine ski sector. Tour. Manag. 35, 244–254. https://doi.org/10.1016/j.tourman.2012.07.009.

Egan, P.A., Price, M.F., 2017. Mountain Ecosystem Services and Climate Change. UNESCO.

François, H., Samacoïts, R., Bird, D.N., Köberl, J., Prettenthaler, F., Morin, S., 2023. Climate change exacerbates snow-water-energy challenges for European ski tourism. Nat. Clim. Chang. 13, 935–942. https://doi.org/10.1038/s41558-023-01759-5.

Geneletti, D., Dawa, D., 2009. Environmental impact assessment of mountain tourism in developing regions: a study in Ladakh. Indian Himalaya. Environmental impact assessment review 29 (4), 229–242.

Gilaberte-Búrdalo, M., López-Martín, F., Pino-Otín, M.R., López-Moreno, J.I., 2014. Impacts of climate change on ski industry. Environ. Sci. Policy 44, 51–61. https://doi.org/10.1016/j.envsci.2014.07.003.

Gottlieb, A.R., Mankin, J.S., 2024. Evidence of human influence on Northern Hemisphere snow loss. Nature 625, 293–300. https://doi.org/10.1038/s41586-023-06794-y.

Hendrikx, J., Zammit, C., Hreinsson, E.Ö., Becken, S., 2013. A comparative assessment of the potential impact of climate change on the ski industry in New Zealand and Australia. Clim. Change 119, 965–978. https://doi.org/10.1007/s10584-013-0741-4.

Hernando, M. de G., Fernández-Gil, J., Roa, I., Juan, J., Ortega, F., Calzada, F. de la, Revilla, E., 2021. Warming threatens habitat suitability and breeding occupancy of rear-edge alpine bird specialists. Ecography 44, 1191–1204. https://doi.org/10.1111/ecog.05593.

Hudek, C., Barni, E., Stanchi, S., D'Amico, M., Pintaldi, E., Freppaz, M., 2020. OPEN Mid and Long-Term Ecological Impacts of Ski Run Construction on Alpine Ecosystems.

IPCC (Ed.), 2013. Climate Change 2013: The Physical Science Basis: Summary for Policymakers, a Report of Working Group I of the IPCC: Technical Summary, a Report Accepted by Working Group I of the IPCC but Not Approved in Detail: And Frequently Asked Questions: Part of the Working Group I Contribution to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. WMO, UNEP, s.l.

Keßler, T., Cierjacks, A., Ernst, R., Dziock, F., 2012. Direct and indirect effects of ski run management on alpine Orthoptera. Biodivers. Conserv. 21, 281–296.

Klinga, P., Mikoláš, M., Smolko, P., Tejkal, M., Höglund, J., Paule, L., 2019. Considering landscape connectivity and gene flow in the Anthropocene using complementary landscape genetics and habitat modelling approaches. Landsc. Ecol. 34, 521–536.

Korňan, M., 2020. Potential negative effects of construction of a high-mountain ski resort in the High Tatras, Slovakia, on breeding bird assemblages. Community Ecol. 21, 213–226. https://doi.org/10.1007/s42974-020-00018-3.

Lamboley, Q., Fourcade, Y., 2024. No optimal spatial filtering distance for mitigating sampling bias in ecological niche models. J. Biogeogr. https://doi.org/10.1111/jbi.14854 (n/a).

Legambiente, 2024. NEVEDIVERSA (Il turismo della neve nelle montagne senza neve).

Lehikoinen, A., Brotons, L., Calladine, J., Campedelli, T., Escandell, V., Flousek, J., Grueneberg, C., Haas, F., Harris, S., Herrando, S., Husby, M., Jiguet, F., Kålås, J.A., Lindström, Å., Lorrillière, R., Molina, B., Pladevall, C., Calvi, G., Sattler, T., Schmid, H., Sirkiä, P.M., Teufelbauer, N., Trautmann, S., 2019. Declining population trends of European mountain birds. Glob. Change Biol. 25, 577–588. https://doi.org/10.1111/gcb.14522.

Leu, M., Hanser, S.E., Knick, S.T., 2008. The human footprint in the west: a large-scale analysis of anthropogenic impacts. Ecol. Appl. 18 (5), 1119–1139.

Liu, C., Newell, G., White, M., 2016. On the selection of thresholds for predicting species occurrence with presence-only data. Ecol. Evol. 6, 337–348. https://doi.org/10.1002/ece3.1878.

Marchand, P.J., 2014. Life in the Cold: An Introduction to Winter Ecology. UPNE.

Miquet, A., 1990. Mortality in black grouse Tetrao tetrix due to elevated cables. Biol. Conserv. 54, 349–355. https://doi.org/10.1016/0006-3207(90)90146-G.

Mitterwallner, V., Steinbauer, M., Mathes, G., Walentowitz, A., 2024. Global reduction of snow cover in ski areas under climate change. PloS One 19, e0299735. https://doi.org/10.1371/journal.pone.0299735.

Morelli, T.L., Barrows, C.W., Ramirez, A.R., Cartwright, J.M., Ackerly, D.D., Eaves, T.D., Ebersole, J.L., Krawchuk, M.A., Letcher, B.H., Mahalovich, M.F., Meigs, G.W., Michalak, J.L., Millar, C.I., Quiñones, R.M., Stralberg, D., Thorne, J.H., 2020. Climate-change refugia: biodiversity in the slow lane. Front. Ecol. Environ. 18, 228–234. https://doi.org/10.1002/fee.2189.

Negro, M., Isaia, M., Palestrini, C., Schoenhofer, A., Rolando, A., 2010. The impact of high-altitude ski pistes on ground-dwelling arthropods in the Alps. Biodivers. Conserv. 19, 1853–1870.

O'Connor, R.S., Le Pogam, A., Young, K.G., Love, O.P., Cox, C.J., Roy, G., Robitaille, F., Elliott, K.H., Hargreaves, A.L., Choy, E.S., Gilchrist, H.G., Berteaux, D., Tam, A., Vézina, F., 2022. Warming in the land of the midnight sun: breeding birds may suffer greater heat stress at high- versus low-Arctic sites. Proc. R. Soc. B Biol. Sci. 289, 20220300. https://doi.org/10.1098/rspb.2022.0300.

Patthey, P., Wirthner, S., Signorell, N., Arlettaz, R., 2008. Impact of outdoor winter sports on the abundance of a key indicator species of alpine ecosystems. J. Appl. Ecol. 45, 1704–1711. https://doi.org/10.1111/j.1365-2664.2008.01547.x.

Pearce-Higgins, J.W., Eglington, S.M., Martay, B., Chamberlain, D.E., 2015. Drivers of climate change impacts on bird communities. J. Anim. Ecol. 84, 943–954. https://doi.org/10.1111/1365-2656.12364.

Pepin, N.C., Arnone, E., Gobiet, A., Haslinger, K., Kotlarski, S., Notarnicola, C., Palazzi, E., Seibert, P., Serafin, S., Schöner, W., Terzago, S., Thornton, J.M., Vuille, M., Adler, C., 2022. Climate changes and their elevational patterns in the mountains of the world. Rev. Geophys. 60, e2020RG000730. https://doi.org/10.1029/2020RG000730.

Perlik, M., Messerli, P., Bätzing, W., 2001. Towns in the Alps: urbanization processes, economic structure, and demarcation of European Functional Urban Areas (EFUAs) in the Alps. Mt. Res. Dev. 21, 243–252. https://doi.org/10.1659/0276-4741(2001)021[0243:TITA]2.0.CO;2.

Rahbek, C., Borregaard, M.K., Colwell, R.K., Dalsgaard, B.O., Holt, B.G., Morueta-Holme, N., et al., 2019. Humboldt's enigma: what causes global patterns of mountain biodiversity? Science 365 (6458), 1108–1113.

Impacts of outdoor winter recreation on alpine wildlife and mitigation approaches: a case study of the black grouse. In: Rixen, C., Rolando, A. (Eds.), 2013. The Impacts of Skiing and Related Winter Recreational Activities on Mountain Environments. BENTHAM SCIENCE PUBLISHERS, pp. 137–154. https://doi.org/10.2174/97816080548861130100111.

Rodríguez-Rodríguez, D., Bomhard, B., 2012. Mapping direct human influence on the world's mountain areas. Mt. Res. Dev. 32, 197–202. https://doi.org/10.1659/MRD-JOURNAL-D-10-00111.1.

Rolando, A., Caprio, E., Rinaldi, E., Ellena, I., 2007. The impact of high-altitude ski-runs on alpine grassland bird communities. J. Appl. Ecol. 44, 210–219. https://doi.org/10.1111/j.1365-2664.2006.01253.x.

Romeo, R., Russo, L., Parisi, F., Notarianni, M., Manuelli, S., Carvao, S., 2021. Mountain Tourism—Towards a More Sustainable Path. Food and Agriculture Organization (FAO), Rome, Italy, 2021; ISBN 9789251354162.

Rutty, M., Scott, D., Johnson, P., Pons, M., Steiger, R., Vilella, M., 2017. Using ski industry response to climatic variability to assess climate change risk: an analogue study in Eastern Canada. Tour. Manag. 58, 196–204. https://doi.org/10.1016/j.tourman.2016.10.020.

Sanecki, G.M., Green, K., Wood, H., Lindenmayer, D., 2006. The implications of snow-based recreation for small mammals in the subnivean space in south-east Australia. Biol. Conserv. 129 (4), 511–518.

Sato, C.F., Wood, J.T., Lindenmayer, D.B., 2013. The effects of winter recreation on alpine and subalpine fauna: a systematic review and meta-analysis. PLoS ONE 8, e64282. https://doi.org/10.1371/journal.pone.0064282.

Schirpke, U., Scolozzi, R., Dean, G., Haller, A., Jäger, H., Kister, J., Kovács, B., Sarmiento, F.O., Sattler, B., Schleyer, C., 2020. Cultural ecosystem services in mountain regions: conceptualising conflicts among users and limitations of use. Ecosyst. Serv. 46, 101210. https://doi.org/10.1016/j.ecoser.2020.101210.

Scott, D., McBoyle, G., 2007. Climate change adaptation in the ski industry. Mitig. Adapt. Strateg. Glob. Change 12, 1411–1431. https://doi.org/10.1007/s11027-006-9071-4.

Scott, D., Gössling, S., Hall, C.M., 2012. International tourism and climate change. WIREs Clim. Change 3, 213–232. https://doi.org/10.1002/wcc.165.

Scridel, D., Brambilla, M., Martin, K., Lehikoinen, A., Iemma, A., Matteo, A., Jähnig, S., Caprio, E., Bogliani, G., Pedrini, P., Rolando, A., Arlettaz, R., Chamberlain, D., 2018. A review and meta-analysis of the effects of climate change on Holarctic mountain and upland bird populations. Ibis 160, 489–515. https://doi.org/10.1111/ibi.12585.

Sekercioglu, C.H., Schneider, S.H., Fay, J.P., Loarie, S.R., 2008. Climate change, elevational range shifts, and bird extinctions. Conserv. Biol. 22, 140–150. https://doi.org/10.1111/j.1523-1739.2007.00852.x.

Steiger, R., Abegg, B., 2013. The sensitivity of Austrian ski areas to climate change. Tour. Plan. Dev. 10, 480–493. https://doi.org/10.1080/21568316.2013.804431.

Suzuki-Parker, A., Miura, Y., Kusaka, H., Kureha, M., 2018. Assessing the sustainability of ski fields in southern Japan under global warming. Adv. Meteorol. 2018, 1–10. https://doi.org/10.1155/2018/8529748.

Tasser, E., Leitinger, G., Tappeiner, U., Schirpke, U., 2024. Shaping the European Alps: trends in landscape patterns, biodiversity and ecosystem services. Catena 235, 107607. https://doi.org/10.1016/j.catena.2023.107607.

Urbanska, K.M., Erdt, S., Fattorini, M., 1998. Seed rain in natural grassland and adjacent ski run in the Swiss Alps: a preliminary report. Restor. Ecol. 6 (2), 159–165.

Vigl, L. e, Marsoner, T., Schirpke, U., Tscholl, S., Candiago, S., Depellegrin, D., 2021. A multi-pressure analysis of ecosystem services for conservation planning in the Alps. Ecosyst. Serv. 47, 101230. https://doi.org/10.1016/j.ecoser.2020.101230.

Walther, G.-R., Post, E., Convey, P., Menzel, A., Parmesan, C., Beebee, T.J.C., Fromentin, J.-M., Hoegh-Guldberg, O., Bairlein, F., 2002. Ecological responses to recent climate change. Nature 416, 389–395. https://doi.org/10.1038/416389a.

Watson, A., Moss, R., 2004. Impacts of ski-development on ptarmigan (Lagopus mutus) at cairn Gorm. Scotland. Biol. Conserv. 116, 267–275. https://doi.org/10.1016/S0006-3207(03)00197-6.

Watson, J.E.M., 2014. Human responses to climate change will seriously impact biodiversity conservation: It's time we start planning for them. Conserv. Lett. 7, 1–2. https://doi.org/10.1111/conl.12083.

Weiskopf, S.R., Rubenstein, M.A., Crozier, L.G., Gaichas, S., Griffis, R., Halofsky, J.E., Hyde, K.J.W., Morelli, T.L., Morisette, J.T., Muñoz, R.C., Pershing, A.J., Peterson, D. L., Poudel, R., Staudinger, M.D., Sutton-Grier, A.E., Thompson, L., Vose, J., Weltzin, J.F., Whyte, K.P., 2020. Climate change effects on biodiversity, ecosystems, ecosystem services, and natural resource management in the United States. Sci. Total Environ. 733, 137782. https://doi.org/10.1016/j.scitotenv.2020.137782.

Wilkins, E.J., Akbar, H., Saley, T.C., Hager, R., Elkin, C.M., Belmont, P., Flint, C.G., Smith, J.W., 2021a. Climate change and Utah ski resorts: impacts, perceptions, and adaptation strategies. Mt. Res. Dev. 41. https://doi.org/10.1659/MRD-JOURNAL-D-20-00065.1.

Wilkins, E.J., Chikamoto, Y., Miller, A.B., Smith, J.W., 2021b. Climate change and the demand for recreational ecosystem services on public lands in the continental United States. Glob. Environ. Change 70, 102365. https://doi.org/10.1016/j.gloenvcha.2021.102365.

Zalasiewicz, J., Waters, C.N., Williams, M., Summerhayes, C.P. (Eds.), 2019. The Anthropocene as a Geological Time Unit: A Guide to the Scientific Evidence and Current Debate, 1st ed. Cambridge University Press. https://doi.org/10.1017/9781108621359.