Climate change will increase the potential conflict between skiing and high-elevation bird species in the Alps

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5   **elevation bird species in the Alps**

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21   **ABSTRACT**

22   **Aim** To assess the extent of the possible future conflict between skiing and biodiversity driven by

23   climate change, human adaptation and species' distribution shifts.

24   **Location** Italian Alps.

25   **Methods** We assessed the extent of the possible future conflict between skiing and biodiversity by

26   predicting locations likely to be suitable for both skiing and for high-elevation birds in the Italian

27   Alps by modelling ski-piste and species presence in relation to climate, topography and habitat.

28   Potential conflict was assessed by comparing the overlap of areas projected as suitable for skiing

29   and those suitable for five high-elevation bird species under different scenarios of climate change

30   for the year 2050.

31   **Results** Areas suitable for both ski-pistes and birds were projected to contract towards upper

32   elevations, which for birds resulted in an average decrease of 58% - 67% of suitable area. The

33   degree of overlap between species and skiing was projected to increase, especially for the most

34   valuable sites, i.e. those hosting the most species, or the most threatened species.

35   **Main conclusions** Given the alarming range contractions forecast for high elevation species, and

36   the potential impact of ski-pistes on those species, it is essential to safeguard high mountain

37   grasslands against negative effects of ski development. An effective conservation strategy at a

38   landscape scale needs to consider prevention of ski-piste construction in sites of high conservation

39   value. The approach developed here provides a means by which such a strategy could be

40   formulated, and which could be potentially applied elsewhere to investigate the effect of human

41   adaptation on biodiversity.

42

43   **Keywords:** alpine grassland; bird conservation; global warming; human adaptation; mountain; ski-

44   piste

INTRODUCTION

Climate change induced by anthropogenic emissions of greenhouse gases is among the most severe threats to ecosystems and species at a global level (IPCC, 2013). Indirect impacts arising from human adaptation to new climates (i.e. taking appropriate action to prevent or minimize the adverse effects of climate change) pose imminent and important threats to biodiversity (Bradley *et al.*, 2012; Chapman *et al.*, 2014), and may impair species' ability to cope with climate change (Watson, 2014). However, the impacts driven by human adaptation are rarely considered in the conservation literature (Watson & Segan, 2013; Chapman *et al.*, 2014), although notable exceptions exist (e.g. Bradley *et al.*, 2012; Wetzel *et al.*, 2012). Humans continue to respond to climate change, and such a response is to some degree predictable (Watson, 2014). Therefore, researchers need to focus not only on the direct effect of changing climate, but also on the climate-related variation in human-mediated threats (Turner *et al.*, 2010; Watson, 2013). The latter can have quite immediate and overwhelming impacts, being of equal or greater intensity for species and ecosystems than the direct impacts of climate change (Turner *et al.*, 2010; Watson & Segan, 2013; Chapman *et al.*, 2014).

High-mountain regions harbour a relatively high biodiversity (Dirnböck *et al.*, 2011) and a high percentage of both endemic (Essl *et al.*, 2009) and vulnerable species (Viterbi *et al.*, 2013). Many species are restricted to the upper elevations of their former range because of human pressures (Martin, 2001) and thus careful management of mountains is crucial for conservation (Rolando *et al.*, 2013). Mountain regions are particularly threatened by climate change (Brunetti *et al.*, 2009) and show a higher rate of warming compared to the global average (Böhm *et al.*, 2001). Species and habitats are already undergoing elevational range shifts due to climate warming, which is predicted to have important impacts on biodiversity at high elevation (Sekercioglu *et al.*, 2008; Dirnböck *et al.*, 2011; Chamberlain *et al.*, 2013). However, habitat changes caused by human action may have more severe consequences than climate change (Jetz *et al.*, 2007), or may interact with it,

71   showing synergistic effects (Mantyka-Pringle *et al.*, 2012).

72   Recreational activities, and in particular winter sports, represent one of the main threats to

73   wild species in many mountain regions (e.g. Buckley *et al.*, 2000; Arlettaz *et al.*, 2013). There is

74   increasing evidence of negative effects of skiing activities from a range of taxa (Rixen & Rolando,

75   2013) via habitat destruction/alteration/fragmentation, soil degradation, and ski-related urban

76   development (Rolando *et al.*, 2013). Ski-pistes for downhill skiing in the Alps are associated with

77   both lower bird species richness and bird abundance (Rolando *et al.*, 2007; Caprio *et al.*, 2011;

78   Rolando *et al.*, 2013). The negative effect of ski-pistes is mostly tied to the removal of vegetation

79   and soil (Fig. S1 in Appendix S1); this is not invariably performed on all ski-pistes, but has become

80   the standard practice for modern ski-piste construction (Negro *et al.*, 2013). Altered soil structure,

81   harsh climate and plant species traits together prevent the re-establishment of vegetation, and grass

82   cover for wild species remains extremely low for long periods even with modern restoration

83   techniques such as hydro-seeding (Negro *et al.*, 2013).

84   Skiing activities are likely to be affected by climate change, and in particular by temperature

85   rise and variation in precipitation regimes (Behringer *et al.*, 2000; Uhlmann *et al.*, 2009), and as

86   such they have the potential to cause indirect impacts on biodiversity deriving from human

87   adaptation. Due to decreasing snowfall and/or less reliable snow cover at lower altitudes, the area

88   suitable for skiing is likely to show a range contraction and an upwards altitudinal shift (Elasser &

89   Messerli, 2001; Disch *et al.*, 2007; Scott *et al.*, 2008), as already evident in some alpine areas

90   (Pozzi, 2009; Marty, 2013). Given that a similar pattern of range contraction is likely to occur in the

91   distribution of many mountain species (e.g. Sekercioglu *et al.*, 2008; Chamberlain *et al.*, 2013), this

92   could lead to an increase in the potential conflict between winter sports and wildlife. However, the

93   potential consequences for mountain wildlife of changes in ski developments as a response to

94   climate change have not been fully assessed.

95   We aim to describe the increase in the potential impact of ski-pistes on alpine biodiversity

96   by modelling the potential future distributions of both species and ski-pistes in relation to projected

97   climate changes in the European Alps. Our goal is to highlight where conflicts between downhill

98   skiing and nature conservation are most likely to occur over the next decades, by constructing

99   spatially explicit models of conflict zones between ski-pistes for downhill skiing and wildlife

100   (Braunisch *et al.*, 2011), using high-elevation birds as an example group. We first model the current

101   and future distribution of some high-altitude bird species potentially vulnerable to ski-piste

102   development in relation to climate, habitat and topography. Then, we model the current and future

103   distribution of ski-pistes in relation to climate and topography; finally, we adopt an approach to

104   reduce possible future conflicts by evaluating where they may arise. Among the areas that should be

105   considered as high-priority for the conservation of high-elevation species in a warmer climate, we

106   identify those which are likely to be suitable for ski-pistes in the future, and hence those where ski-

107   developments should be restricted or regulated.

108 **MATERIALS AND METHODS**

109

110 **Study area, fieldwork and model species**

111 The study area comprised a large area of the southern Alps in northern Italy included within the

112 borders defined by the Alpine Convention (Fig. 1). As model species, we selected passerine birds

113 that in the Alps are mostly or exclusively tied to grassland and other open habitats at high elevation,

114 and that could be potentially affected by climate change and by the occurrence of ski-pistes (Tables

115 S1 and S2 in Appendix S1): water pipit *Anthus spinoletta*, alpine accentor *Prunella collaris*,

116 northern wheatear *Oenanthe oenanthe*, black redstart *Phoenicurus ochruros*, and snowfinch

117 *Montifringilla nivalis*. Bird data were collated from different studies that were carried out between

118 2000 and 2015 in all the main sectors of the study region (see Appendix S1).The number of

119 occurrences for each species was: water pipit 658; alpine accentor 235; northern wheatear 443;

120 black redstart 1428; snowfinch 74.

121

122 **Modelling species distributions**

123 Species distributions were modelled using MaxEnt (release 3.3.3k; Phillips *et al.*, 2006), which can

124 deal appropriately with the climate variables potentially relevant for species distribution (Braunisch

125 *et al.*, 2013) and is routinely adopted to analyse species distribution using data collected with

126 different survey methodologies, as here (Appendix S1) or collected by means of unknown field

127 methods (e.g. Engler *et al.*, 2014). All bird data were collected at a spatial resolution ≤100-m.

128 To make distribution models as general and robust as possible, we applied the approach

129 proposed by Radosavljevic & Anderson (2014), adopting a masked geographically structured

130 evaluation of models. We divided our study area into four longitudinal belts (see Fig. S8 in

131 Appendix S2), and used records and background points (10 000) from eastern and central-western

132 portions to build models (training data), and records from western and central-eastern portions to

133 evaluate models (test data).

134   Environmental variables included land cover, bioclimatic and topographical variables (Table

135   S3). Ten land cover types were selected from the CORINE Land Cover (CLC2006; EEA, 2007)

136   database in order to describe the habitat composition of each cell, assuming constant land cover

137   over the time period (up to 2050). Two bioclimatic variables, annual temperature and precipitation,

138   were calculated for each grid cell from the values downloaded from WorldClim v.1.4 (Hijmans *et*

139   *al.*, 2005; http://www.worldclim.org; resolution 30 arc-seconds, corresponding to less than 1-km at

140   this latitude). Slope and solar radiation (calculated taking 21st June as the reference day), were

141   extracted from a Digital Terrain Model (resolution 20 m) of the study area. Before distribution

142   modelling, we checked for multicollinearity among environmental predictors in order to minimize

143   the risk of overfitting species' responses to climate. Variance Inflation Factors (VIFs) were

144   evaluated, and highly collinear variables (VIF > 5) were omitted, following Zuur et al. (2009). This

145   procedure included an evaluation of seasonal, in addition to annual, bioclimatic variables, but the

146   former showed high levels of collinearity, therefore only annual values were used in distribution

147   modelling (see below).

148   All environmental variables were calculated for 40 m x 40 m cells; for each cell, values

149   represented i) the sum of cover (total area) per each type of land cover, ii) the average slope, and iii)

150   the mean solar radiation, all referring to a radius of c. 100 m from each cell. For bioclimatic

151   variables, we assigned to each 40 m x 40 m cell the value of the 30 arc-seconds cell with which it

152   overlapped. Given the raster structure, this resulted in variables measured over an area of slightly

153   more than 2 ha, a grain that matches fairly well with the supposed territory sizes, and hence the

154   main areas of activity, of the species considered (Cramp, 1998; Gustin *et al.*, 2010). To reduce the

155   risk of overfitting, we fitted models considering only linear and quadratic terms (dropping

156   interaction, threshold and hinge functions), irrespective of sample size.

157

158   **A spatial test of the representativeness of the climatic niche defined by the data**

159   Given that we focussed on a portion of the range of our study species, we could potentially

160   overestimate the effect of climate change on those species (Barbet-Massin *et al.*, 2010). To avoid

161   this risk, using our data (all locations per each species) and only climatic factors, we modelled

162   species distribution across a large part of Europe (using tile no. 16 of the wordlclim database as a

163   study area, from southern Scandinavia to north Africa) and compared it with independent estimates

164   of species distributions at larger scales (e.g. Cramp, 1998). Moreover, we compared the distribution

165   predicted for Italy with the distribution data derived from the reporting to the EU under the Birds

166   Directive (Nardelli *et al.*, 2015; data downloaded from

167   http://cdr.eionet.europa.eu/it/eu/art12/envuzmuow/).

168   We compared models obtained using only either annual temperature, or temperature and

169   rainfall, and selected the model better describing the European and Italian distribution for each

170   species (Appendix S1) using visual assessment (in accord with the general approach of Zuur et al.

171   2009). We obtained reliable climate models for all species except northern wheatear, which was

172   excluded from subsequent analyses.

173

174   **Future distribution models**

175   To simulate future conditions under climate warming, we chose two scenarios with different

176   values of representative concentration pathways (RCPs; van Vuuren *et al.*, 2011), with respectively

177   low and high rates of climate change. We selected the RCP values of +4.5 and +8.5 W/m^2

178   (Brambilla *et al.*, 2015), corresponding to an average increase of +1.4 and 2.0˚C respectively in

179   global temperature (IPCC 2013), and of +3.3 and 4°C in our study area, consistent with previously

180   recorded rates of warming in the Alps that are approximately double the global average (Brunetti *et*

181   *al.*, 2009). We downloaded relative bioclimatic variables for 2050, according to the Hadley Global

182   Environment Model 2 (HadGEM2-ES), at a resolution of 30" from www.worldclim.org. Our choice

183   of using 2050 as a future reference was due to the need to measure impacts on a rather short-term

184   timescale, given that human decisions are rarely established on the basis of long-term predictions

185   and assessments, and that the life-cycle of species is usually much shorter than the timescale often

186 considered in studies on the effect of climate change (Chapman *et al.*, 2014).

187   We selected logistic model output to allow for a binary reclassification (into suitable and

188 unsuitable sites) of the continuous estimate of habitat suitability from MaxEnt using recommended

189 thresholds for presence-only models (e.g. Liu *et al.*, 2013; Appendix 2), selected by mapping the

190 predicted occurrences on the basis of the individual thresholds, and comparing them with the

191 current species range (Nardelli *et al.*, 2015). To assess model validity, we considered the respective

192 performance over the test data set. We expected good models to show a substantial stability of the

193 area under the curve (AUC) of the receiver-operator plot between training and test data sets (see

194 above and Appendix S2). In general, very small differences in AUC values suggested model

195 stability, with the partial exception of black redstart (Table S4 in Appendix S2).

196

197 **A model for ski-piste distribution**

198   We used all available information on the location of ski-pistes to identify their current

199 distribution. Then, we manually placed in a GIS environment (by looking at detailed and updated

200 aerial photographs) points over ski-pistes known to be currently in use, each separated by a

201 minimum of 500m and a maximum of 1000m from the next nearest point; this procedure resulted in

202 610 points placed along ski-pistes throughout the entire study area. As we knew both occurrence

203 and true absence sites, we adopted a presence-absence modelling approach. We used multivariate

204 adaptive regression splines (MARS, Milborrow, 2011) in R (R Development Core Team, 2013) to

205 develop a model for ski-piste occurrence (Appendix 2). We compared the 610 points representing

206 ski-pistes with 610 randomly placed points representing areas free from ski-pistes. The latter were

207 placed at 5-10 kilometers from ski-piste points, to simultaneously avoid overlap with ski-areas and

208 ensure that absence points were in mountain areas potentially suitable for ski-pistes, and were

209 outside protected areas to avoid biases due to regulatory instead of morphological/climatic factors.

210 We tested the potential effect of mean slope, mean radiation, annual temperature, annual rainfall,

211 and the relative interactions. Minimum temperature and precipitation of the coldest quarter were

212 also tested, but they were removed because of high VIF values. Variables were calculated using the

213 same environmental layers and resolution adopted for species distribution modelling. The evimp

214 command was used to evaluate relative variable importance (Milborrow, 2011; Jedlikowski *et al.*,

215 2014) and to confirm model validity (Appendix S2). Minimum and maximum suitable areas

216 actually used for ski-pistes varied between 2.7 to almost 30 000 ha (average 2 231 ha ± 3 877 SD).

217 Then, we projected the model over the whole study area both for current and future climatic

218 conditions.

219

220 **Evaluating the risk of potential overlap between birds and ski-pistes**

221 We evaluated the overlap between the area potentially suitable for ski-pistes and variables

222 representing the distribution of target species considering: i) the area potentially suitable for each

223 target species, ii) the area suitable for different numbers of target species (from one to four), iii) the

224 areas suitable for all the species except for snowfinch (the species displaying the most extreme

225 variation), iv) the conservation priority areas for high-elevation passerine birds. For the latter, we

226 identified those areas which would harbour the largest number of species, or the most affected

227 species (snowfinch; see Results).

228 Ski-piste expansion is more likely to occur in the proximity of already existing ski-resorts,

229 because of accessibility and other practical reasons. Therefore, we re-ran the above analyses for

230 each species, limiting areas potentially suitable for ski-pistes to within 5-km of existing ski-pistes

231 (i.e. considering the 610 points mapped to define the current occurrence of ski-pistes; see above).

232 We selected the 5 km buffer as this figure matched the average linear extent of existing ski-resorts

233 (mean 4.75 km ± 3.00 SD, N = 48). In summary, four different scenarios were considered, low and

234 high rates of warming where any climatically and topographically suitable area could be considered

235 for future ski-piste development, and low and high rates of warming where only climatically and

236 topographically suitable areas within close proximity of an existing ski-piste could be considered

237 for future ski development.

RESULTS

Average temperature had consistently high contributions to predicting distributions across species (Appendix S2). Consequently, all species were projected to undergo a more or less marked reduction in potentially suitable areas in the future, ranging from 24% (black redstart, RCP +4.5) to 97% (snowfinch, RCP +8.5) of the current range, with an average decrease across species of 58% - 67% according to the two scenarios, with the scenario of higher rates of warming having the highest impact (Table 1). As expected for species tied to grassland and rocky habitats, a negative effect of forest habitats and/or a positive effect of natural grassland and other open habitats was found in all species (Table S4).

Ski-piste occurrence was associated with annual temperatures below 6-7° (with a peak in occurrence probability at 3.1°), slopes lower than 27-28°, and was affected by the interactions between annual temperature and both slope and mean radiation (Appendix S2): ski-piste occurrence probability was particularly low in areas less favourable to snow accumulation, i.e. the steepest gradients and relatively warmer areas, as well as in areas with high solar radiation. The area potentially suitable for ski-pistes was also projected to decrease from 529 000 ha to 254 000 ha (RCP +4.5) or 196 000 ha (RCP +8.5), thus being more than halved in 2050 compared to current conditions. The potential location of ski-pistes and the distribution of the target species were projected to show a contraction towards upper elevations (Appendix S2).

In addition to the overall contractions in species range, for some species the models also predicted a decrease in the proportion of species distributions unsuitable for ski-piste developments, i.e. the overlap between areas potentially suitable for alpine birds and areas potentially suitable for ski-pistes will increase. This was the case for water pipit, alpine accentor and snowfinch (under the RCP +4.5 scenario), whereas the potential overlap for black redstart was predicted to decrease (Table 1). The areas potentially suitable for all the target species were projected to undergo a large decline (91%-97% according to scenario), and the potential conflict with ski-pistes for these areas

264   to increase, from 66% to 68%-70%. Similar results were found for the areas potentially suitable for

265   three out of four species, with a less dramatic overall decrease (44%-60%) coupled with a greater

266   increase in potential conflict with ski-pistes, from 44% to 61%-64% (Table 2). The pattern of

267   variation in areas suitable for all species combined except snowfinch was similar, although of lower

268   magnitude: a decrease in potentially suitable areas of 56%-70% and an increase in potential overlap

269   with ski-pistes from 60% to 63%-65% were predicted.

270   The procedure for priority area definition identified c. 118000 hectares, dispersed throughout

271   the study area. Of those priority sites, 50% are currently also potentially suitable for ski-pistes; in

272   2050, the proportion of these areas also suitable for ski-pistes will increase to 63%-65% (RCP +4.5

273   and RCP +8.5 respectively).

274   Repeating the analyses for areas within 5 km of existing ski-pistes, the pattern of variation in

275   overlap between areas suitable for a given species (or for a given number of species) and the areas

276   suitable for ski-pistes mirrored the general pattern, although overlap was obviously lower (Tables 3

277   and 4). The potential overlap between priority areas and areas suitable for pistes was projected to

278   increase from 16% to 20%-21%. This projected increase in overlap was found despite a 51%-63%

279   decrease in the areas suitable for pistes (from 172 448 ha to 83 907-63 656 ha) within the adjacent

280   5-km area, i.e. fewer areas adjacent to ski-pistes will be potentially suitable for ski-piste

281   development, but there will still be an increase in the overlap with areas potentially suitable for bird

282   species.

283 **DISCUSSION**

284

285 Future climate change is likely to increase the potential conflict between high elevation bird species

286 and skiing activities. Model outcomes suggested a shrinkage towards higher elevations and a

287 contraction in range for both high-elevation bird distributions and locations suitable for ski-pistes in

288 the Italian Alps by 2050. Moreover, the overlap between areas potentially suitable for high-

289 elevation birds and those for skiing is projected to increase to the extent that most of the area above

290 the treeline could be potentially subject to human-wildlife conflict: 61-70% of the area predicted as

291 potentially suitable in the future for three or four species and two thirds of conservation priority

292 areas will also be potentially suitable for ski-pistes. Limiting potentially suitable areas for ski-pistes

293 to within 5 km of existing ones still suggested an increase in the overlap between areas potentially

294 suitable for three bird species (not black redstart) and areas potentially suitable for ski-pistes.

295 Obviously, the absolute overlap over the whole potential range of each species is much weaker, but

296 importantly, this confirmed that an increase in the potential conflict due to climate change between

297 ski-pistes and high-elevation bird species should be expected in any case.

298 Black redstart makes wide use of urban habitats in addition to open mountain habitats,

299 unlike the other species considered, and is projected to disappear from middle-elevation sites, but to

300 retain a reasonable extent of potentially suitable areas both at high elevations and in urban habitats.

301 However, the other three species are projected to lose a large part of their potential distribution.

302 Some of these species are already declining or contracting their range in Italy (Gustin *et al.*, 2010;

303 Rete Rurale Nazionale & LIPU, 2014; Nardelli *et al.*, 2015), and as a result of such shifts, the status

304 of mountain grassland birds is particularly concerning (Chamberlain *et al*., 2013; Rete Rurale

305 Nazionale & LIPU, 2014). The pattern of range contraction was projected to be quite similar across

306 species (Appendix S2), and it is likely that a similar distributional change may also be relevant to

307 other high-elevation species of open habitats in the future, including birds (e.g. rock ptarmigan

308 *Lagopus muta helvetica*) and other taxa for which high altitude grasslands hold a high diversity

309 and/or species of conservation interest (e.g. flowers, butterflies, carabids, dung beetles - Nagy *et al.*,

310 2003; Tocco *et al.*, 2013). To that extent, our results can be considered to represent threats not just

311 to alpine birds, but to biodiversity of high altitude open habitats in general.

312 A similar pattern of range contraction is predicted for ski-pistes. The ski industry will be

313 affected by climate change (Behringer *et al.*, 2000; Disch *et al.*, 2007; Uhlmann *et al.*, 2009), and

314 our results suggest a potentially marked contraction of the areas suitable for ski-pistes. Notably,

315 given that climatic variables are representative of the period 1950-2000 (Hijmans *et al.*, 2005) and

316 that the ski industry is particularly sensitive to climate variations, the potential distribution

317 modelled on the basis of the 'current' conditions gave a good representation of the distribution of

318 areas suitable for skiing in the second half of the past century. Some of the ski-pistes located in the

319 'marginal' parts of our study area (e.g. in the pre-Alps in Lombardy), in sites predicted by the model

320 to be on the edge of the suitable area and to be less suitable for ski-pistes than those located in the

321 'core' of the Alpine region, have already been decommissioned in recent years, because of the

322 prolonged lack of adequate snow cover, in particular at lower elevations (Pozzi, 2009; Marty, 2013).

323 Future projections suggest that other sites at medium and low elevations will probably be

324 decommissioned (Pozzi, 2009; Marty, 2013), in keeping with our own results. Even if the use of

325 artificial snow (a non-sustainable adaptation; Disch *et al.*, 2007) may to some extent buffer against

326 decreased snow cover, it is likely that ski-pistes will contract towards higher elevations to track the

327 availability of suitable temperatures and snow cover.

328

329 **Model assumptions**

330 We used scenarios derived from a single global climate model to evaluate potential conflicts

331 with ski-pistes. Future species distribution models based on scenarios derived from an alternative

332 global model (MIROC-ESM-CHEM; Watanabe et al. 2011) led to consistent, though less severe,

333 predictions (Appendix 2). Although this general agreement and the fact that the predictions about

334 temperature increase in the Alps are rather consistent across different models (Giorgi & Lionello,

335 2008; in our study area, the correlation between average temperature values according to the

336 scenario RCP +8.5 of the two climate models was 0.98), we cannot exclude some possible minor

337 differences in future predictions according to scenarios taken from other global models. However,

338 we used different scenarios (RCP +4.5 and +8.5 W/m^2) and different assumptions (restricted or

339 unrestricted development of ski-pistes) to provide a range of scenarios, in keeping with our

340 generally conservative approach (see below). It is unlikely that the possible variation from using

341 different circulation models would be greater than that associated with different emission

342 scenarios/RCP values used – whilst there would be some variation, we expect that the general

343 patterns would very likely be the same.

344   In our approach, we assumed constant land cover over the period considered. Significant

345 land cover changes due to climate change at high elevation can require a fairly long time to become

346 discernible due to lagged responses (e.g. Cannone *et al.*, 2007), although there is clearly much

347 geographic variation (e.g. Harsch *et al.*, 2009; Carlson *et al.*, 2014). Nevertheless, we feel our

348 approach is justified in that it gives a conservative estimate of species distribution decrease, as the

349 most likely scenario of climate-induced habitat change is loss of open grassland habitat as treelines

350 continue to shift upslope. Without management intervention, this may cause potentially severe

351 reductions in the area of alpine grasslands, and increased fragmentation of remaining patches, with

352 subsequent negative impacts on grassland species (Chamberlain *et al.*, 2013). At the same time, ski-

353 pistes are not likely to be constrained by habitat changes, as they can be constructed on any habitat

354 that is topographically suitable. A model that considered both altitudinal shifts in the treeline in

355 conjunction with expansion of ski-pistes to higher altitudes would therefore almost certainly result

356 in more severe model outcomes compared to our conservative approach. It is all the more striking

357 then that even under the relatively conservative scenarios adopted here, there are nonetheless some

358 major declines and increased conflicts predicted.

359   We considered only ski-pistes, but their impact extends beyond the piste itself, as the

360 development of a ski-area also includes the development of infrastructure (e.g. roads, hotels,

361   restuarants; Rolando *et al.*, 2013). Off-piste skiing may also be expected to respond to climate

362   changes in the same way, which also has negative consequences for biodiversity (Arlettaz *et al.*,

363   2007). The fact that wider impacts of development of infrastructure and of off-piste skiing were not

364   explicitly included in the approach are further factors which makes the estimates of negative

365   impacts fairly conservative. Our model outcomes can therefore be considered to be relatively

366   optimistic given the underlying assumptions.

367   Regarding the distribution models, the use of a rather coarse land-cover map, the lack of

368   explicit information about model transferability, and the relatively small sample size for snowfinch

369   should lead to some caution when interpreting the model outcomes. First, despite the low resolution

370   of the Corine Land Cover map, the species-habitat relationships we modelled were all coherent with

371   the basic species' ecology, and the reliable output we obtained (e.g. in terms of high AUC values)

372   further confirmed that at the scale considered, the use of such data coupled with climatic data

373   provides valuable insights into species distributions. Second, although we did not explicitly

374   evaluate model transferability across different sub-regions, the general consistency of the

375   discriminatory ability of models across the geographically independent training and testing data

376   (Table S4) suggested an overall validity of the species-environment relationships over the study

377   area. Furthermore, consistency in the species trends along altitudinal gradients in different Alpine

378   regions (unpubl. data) suggests that model transferability is likely to be high. Third, sample size was

379   relatively low for the snowfinch (N = 74) compared to the other species. However, MaxEnt is less

380   sensitive to sample size than other methods (Wisz *et al.*, 2008), and there are several examples in

381   the literature of robust MaxEnt models with much lower sample sizes (e.g. Guisan *et al.*, 2007;

382   Wisz *et al.*, 2008; Brambilla, 2015), and indeed, snowfinch models evaluated by visual assessment

383   and by AUC had good predictive ability. Nevertheless, future insights based on a larger sample may

384   potentially increase model accuracy and hence would be desirable for this scarce high altitude

385   specialist.

386   Future specific work is required to further understand the ultimate mechanisms driving

387   species occurrence. In common with the general climate envelope modelling approach, we

388   implicitly assume that climate, either directly or indirectly (e.g. via resources) is a key determinant

389   of species distributions, although such approaches have limitations on estimating the true niche of a

390   species (Schurr *et al.*, 2012). We can conclude little on the precise mechanisms that may influence

391   species distributions. There is a need for further studies, especially in mountain environments which

392   are relatively poorly studied, to understand mechanisms underpinning apparently climate-limited

393   species distributions and hence to identify potential compensatory or mitigation measures

394   (Chamberlain et al. 2012).

395

396   **Applications**

397   Given the alarming range contractions forecast for high elevation species in general, and the

398   increasing potential impact of ski-pistes on those species, it is essential to develop conservation

399   strategies to safeguard high alpine habitats against negative effects of ski development. There is a

400   need to promote better management of existing ski-pistes to minimise their negative impacts,

401   through grassland restoration and minimization of deleterious management practices (Negro *et al.*,

402   2013; Rixen & Rolando, 2013). However, the priority should be to secure the persistence of

403   climatically and structurally suitable sites for those threatened species, unaltered by development.

404   We identified c. 118 000 hectares that are currently suitable for the most threatened species

405   (snowfinch) and/or for all the other species belonging to the species assemblage (mountain

406   grassland birds), and that will remain suitable in the future, whatever the scenario considered; those

407   areas should be regarded as conservation priorities, where the development of ski infrastructures

408   should be avoided. Unfortunately, the potential pressure on those areas will be high, as two thirds of

409   them will also be suitable for future ski-piste development. The scenarios which considered that

410   potentially suitable areas for ski-pistes will only be in the proximity of existing ski-pistes predicted

411   a consequently lower overlap with areas potentially suitable for high-elevation bird species.

412   However, many areas close to and including existing ski-pistes may not be climatically suitable for

413 adequate snow conditions in the future, hence there is likely to be further pressure to develop new

414 ski resorts far from existing ones.

415   The skiing industry provides economic benefits to local mountain communities which

416 otherwise could have limited economic capacity (Elsasser and Messerli 2001). Adaptation of skiing

417 activities in response to climate change via the construction of pistes in more climatically suitable

418 areas could be therefore desirable for the local economy. Given that there are some areas which are

419 predicted to be potentially suitable for ski-pistes, but which are not within the conservation priority

420 areas, a way to minimize the impact of new developments would be to perform a first selection of

421 areas for new ski-pistes among those sites. Clearly, other factors should then be taken into account

422 (e.g. occurrence of other species or habitats of conservation concern, accessibility, economic

423 feasibility, etc.), but our outputs could provide spatially explicit guidance in avoiding planned

424 development in the most important sites for the conservation of high-elevation biodiversity.

425   A clear conservation strategy is required to preserve suitable conditions in the priority areas

426 for the protection of alpine biodiversity (Fig. 2). The winter tourism industry is already adapting to

427 climate changes, via a range of different measures adopted to offset adverse economic impacts,

428 putting new pressures on mountain environments (Marty, 2013). Consequently, effective

429 conservation strategies, implemented at a landscape scale, need to consider prevention of ski-piste

430 construction in sites characterized by high conservation value. The approach developed here

431 provides a means by which such a strategy could be formulated.

432

433 **ACKNOWLEDGMENTS**

434

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443

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Supporting Information

Additional Supporting Information may be found in the online version of this article:

S.1. Dataset of bird occurrence and selection of target species

S.2. Modelling distribution of ski-piste and bird species

BIOSKETCH

Our research focus is on animal ecology and conservation in high altitude habitats, with particular emphasis on the effects of environmental change and of direct and indirect human impacts on alpine faunal biodiversity.

Author contributions: M.B. and D.E.C. collected part of the field data; P.P. and A.R. managed fieldwork in Trentino and Piemonte, respectively; M.B. took a lead on the analyses; M.B. and D.E.C. wrote a first draft of the paper; all authors contributed to the final version of the paper.

637 **Table 1** Predicted decrease in species range and overlap with cells potentially suitable for ski-pistes

638 in current and future scenarios according to the climates predicted under RCPs of +4.5 and +8.5

639 (general overlap and overlap considering sites potentially suitable for ski-pistes only within 5 km

640 from existing ones).

641

	suitable area (ha*1000)			Distribution change		overlap with areas suitable for ski-pistes			overlap with areas suitable for ski-pistes (< 5 km)		
	current	+4.5	+8.5	+4.5	+8.5	current	+4.5	+8.5	current	+4.5	+8.5
water pipit	617	264	184	-57%	-70%	53%	61%	64%	17%	19%	20%
alpine accentor	615	261	193	-57%	-69%	43%	48%	49%	14%	15%	15%
black redstart	902	685	622	-24%	-31%	47%	31%	26%	16%	10%	9%
snowfinch	318	27	10	-91%	-97%	42%	47%	42%	14%	15%	15%

642 **Table 2** Suitable area for different levels of species richness, and the relative overlap with areas

643 potentially suitable for skiing under current and future conditions (general overlap and overlap

644 considering sites potentially suitable for ski-pistes only within 5 km from existing ones).

645

no. of species	area (ha * 1000)			overlap with ski			overlap with ski (< 5 km)		
	current	+4.5	+8.5	current	+4.5	+8.5	current	+4.5	+8.5
1	431	476	473	24%	13%	11%	9%	5%	4%
2	161	87	68	40%	51%	52%	7%	28%	16%
3	308	171	124	44%	61%	64%	14%	19%	20%
4	193	18	6	66%	70%	68%	23%	23%	25%

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649   **Figure 1** Location of the study area in Italy, defined as the provinces included in the Alpine

650   Convention in Piedmont, Lombardy and Trentino. Extent 40,569 km^2, elevation range 30-4,600 m

651   asl.

652

653

654   **Figure 2** Spatial relationship between conservation priority sites (sites suitable for snowfinch and/or

655   all the other high-elevation species in 2050) and sites suitable for ski-pistes in 2050 (upper: RCP

656   +4.5; lower: RCP: +8.5), on the southern Alps, and in two sample areas (for RCP +4.5), Val

657   d'Ossola (left) and Valtellina (right).