

## Changes in plant species diversity revealed by long-term monitoring on mountain summits in the Dolomites (northern Italy)

Změny druhové diverzity zjištěné dlouhodobým sledováním vegetace horských vrcholů v Dolomitech (severní Itálie)

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Dedicated to the memory of Leoš Klimeš

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Vegetation on mountains is expected to react in a highly sensitive way to climate change and species losses are predicted in the near future. By means of monitoring studies changes in species diversity can be continuously recorded. In this paper the results of a 7-year study in the Southern Alps are reported. As part of the worldwide network GLORIA (The Global Observation Research Initiative in Alpine Environments) four summits, at altitudes ranging from the treeline to the alpine-subnival ecotone (2199, 2463, 2757 and 2893 m a.s.l.) in the Dolomites (northern Italy) were studied. Sites on the four summits were used to determine the effects of climate warming and observe changes in the numbers of species of vascular plants, frequency and composition. It is hypothesized that ‘thermophilization’ is likely to occur over a period of 7 years (i.e. species from lower altitudes are expected to migrate to the summits due to climate warming). It is also hypothesized that nival, alpine-subnival and endemic species might decrease due to competitive displacement by species from lower altitudes. The summit areas were comprehensively sampled (from the highest point down to the 10 m contour line) in 2001, 2006 and 2008. In addition, 4 × 1 m<sup>2</sup> permanent plots located 5 m below the highest summit point on the north, south, east and west sides of each summit were sampled. The results of revisiting the summits indicate that the number of species increased on all four summits, with the greatest gains (15% and 18%) recorded on the two highest summits and moderate gains (4% and 9%) on the two lower summits. Species’ frequencies within the 1 m<sup>2</sup> plots also increased during the 2001–2008 period. A thermophilization trend was demonstrated in which species with distribution centres in the montane or tree line zones were found for the first time on three of the summits. On the lowest summit, the vigorous growth of trees and establishment of new saplings indicate an upward migration of the forest boundary. Species that disappeared from the four summits belonged to species with different altitudinal ranges; however, nival and subnival-alpine species remained. One endemic species, *Potentilla nitida*, disappeared from the highest summit. Further changes and clearer trends are expected in the next decade.

**Key words:** alpine ecosystems, Dolomites, climate change, altitudinal range, GLORIA, migration, species diversity, revisitation

## Introduction

Alpine ecosystems are hotspots of biodiversity and contain a high portion of species from regional and local floras (Körner 2003, Nagy & Grabherr 2009). During the International Year of Biodiversity 2010, scientists and non-governmental organizations worldwide outlined major concerns regarding species losses in high mountains due to climate change. For the relatively pristine summits in the Alps, specific monitoring data have already identified migration trends and range expansions of species due to climate warming (Grabherr et al. 1994, 1995, Bahn & Körner 2003, Pauli et al. 2003, 2007, Walther et al. 2005, Holzinger et al. 2008, Parolo & Rossi 2008, Erschbamer et al. 2009). Considerable losses of endemic plant species on mountains with low altitudes (Grabherr et al. 1995, Pauli et al. 2003), on isolated summits and for certain regions such as Mediterranean mountains are predicted (Rossi & Parolo 2005, Stanisci et al. 2005, Kazakis et al. 2007). Pauli et al. (2007) detected a remarkable reduction in the cover of subnival herbaceous species over a 10-year period due to the vigorous spread of competitive alpine species. Experiments carried out in the Alps reveal that the responses to warming are species-specific, with distinct winners and losers (Erschbamer 2007). However, not only single species, but also entire plant communities are changing with time (Vittoz et al. 2008, Britton et al. 2009). During the 20th century, climate warming caused a significant upward shift in the distribution ranges of species (Lenoir et al. 2008). Such changes are detectable only over long periods of time.

In 2001, GLORIA (The Global Observation Research Initiative in Alpine Environments) was initiated as a landmark project with 18 European high-mountain target regions. Currently, the project integrates 85 target regions on five continents ([www.gloria.ac.at](http://www.gloria.ac.at)). The Dolomites in northern Italy were one of the 18 initially selected European target regions. Four summits along an altitudinal gradient (from the tree line to the subnival ecotone) were selected, according to a standardized protocol (Pauli et al. 2001, 2004). The initial sampling was performed in 2001 and regular resampling is expected every 5–10 years. This paper presents the results of three samples (2001, 2006 and 2008) and compares the changes at large (entire summit areas) and small (1 m<sup>2</sup> permanent plots) scales. The major aims of the study were to outline changes in diversity patterns, migration trends and potential threats to endemic, subnival-alpine and nival species at the tree line ecotone, the lower and upper alpine zone and the subnival ecotone. Most revisitation studies have revealed an increase in the numbers of species on the summits in the European Alps (Hofer et al. 1992, Gottfried et al. 1994, Grabherr et al. 1994, Bahn & Körner 2003, Walther et al. 2005, Holzinger et al. 2008). Therefore, a general increase in species numbers at the selected summits was expected. This study focused on analyzing trends of the species groups occurring at different altitudinal ranges and providing information on species migrations from lower altitudes to the summits (i.e. provide evidence of ‘thermophilization’). In particular, the following hypotheses were addressed: (i) significant changes in species numbers occur at both small and large scales (e.g., at the scale of 1 m<sup>2</sup> permanent plots or at the scale of a summit); (ii) ‘thermophilization’ occurs (i.e. species with altitudinal ranges at or below the tree line appearing at higher altitudes); and (iii) decreases in the abundance of nival, subnival-alpine and endemic species on the four summits, indicating that these species are being competitively displaced by species from lower altitudes.

## Materials and methods

### Study area

Four summits were selected in the western Dolomites (Trentino-South Tyrol region, northern Italy). Three of the summits are in the Latemar group (46°19'–46°23'N, 11°33'–11°37'E) and the highest in the Sella group (46°31'N, 11°37'E). Most of these summits have no official names; therefore they are identified as A (2199 m a.s.l. – treeline ecotone), B (2463 m a.s.l. – lower alpine zone), C (2757 m a.s.l. – upper alpine zone) and D (2893 m a.s.l. – subnival ecotone). The tree line is at about 2100 m a.s.l. in the study area and the upper margin of the montane zone about 1800–1900 m a.s.l. Single trees (*Larix decidua*, *Pinus cembra*) of 2–3 m in height may occur occasionally at 2300 m a.s.l. throughout the study area.

On each summit, soil temperatures were recorded at a depth of 10 cm, 5 m below the highest summit in each compass direction, using TidbiT dataloggers (Onset Computer Corporation, Pocasset, MA, USA).

Geologically, the study area consists of calcareous or dolomitic bedrock (Vardabasso 1930, Leonardi 1967, Bosellini 1998, Erschbamer 2004). Species lists and vegetation types for the selected summits are given in Erschbamer et al. (2003, 2006, 2009).

### Sampling

A standardized protocol (Pauli et al. 2001, 2004) was used for the monitoring. Data were collected and compared at two different scales: (i) the scale of a summit area by recording presence/absence of all species from the highest point down to the 10 m contour line; (ii) the scale of 1 m<sup>2</sup> permanent plots by a cluster of 4 × 1 m<sup>2</sup> plots, one in each compass direction on the 5 m contour line below the highest point (Fig. 1, A: 16 plots, B: 14 plots, C: 15 plots, D: 15 plots; due to steep mountain faces equal sampling of all clusters was not possible, therefore for the higher summits the plot numbers were reduced). The sampling of the 1 m<sup>2</sup> plots consisted of frequency counts using a 1 m<sup>2</sup> frame, divided into 100 subplots. Presence/absence of species was recorded per subplot and total species number per 1 m<sup>2</sup> was obtained by summing species recorded in all the subplots. Data were collected in July and August of 2001, 2006 and 2008.

### Data analyses

Large-scale (species number per summit) and small-scale (species number per 1 m<sup>2</sup>) data and frequencies of species in the 1 m<sup>2</sup> plots were used in the analyses. Altitudinal ranges of the species were specified according to the local floras (Fischer et al. 2005, 2008). The following six ranges were included: (i) ni: species with distribution centres in the nival zone; (ii) sn-al: species restricted to the subnival-alpine zone; (iii) al: species with distribution centres in the alpine zone; (iv) al-tl: species with ranges extending from the tree line to the alpine zone; (v) tl: species with distribution centres at the tree line; and (vi) mo: species with distribution centres in the montane zone.

Each time series of records  $y$  (species numbers per summit or species frequencies per summit) from  $t = 2001, 2006$  and  $2008$  were evaluated by linear regression analysis:

$$y = a + b \cdot t$$

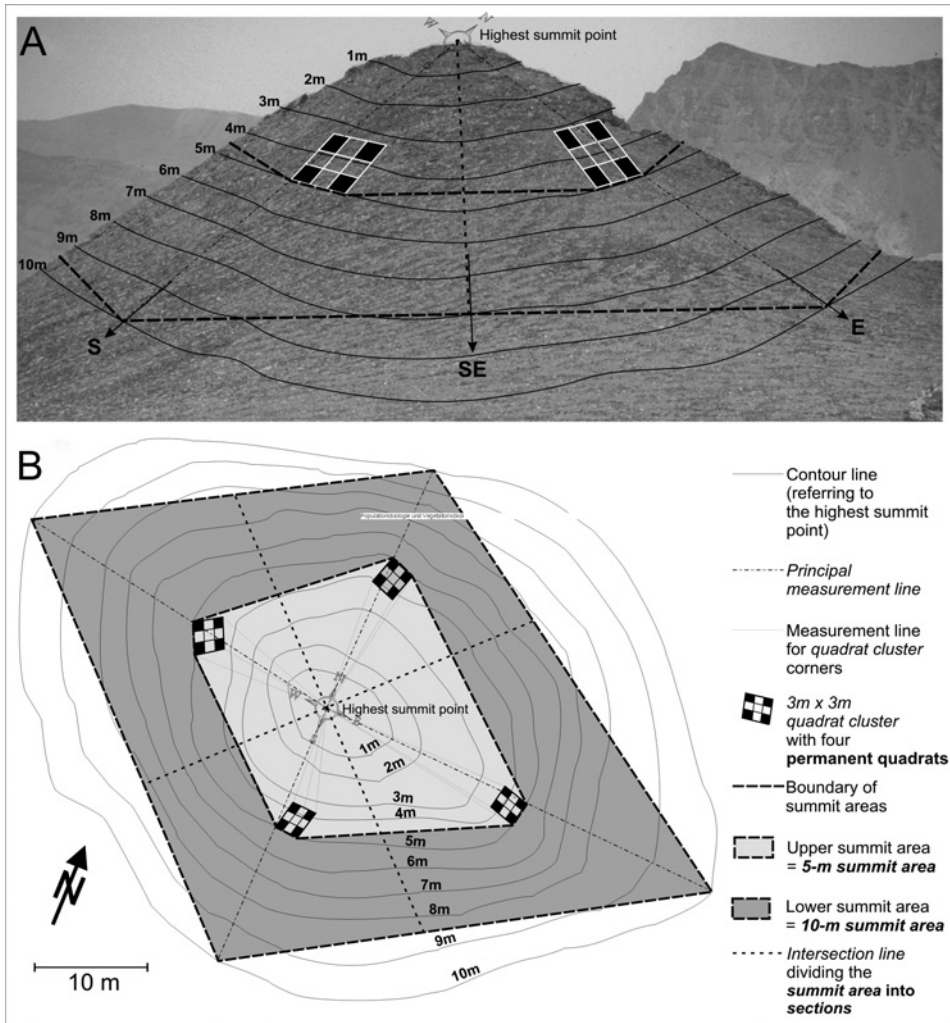


Fig. 1. – Sampling design of the GLORIA method: (A) view of an idealized summit with schematic contour lines 5 and 10 m below the highest summit point; (B) top view of the area sampled (light and dark grey area), showing the  $4 \times 1 \text{ m}^2$  permanent plots (black quadrats), one in each compass direction. Additional explanations can be found in Pauli et al. (2004).

The regression coefficient  $b$  represents changes in number of species or species frequency per year, whereas the ordinate section  $a$  had no meaning in this context. The graphing program SigmaPlot 10.0 was used for the regression analyses and tests of statistical significance of regression coefficients  $b$ . The tables include coefficients  $b$ , coefficients relative to the initial value of  $t = 2001$  ( $b/y_{2001}$ ) and coefficients of determination  $r^2$ . These were checked for statistical significance.

## Results

### *Microclimate*

The yearly mean soil temperatures for 2002–2007 on the northern side of each summit were: A = +1.69 °C; B = +1.19°C; C = -0.31 °C; and D = -0.54 °C. On the southern side the mean temperatures were: A = +4.95°C; B = +2.80°C; C = +1.83°C; and D = +0.14 °C. Daily means are shown in Fig. 2; the length of the growing season (i.e. number of days with a mean daily soil temperature above 2 °C) is given in Table 1. The length of the growing season on the north side was shorter than on the south sides of the summits, amounting up to 2–3 days per year. The trends were remarkably equal on all four summits.

Table 1. – Length of the growing season (number of days with daily means of > 2 °C) on the south and north sides of the four summits (A–D) in the Dolomites, northern Italy, from 2002 to 2007.

Summit	Side	2002	2003	2004	2005	2006	2007
A	south	206	254	187	192	240	223
	north	140	151	152	138	154	154
B	south	161	178		164	184	178
	north	125	146	134	131	147	151
C	south	126	150	122	156	150	144
	north	92	98	92	111	115	100
D	south	87	115	88	94	99	96
	north	74	93	67	82	96	85

### *Changes in numbers of species*

In 2001, the total number of species of vascular plants recorded was 145 on summit A, 78 on B, 74 on C and 33 on D (Fig. 3). The net increase in the number of species from 2001 to 2008 was 4% on A, 9% on B, 15% on C and 18% on D. On the higher summits, there was a clear increase in the number of species (Table 2), which was statistically significant for D and nearly significant for C. On the lower summits (A and B), there were no clear trends in total number of species (Table 2). However, there was a notable turnover of species (Appendix 1).

The number of species at the small scale (1 m<sup>2</sup> plots) also increased, with the exception of those on summit B (Table 3). The variations between plots were very high, with mean annual losses or gains in numbers of species ranging between -0.6 and +1.1 species per plot (Table 3). In total, the frequencies of species in the 1 m<sup>2</sup> plots on all the summits increased, except on summit D; however, the trend was only statistically significant for summit C (Table 4).

### *Changes in species composition*

Although the changes in the altitudinal ranges of the species groups were not significant, some trends were identified (Table 2). On summit A, species newly appeared that are known to have distribution centres in the montane zone, but also alpine-zone species were newly recorded there (Table 2, Fig. 4). Juvenile trees have increased or appeared for the

Table 2. – Trends in the numbers of species on the four summits (A–D) for all species and for altitudinal range groups separately. Given are regression coefficients  $b$  (average change in species number per year)  $b/y_{2001}$  (coefficients  $b$  relative to the initial value  $y$  for  $t = 2001$ ) and coefficients of determination  $r^2$ . The trend was statistically significant only for  $r^2 > 0.99$  (bold numbers). For altitudinal ranges, see Materials and methods.

Summit areas		All species	ni	sn-al	al	tl-al	tl	mo
A	$b$	0.69	–	0	0.15	–0.04	0.31	0.27
	$b/y_{2001}$	0.005		0	0.007	–0.001	0.007	0.012
	$r^2$	0.67			0.92	0.08	0.18	0.94
B	$b$	1.15	0	0.31	0.38	0.35	0.35	–0.23
	$b/y_{2001}$	0.015	0	0.04	0.015	0.014	0.023	–0.077
	$r^2$	0.48		0.92	0.48	0.67	0.67	0.52
C	$b$	1.5	0	0.12	0.31	0.35	0.69	0.04
	$b/y_{2001}$	0.02	0	0.01	0.011	0.017	0.077	
	$r^2$	0.96		0.52	0.28	0.67	0.67	0.06
D	$b$	<b>0.85</b>	0	0.31	0.54	0	0	–
	$b/y_{2001}$	<b>0.03</b>	0	0.04	0.034	0	0	
	$r^2$	<b>0.99</b>		0.92	0.94			

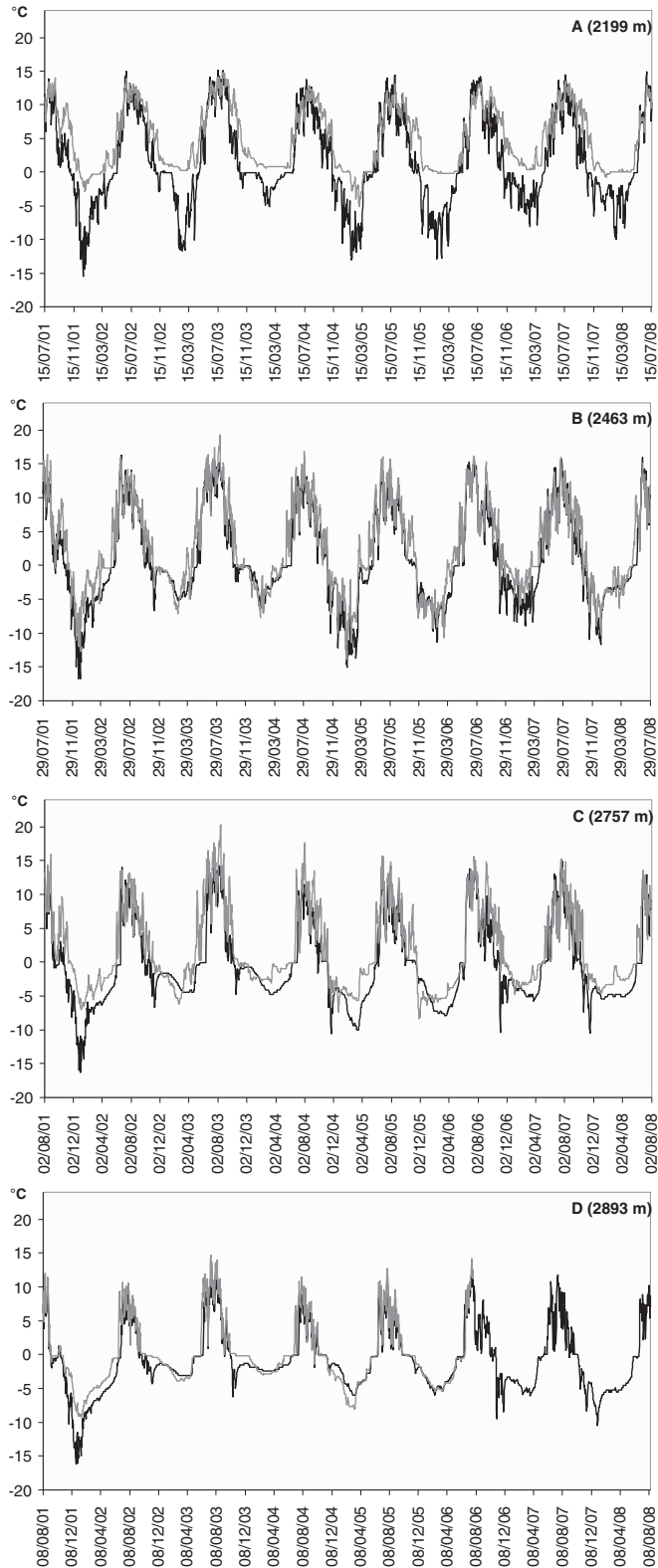
Table 3. – Changes in the numbers of species in the 1 m<sup>2</sup> plots from 2001–2008 on the four summits (A–D). Means, minima and maxima for the whole period, and minima, maxima per year are shown.

Summit	Mean	Minima	Maxima	Yearly min	Yearly max
A	0.4	–4	6	–0.57	0.86
B	–1.2	–4	2	–0.57	0.29
C	0.8	–4	8	–0.57	1.14
D	1.3	0	3	0	0.43

Table 4. – Trends in species frequencies on the four summits (A–D) for all species and for altitudinal range groups separately. Given are regression coefficients  $b$  (average change in species number per year)  $b/y_{2001}$  (coefficients  $b$  relative to the initial value  $y$  for  $t = 2001$ ), and coefficients of determination  $r^2$ . The trend was statistically significant only for  $r^2 > 0.99$  (bold numbers). For altitudinal ranges, see Materials and methods.

Summit areas		All species	ni	sn-al	al	al-tl	tl	mo
A	$b$	31.4	–	<b>1.7</b>	2.9	8.3	<b>11.3</b>	11.5
	$b/y_{2001}$	0.12		<b>0.01</b>	0.006	0.007	<b>0.022</b>	0.043
	$r^2$	0.89		0.99	0.87	0.57	<b>0.99</b>	0.94
B	$b$	2.69	–	–3.1	1.8	2.5	1.5	–
	$b/y_{2001}$	0.003		–0.058	0.003	0.009	0.19	
	$r^2$	0.08		0.87	0.18	0.31	0.82	
C	$b$	<b>8.8</b>	–1.2	1.6	6.4	1.3	0.77	–
	$b/y_{2001}$	<b>0.013</b>	–0.016	0.011	0.022	0.009	0.096	
	$r^2$	<b>0.99</b>	0.6	0.25	0.89	0.82	0.92	
D	$b$	–5.3	0.26	0.68	2.4	<b>–8.6</b>	–	–
	$b/y_{2001}$	–0.011	0.004	0.14	0.009	<b>–0.059</b>		
	$r^2$	0.86	0.11	0.93	0.94	<b>0.99</b>		

Fig. 2. – Soil temperatures recorded on the four summits (A–D) in the Dolomites (northern Italy). Black line – daily means on the north side, grey line – daily means on the south side. For summit D, data for the south side are missing from 2006 to 2008 due to problems with the data logger. ►



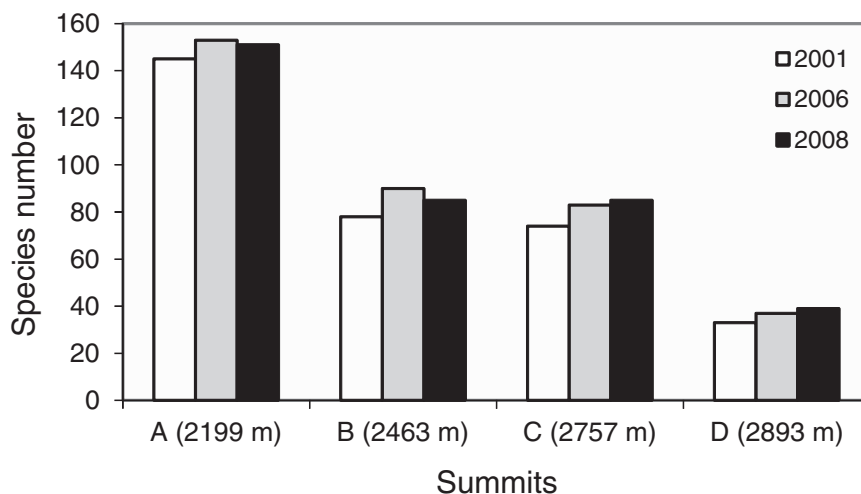


Fig. 3. – Total number of species of vascular plants recorded in 2001, 2006 and 2008 on the four summits (A–D) in the Dolomites (northern Italy).

Table 5. – Numbers of young trees on summits (A–D) in 2001, 2006 and 2008.

Summit	Species	2001	2006	2008
A	<i>Larix decidua</i>	0	3	5
	<i>Picea abies</i>	1	2	3
	<i>Pinus cembra</i>	3	5	9
	<i>Sorbus aucuparia</i>	0	0	1
B	<i>Larix decidua</i>	0	1	3
C	<i>Larix decidua</i>	0	1	2
D	no tree species			

first time mainly on summit A (Table 5). On summits B and C, around 40% of the new arrivals are tree line species and those with distribution ranges from the tree line to the alpine zone. On both summits, young saplings of *Larix decidua* were found in 2006 and 2008 (Table 5). On summit D, almost all the newcomers were species from the alpine or subnival-alpine species pool (Table 2, Fig. 4).

Significant increases in frequencies within the 1 m<sup>2</sup> plots were found on summit A for tree line and subnival-alpine species (Table 4). No significant trend was found in these frequencies on summits B and C. On summit D, species of the group with the highest altitudinal ranges (alpine, subnival-alpine) increased in frequency (although not significantly), and tree line-alpine species significantly decreased in frequency (Table 4).

None of the subnival-alpine or nival species became extinct during the observation period (Fig. 4). One southern alpine endemic species was lost on the highest summit (*Potentilla nitida*, Appendix 1).



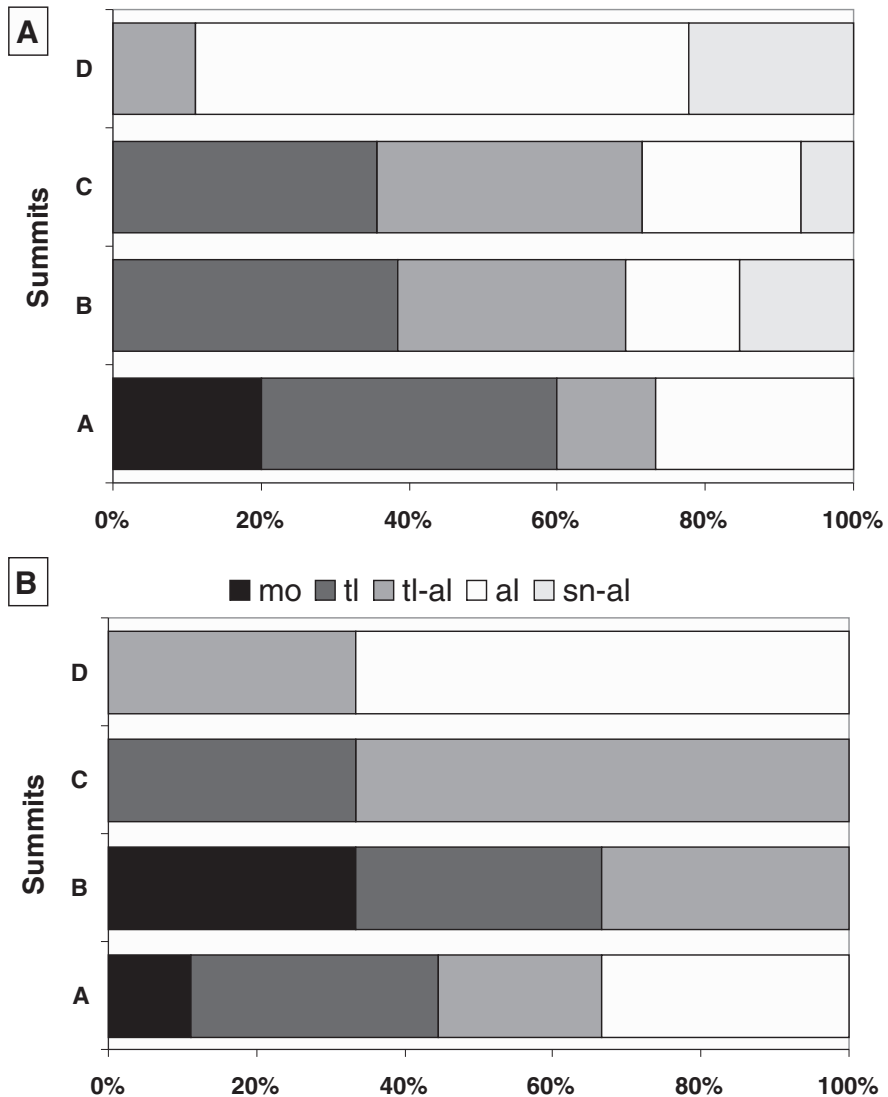


Fig. 4. – Species altitudinal ranges of new (A) and lost species (B) on the four summits (A–D): mo – montane, tl – tree line, tl-al – tree line-alpine, al – alpine, sn-al – subnival-alpine. Total number of new species in 2008: A – 15; B – 13; C – 14; D – 9; total number of species lost: A – 9; B – 6; C – 3; D – 3 (for species composition see Appendix 1).

## Discussion

Short-term studies cannot resolve the uncertainty of whether recorded signals are only fluctuations or consistent trends towards serious changes in numbers of species and composition. The increases in the numbers of species of vascular plants at the summit-area scale, presented here as part of the GLORIA project, accord with the long-term observations of species enrichment in the Alps (Grabherr et al. 1994, Walther et al. 2005, Pauli et

al. 2007 and review therein; Holzinger et al. 2008, Parolo & Rossi 2008, Erschbamer et al. 2009, Grabherr et al. 2010). On all summits, the number of species that have arrived recently was greater than the number of species lost. Holzinger et al. (2008) point out that species should more readily colonize sparsely vegetated high summits than those with closed grassland vegetation. Erschbamer et al. (2009) hypothesize that facilitative effects might play a prominent role in species establishment on the highest summits. In general, facilitation should increase with altitude (Choler et al. 2001, Callaway et al. 2002); however, the results of Dullinger et al. (2007) analyses of the Europe-wide GLORIA data set do not support this hypothesis.

The increases in species richness at the small scale (i.e. the 1 m<sup>2</sup> plots), also accord with the results of other studies, such as those at the GLORIA master-site Schrankogel (Central Alps, Austria; Pauli et al. 2007). There, species numbers increased by an average of 0.14 species per m<sup>2</sup> per year. This value corresponds to the yearly mean of species increase on summit C and D in this study (0.15 species per m<sup>2</sup> per year). The increase in frequency recorded in this study is comparable with that recorded on certain summits of the Central Alps, such as Piz Linard, where Pauli et al. (1996, 2003) report a significant increase in the number of populations already present in 1947 (although species numbers did not increase). The high risk of erosion on that summit is thought to be responsible for the stagnation of species richness there (Pauli et al. 1996).

Climate change scenarios for alpine species predict an increase in plant height and biomass production by 77% and 45%, respectively, due to the increase in the length of the growing season (Rammig et al. 2010). The increase in species occurrence on the summits studied may also be related to the continuously increasing length of the growing season. Because responses of species to warming are individualistic (Stenström et al. 1997, Arft et al. 1999, Molau 2001, Erschbamer 2007, Schöb et al. 2009) it remains to be seen how species composition and dominances may change. These changes will certainly depend on the growth and competitive abilities of the species involved. Thus, determining frequencies, at least every decade is an ideal tool for assessing long term changes.

A ‘thermophilization’ trend is demonstrated with species from lower altitudes, such as *Larix decidua*, *Sorbus aucuparia*, *Hieracium murorum* and *Alchemilla vulgaris* agg., found for the first time on the summits. However, only summits in the tree line ecotone to the upper alpine zone (A–C) had species characteristic of lower altitudes. In the tree line ecotone, the newly appearing tree species and the vigorous growth of *Larix decidua*, *Pinus cembra* and *Picea abies* may be regarded as signs of the upward migration of the tree line. Similar responses of forest vegetation are reported from other countries (Grace et al. 2002, Kullmann 2002, 2007, Kapralov et al. 2006, Gehrig-Fasel et al. 2007, Vittoz et al. 2008, Kharuk et al. 2009, 2010, Kullmann & Öberg 2009) or revealed by comparing old and recent photographs (Moiseev & Shiyatov 2003) or simulated by different climate change scenarios (Thuiller et al. 2005, Dirnböck et al. 2011). Most of the evidence for upward shifts of plant species was recorded during the last decades of the 20th century (Walther et al. 2005, Lenoir et al. 2008). Altitudinal ranges shift on average by 29 m per decade (Lenoir et al. 2008) and, interestingly, the average distance moved by forest plants was more or less the same as that by alpine plants. Individual trees must survive at these altitudes for the next few decades; thus, it is difficult to make definitive statements about tree migration at this time. The critical growing season temperatures for tree growth, i.e. mean soil temperatures at a depth of 10 cm of around 6 °C (Körner 2003, Körner & Hoch 2006)

were recorded on both sides of summit A and B in the growing seasons 2002–2005 (1 June to 30 September); on summit C only on the south side. On summit D (2893 m a.s.l.) the length of the growing season was considerably shorter than on the lower summits, mean temperatures of about 6° C being recorded in only two months (July–August) on the eastern and southern sides.

Little is known about the upper altitudinal limits of montane herbaceous species and transplantation experiments are urgently needed. From transplantations in the western Himalayas it is known that herbaceous species are limited by ‘physiological constraints’ (Klimeš & Doležal 2010) and not by topographical circumstances. On the highest summit (2893 m), all new species were from the subnival-alpine species pool. Colonization of the sparsely vegetated summit was associated with the increasing length of the growing season. According to climate change scenarios, nival species react differently to microclimatic changes compared to species with alpine altitudinal ranges. Gottfried et al. (2002) show that nival and alpine species have different niches in terms of mean night time temperature and snow cover, the former being restricted to a lower temperature regime and long-lasting snow cover. Until 2008, no general trends were observed for species with narrow altitudinal ranges (nival or subnival-alpine species). Nival species occurred on the summits B, C and D. Their number did not change until 2008, and their frequencies showed only minor shifts (on summit C and D). The observation period of 7 years was probably too short to reveal significant changes. For reliable results at least 10 years of observation (Pauli et al. 2007) or possibly longer (Britton et al. 2009) are needed.

The summit in the lower alpine zone (B) had an exceptionally high turnover of species and a remarkable number of species disappeared from the 1 m<sup>2</sup> plots. Dry summer conditions (especially in 2003) and/or the labile scree substrate may be possible causes. The lost species on this summit belong to species groups with montane-tree line and alpine altitudinal ranges. This also holds for the lowest summit, in the tree line ecotone (A). On the two highest summits, only a few species were lost; on summit C most of them had a broad altitudinal range. On summit D, one of the endemic species (*Potentilla nitida*), together with two other alpine species, were lost. According to Theurillat (1995) endemics with wide distributions (such as *Potentilla nitida*; Erschbamer et al. 2009) are expected to be less endangered, whereas local endemics restricted to a few summits or only one mountain range are regarded as highly threatened (Gottfried et al. 1994, Grabherr et al. 1994, 1995, Guisan et al. 1995, Dirnböck et al. 2003, Pauli et al. 2003, Kazakis et al. 2007, Essl et al. 2009).

The trends revealed in our study, i.e. increasing species numbers and ‘thermophilization’, are expected to continue with climate warming. After 7 years, one endemic species became extinct, and revisiting sites every 10 years will reveal whether more nival, subnival-alpine and endemic species face extinction. In terms of future research, transplantation experiments of montane species to higher altitudes should be performed to test their adaptive potential.

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## Souhrn

Hory jsou považovány za velmi citlivé k působení klimatických změn a předpokládá se, že v blízké budoucnosti by se měla jejich druhová bohatost snižovat. Změny v druhové bohatosti lze vhodně studovat opakovaným monitoringem. V předkládané studii představujeme výsledky sedmiletého sledování těchto trendů v Jižních Alpách. Pro monitoring byly vybrány čtyři vrcholy v Dolomitech (severní Itálie) zasahující od hranice lesa do alpínsko-subnivální zóny (v nadmořských výškách 2199, 2463, 2757 a 2893 m); projekt je součástí celosvětové monitorovací sítě GLORIA (The Global Observation Research Initiative in Alpine Environments). Vrcholy byly využity jako studijní místa pro zaznamenání vlivu oteplování klimatu a pozorování změn v počtu druhů cévnatých rostlin, jejich frekvence a druhového složení. Testovali jsme následující hypotézy: během sedmi let sledování se projeví oteplování klimatu a druhy nižších poloh se rozšíří do vyšších nadmořských výšek; nivální, alpínsko-subnivální a endemické druhy se stanou vzácnějšími díky druhům expandujícím z nižších nadmořských výšek. Sběr dat proběhl na vrcholech studovaných hor (od nejvyššího bodu po linii vzdálenou 10 metrů) v letech 2001, 2006 a 2008. Navíc byly ve směru hlavních světových stran založeny trvalé plochy  $4 \times 1 \text{ m}^2$  ve vzdálenosti 5 m od vrcholu. Výsledky opakovaného sledování ukazují zvýšený počet druhů na všech čtyřech vrcholech s největším nárůstem na nejvyšších vrcholech (15% a 18%) a s menšími nárůsty na nižších vrcholech (4% a 9%). Frekvence druhů na plochách  $1 \text{ m}^2$  se v období 2001–2008 také zvýšily. Skutečně jsme tedy ve studovaném období našli příznaky oteplování klimatu, některé druhy s centrem rozšíření v montánním stupni nebo v oblasti hranice lesa byly na třech vrcholech nalezeny poprvé. Bujný růst dřevin a uchycení nových jedinců stromovitých druhů na nejnižším vrcholu může být také považováno za zvyšování úrovně horní hranice lesa. Druhy, které za sledované období na čtyřech alpínských vrcholech zmizely, náležejí mezi rostliny preferující různé nadmořské výšky; rostliny z niválního a alpínsko-subniválního stupně neustoupily ani co do počtu druhů ani pokud jde o frekvenci. Jeden endemický druh, *Potentilla nitida*, zmizel z nejvyššího vrcholu. Další změny a jasnější trendy můžeme očekávat v příštích desetiletích.

## References

- Arft A. M., Walker M. D., Gurevitch J., Alatalo J. M., Bret-Harte M. S., Dale M., Diemer M., Gugerli F., Henry G. H. R., Jones M. H., Hollister R. D., Jónsdóttir I. S., Laine K., Lévesque E., Marion G. M., Molau U., Mølgård P., Nordenhäll U., Raszhivin V., Robinson C. H., Starr G., Stenström A., Stenström M., Totland O., Turner P. L., Walker L. J., Webber P. J., Welker J. M. & Wookey P. A. (1999): Responses of tundra plants to experimental warming: meta-analysis of the International Tundra Experiment. – *Ecol. Monogr.* 69: 491–511.
- Bahn M. & Körner C. (2003): Recent increases in summit flora caused by warming in the Alps. – In: Nagy L., Grabherr G., Körner C. & Thompson D. B. A. (eds), *Alpine biodiversity in Europe*, p. 437–441, Springer, Berlin.
- Bosellini A. (1998): *Geologie der Dolomiten*. – Verlagsanstalt Athesia, Bozen.
- Britton A. J., Beale C. M., Towers W. & Hewison R. L. (2009): Biodiversity gains and losses: evidence for homogenisation of Scottish alpine vegetation. – *Biol. Cons.* 142: 1728–1739.
- Callaway R. M., Brooker R. W., Choler P., Kikvidze Z., Lortie C. J., Michalet R., Paolini L., Pugnaire F. I., Newingham B., Aschoug E. T., Armas C., Kikodze D. & Cook B. J. (2002): Positive interactions among alpine plants increase with stress. – *Nature* 417: 844–848.
- Choler P., Michalet R. & Callaway R. M. (2001): Facilitation and competition on gradients in alpine plant communities. – *Ecology* 82: 3295–3308.
- Dirnböck T., Dullinger S. & Grabherr G. (2003): A regional impact assessment of climate change and land-use change on alpine vegetation. – *J. Biogeogr.* 30: 401–417.
- Dirnböck T., Essl F. & Rabitsch W. (2011): Disproportional risk for habitat loss of high-altitude endemic species under climate change. – *Glob. Change Biol.* 17: 990–996.
- Dullinger S., Kleinbauer I., Pauli H., Gottfried M., Brooker R., Nagy L., Theurillat J. P., Holten J. I., Abdaladze O., Benito J. L., Borel J. L., Coldea G., Ghosn D., Kanka R., Merzouki A., Klettner C., Moiseev P., Molau U., Reiter K., Rossi G., Stanisci A., Tomaselli M., Unterluggauer P., Vittoz P. & Grabherr G. (2007): Weak and variable relationships between environmental severity and small-scale co-occurrence in alpine plant communities. – *J. Ecol.* 95: 1284–1295.

- Erschbamer B. (2004): Dolomiten. – In: Burga C. A., Klötzli F. & Grabherr G. (eds), Gebirge der Erde. Landschaft, Klima, Pflanzenwelt, p. 84–92, Ulmer, Stuttgart.
- Erschbamer B. (2007): Winners and loser of climate change in a central alpine glacier foreland. – *Arct. Antarct. Alp. Res.* 39: 237–244.
- Erschbamer B., Kiebacher T., Mallaun M. & Unterluggauer P. (2009): Short-term signals of climate change along an altitudinal gradient in the South Alps. – *Plant Ecol.* 202: 79–89.
- Erschbamer B., Mallaun M. & Unterluggauer P. (2003): Die Dolomiten: hot spots der Artenvielfalt. – *Gredleriana* 3: 361–376.
- Erschbamer B., Mallaun M. & Unterluggauer P. (2006): Plant diversity along altitudinal gradients in the Southern and Central Alps of South Tyrol and Trentino (Italy). – *Gredleriana* 6: 1–22.
- Essl F., Staudinger M., Stöhr O., Schratt-Ehrendorfer L., Rabitsch W. & Niklfeld H. (2009): Distribution patterns, range size and niche breadth of Austrian endemic plants. – *Biol. Cons.* 142: 2547–2558.
- Fischer M. A., Adler W. & Oswald K. (2005): Exkursionsflora für Österreich, Liechtenstein und Südtirol. – Land Oberösterreich, OÖ Landesmuseen, Linz.
- Fischer M. A., Oswald K. & Adler W. (2008): Exkursionsflora für Österreich, Liechtenstein und Südtirol. – Biologiezentrum der Oberösterr. Landesmuseen, Linz.
- Gehrig-Fasel J., Guisan A. & Zimmermann N. E. (2007): Tree line shifts in the Swiss Alps: climate change or land abandonment? – *J. Veg. Sci.* 18: 571–582.
- Gottfried M., Pauli H. & Grabherr G. (1994): Die Alpen im „Treibhaus“: Nachweise für das erwärmungsbedingte Höhersteigen der alpinen und nivalen Vegetation. – *Jahrb. Ver. Schutz Bergw.* 59: 13–27.
- Gottfried M., Pauli H., Reiter K. & Grabherr G. (2002): Potential effects of climate change on alpine and nival plants in the Alps. – In: Körner C. & Spehn E. M. (eds), *Mountain biodiversity: a global assessment*, p. 213–223, Parthenon Publishing, London, New York.
- Grabherr G., Gottfried M., Gruber A. & Pauli H. (1995): Patterns and current changes in alpine plant diversity. – In: Chapin III F. S. & Körner C. (eds), *Arctic and alpine biodiversity: patterns, causes and ecosystem consequences*, p. 167–181, Springer, Berlin.
- Grabherr G., Gottfried M. & Pauli H. (1994): Climate effects on mountain plants. – *Nature* 369: 448.
- Grabherr G., Gottfried M. & Pauli H. (2010): Climate change impacts in alpine environments. – *Geography Compass* 4: 1133–1153.
- Grace J., Berninger F. & Nagy L. (2002): Impacts of climate change on the tree line. – *Ann. Bot.* 90: 537–544.
- Guisan A., Holten J. I., Spichiger R. & Tessier L. (1995): Potential ecological impacts of climate change in the Alps and Fennoscandian Mountains. – *Imprimerie Nationale, Genève*.
- Hofer H. R. (1992): Veränderungen in der Vegetation von 14 Gipfeln des Berninagebietes zwischen 1905 und 1985. – *Ber. Geobot. Inst. ETH, Stift. Rübel.* 58: 39–54.
- Holzinger B., Hülber K., Camenisch M. & Grabherr G. (2008): Changes in plant species richness over the last century in the eastern Swiss Alps: elevational gradient, bedrock effects and migration rates. – *Plant Ecol.* 195: 179–196.
- Kapralov D. S., Shiyatov S. G., Moiseev P. A. & Fomin V. V. (2006): Changes in the composition, structure, and altitudinal distribution of low forests at the upper limit of their growth in the northern Ural Mountains. – *Russ. J. Ecol.* 6: 367–372.
- Kazakis G., Ghosn D., Vogiatzakis I. N. & Papanastasis V. P. (2007): Vascular plant diversity and climate change in the alpine zone of the Lefka Ori, Crete. – *Plant Cons. Biodiv.* 16: 1603–1615.
- Kharuk V. I., Ranson K. J., Im S. T. & Dvinskaya M. L. (2009): Response of *Pinus sibirica* and *Larix sibirica* to climate change in southern Siberian alpine forest-tundra ecotone. – *Scand. J. For. Res.* 24: 130–139.
- Kharuk V. I., Ranson K. J., Im S. T. & Vdovin A. S. (2010): Spatial distribution and temporal dynamics of high-elevation forest stands in southern Siberia. – *Glob. Ecol. Biogeogr.* 19: 822–830.
- Klimeš L. & Doležal J. (2010): An experimental assessment of the upper elevational limit of flowering plants in the western Himalayas. – *Ecography* 33: 590–596.
- Körner C. (2003): *Alpine plant life. Functional plant ecology of high mountain ecosystems*. – Springer, Berlin.
- Körner C. & Hoch G. (2006): A test of treeline theory on a montane permafrost island. – *Arct. Antarct. Alp. Res.* 38: 113–119.
- Kullman L. (2002): Rapid recent range-margin rise of tree and shrub species in the Swedish Scandes. – *J. Ecol.* 90: 68–77.
- Kullman L. (2007): Tree line population monitoring of *Pinus sylvestris* in the Swedish Scandes, 1973–2005: implications for tree line theory and climate change ecology. – *J. Ecol.* 95: 41–52.
- Kullman L. & Öberg L. (2009): Post-Little Ice Age tree line rise and climate warming in the Swedish Scandes: a landscape ecological perspective. – *J. Ecol.* 97: 415–429.

- Lenoir J., Gégout J. C., Marquet P. A., de Ruffray P. & Brisse H. (2008): A significant upward shift in plant species optimum elevation during the 20th century. – *Science* 320: 1768–1771.
- Leonardi P. (1967): Le Dolomiti. Geologia dei monti tra Isarco e Piave. Vol. 1–3 [The Dolomites. Geology of the mountains between Isarco and Piave. Vol. 1–3]. – Giunta Provinciale, Trento.
- Moiseev P. A. & Shiyatov S. G. (2003): Vegetation dynamics at the treeline ecotone in the Ural highlands, Russia. – In: Nagy L., Grabherr G., Körner C. & Thompson D. B. A. (eds), *Alpine biodiversity in Europe*, p. 423–435, Ecological Studies 167, Springer, Berlin.
- Molau U. (2001): Tundra plant responses to experimental and natural temperature changes. – *Mem. Nat. Inst. Pol. Res.* 54: 445–466.
- Nagy L. & Grabherr G. (2009): *The biology of alpine habitats*. – Oxford Univ. Press, Oxford.
- Parolo G. & Rossi G. (2008): Upward migration of vascular plants following a climate warming trend in the Alps. – *Basic Appl. Ecol.* 9: 100–107.
- Pauli H., Gottfried M., Dirnböck T., Dullinger S. & Grabherr G. (2003): Assessing the long-term dynamics of endemic plants at summit habitats. – In: Nagy L., Grabherr G., Körner C. & Thompson D. B. A. (eds), *Alpine biodiversity in Europe*, p. 195–207, Springer, Berlin.
- Pauli H., Gottfried M. & Grabherr G. (1996): Effects of climate change on mountain ecosystems: upward shifting of alpine plants. – *World Res. Rev.* 8: 382–390.
- Pauli H., Gottfried M., Hohenwallner D., Hülber K., Reiter K. & Grabherr G. (2001): GLORIA: the multi-summit approach. – Field Manual, 2nd draft version, Institute of Ecology and Conservation Biology, Univ. Vienna.
- Pauli H., Gottfried M., Hohenwallner D., Reiter K., Casale R. & Grabherr G. (2004): The GLORIA field manual: multi-summit approach. – European Commission DG Research, EUR 21213, Office for Official Publications of the European Communities, European Commission, Luxembourg.
- Pauli H., Gottfried M., Reiter K., Klettner C. & Grabherr G. (2007): Signals of range expansions and contractions of vascular plants in the high Alps: observations (1994–2004) at the GLORIA master site Schrankogel, Tyrol, Austria. – *Glob. Change Biol.* 13: 147–156.
- Rammig A., Jonas T., Zimmermann N. E. & Rixen C. (2010): Changes in alpine plant growth under future climate conditions. – *Biogeosciences* 7: 2013–2024.
- Rossi G. & Parolo G. (2005): Gli effetti dei cambiamenti climatici sulle specie vascolari degli ambienti di alta quota: i casi-studio di Alpi Retiche e dell'Appennino settentrionale [The effects of climate change on vascular plant species in high altitude environments: case studies from the Retic Alps and the Northern Apennin]. – *Inform. Bot. Ital.* 37: 238–239.
- Schöb C., Kammer P. M., Choler P. & Veit H. (2009): Small-scale plant species distribution in snowbeds and its sensitivity to climate change. – *Plant Ecol.* 200: 91–104.
- Stanisci A., Pelino G. & Blasi C. (2005): Vascular plant diversity and climate change in the alpine belt of the central Apennines (Italy). – *Biodiv. Cons.* 14: 1301–1318.
- Stenström M., Gugerli F. & Henry G. H. R. (1997): Response of *Saxifraga oppositifolia* L. to simulated climate change at three contrasting latitudes. – *Glob. Change Biol.* 3: 44–54.
- Theurillat J.-P. (1995): Climate change and the alpine flora: some perspectives. – In: Guisan A., Holten J. I., Spichiger R. & Tessier L. (eds), *Potential ecological impacts of climate change in the Alps and Fennoscandian Mountains*, p. 121–127, Conservatoire Jardin Botanique, Genève.
- Thuiller W., Lavorel S., Araujo M. B., Sykes M. T. & Prentice I. C. (2005): Climate change threats to plant diversity in Europe. – *Proc. Natl. Acad. Sci. USA* 102: 8245–8250.
- Vardabasso S. (1930): Carta geologica del territorio eruttivo di Predazzo e Monzoni nelle Dolomiti di Fiemme e Fassa. 1:25,000 [Geologic map of the eruptive areas of Predazzo and Monzoni in the Dolomites of Fiemme and Fassa. 1:25,000]. – Ministero dei Lavori Pubblici, Padova.
- Vittoz P., Rulence B., Largey T. & Freléchoux F. (2008): Effects of climate change and land-use change on the establishment and growth of Cembran Pine (*Pinus cembra* L.) over the altitudinal treeline ecotone in the Central Swiss Alps. – *Arctic Antarct. Alp. Res.* 40: 225–232.
- Walther G.-R., Beißner S. & Burga C. A. (2005): Trends in the upward shift of alpine plants. – *J. Veg. Sci.* 16: 542–548.

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Appendix 1. – Newly recorded species and those that disappeared during the period 2001–2008 from the four summits studied (A–D) in the Dolomites, northern Italy. Nomenclature follows Flora Europaea (<http://rbg-web2.rbge.org.uk/FE/fe.html>).

Summit	New species	Species that disappeared
A	<i>Carex mucronata</i> <i>Deschampsia flexuosa</i> <i>Erigeron glabratus</i> <i>Euphrasia salisburgensis</i> <i>Gentiana brachyphylla</i> subsp. <i>brachyphylla</i> <i>Gentiana clusii</i> <i>Gymnadenia odoratissima</i> <i>Helianthemum nummularium</i> subsp. <i>grandiflorum</i> <i>Larix decidua</i> <i>Luzula sylvatica</i> <i>Minuartia verna</i> subsp. <i>verna</i> <i>Poa minor</i> <i>Sorbus aucuparia</i> <i>Thalictrum aquilegiifolium</i> <i>Trifolium alpinum</i>	<i>Aster alpinus</i> <i>Cystopteris fragilis</i> <i>Doronicum clusii</i> subsp. <i>clusii</i> <i>Hieracium lactucella</i> <i>Hippocrepis comosa</i> <i>Juncus trifidus</i> subsp. <i>monanthos</i> <i>Luzula alpinopilosa</i> <i>Solidago virgaurea</i> <i>Taraxacum</i> sp.
B	<i>Antennaria carpatica</i> <i>Artemisia genipi</i> <i>Carduus defloratus</i> <i>Carex capillaris</i> <i>Chamorchis alpina</i> <i>Cystopteris fragilis</i> <i>Draba tomentosa</i> <i>Euphrasia salisburgensis</i> <i>Festuca norica</i> <i>Hieracium lactucella</i> <i>Larix decidua</i> <i>Poa minor</i> <i>Soldanella alpina</i>	<i>Carex ornithopoda</i> subsp. <i>ornithopoda</i> <i>Festuca varia</i> <i>Gymnadenia conopsea</i> <i>Hieracium villosum</i> <i>Poa cenisia</i> subsp. <i>cenisia</i> <i>Potentilla crantzii</i>
C	<i>Alchemilla vulgaris</i> agg. <i>Androsace obtusifolia</i> <i>Antennaria carpatica</i> <i>Euphrasia minima</i> <i>Festuca norica</i> <i>Gentiana brachyphylla</i> subsp. <i>favratii</i> <i>Gentiana nivalis</i> <i>Hieracium murorum</i> agg. <i>Hieracium villosum</i> <i>Larix decidua</i> <i>Leontodon hispidus</i> <i>Luzula spicata</i> <i>Oxytropis campestris</i> <i>Saxifraga aizoides</i>	<i>Acinos alpinus</i> subsp. <i>alpinus</i> <i>Crepis jacquini</i> subsp. <i>kernerii</i> <i>Saxifraga paniculata</i>
D	<i>Achillea oxyloba</i> subsp. <i>oxyloba</i> <i>Carex bicolor</i> <i>Carex ornithopoda</i> subsp. <i>ornithopodioides</i> <i>Crepis terglouensis</i> <i>Draba dubia</i> <i>Erigeron uniflorus</i> <i>Phyteuma sieberi</i> <i>Salix retusa</i>	<i>Festuca alpina</i> <i>Leontodon pyrenaicus</i> subsp. <i>helveticus</i> <i>Potentilla nitida</i>