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A. Stanisci;L. Frate;U. Morra Di Cella;G. Pelino;M. Petey;C. Siniscalco;M. L. Carranza. Short-term signals of climate change in Italian summit vegetation: observations at two GLORIA sites. *PLANT BIOSYSTEMS*. 150 (2) pp: 227-235.

DOI: 10.1080/11263504.2014.968232

The publisher's version is available at:

<http://www.tandfonline.com/doi/full/10.1080/11263504.2014.968232>

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# Short-term signals of climate change in Italian summit vegetation: observations at two GLORIA sites

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## Abstract

Short-term changes occurring in high mountain vegetation were analysed using the data from two Italian sites already part of the GLObal Observation Research Initiative in Alpine environments (GLORIA – central Apennines and southwestern Alps). The study focused on a set of floristic (endemics), structural (life forms) and ecological (thermic vegetation indicator) variables. Vegetation data were collected according to the GLORIA multi-summit standardized method during the last decade. The re-visitation revealed a moderate decrease in regional endemic flora and significant variations in structural and ecological parameters. The increase in caespitose hemicryptophytes in both sites, in suffruticose chamaephytes in the central Apennines and in rosette-forming hemicryptophytes in the southwestern Alps emerged, highlighting the rapid responses of the alpine vegetation to climate warming. The increase in perennial life forms is related with the expansion of graminoids and small woody plants. These life forms seem to be most suitable to face climate warming in Italian summits. The increase in the thermic vegetation indicator exceeds the mean European summits increment, and this is due to the expansion of thermophilic species. Short-term analyses with fine spatial and temporal resolutions are still necessary to improve our understanding concerning species behaviour in high-elevation ecosystems.

## Keywords

- *altitudinal ranks,*
- *climate warming,*
- *endemic species,*
- *life forms,*
- *thermic vegetation indicator,*
- *vascular plants*

## Introduction

High mountain areas are hotspots of plant diversity and, in Europe, they host approximately 20% of the native flora (Médail & Quézel [1999](#); Aeschimann et al. [2013](#)). This high plant diversity is related to a rich mosaic of different habitats above the forest line and to the presence of dispersal barriers between mountain ranges that facilitated speciation processes (Körner [1995](#)). Europe shows a general north–south gradient of mountain endemism, increasing from boreal and temperate mountains to the Mediterranean summits (Faverger [1972](#)). Many authors postulate that such gradient on endemic richness existed because, during the Pleistocene, mountains of the Mediterranean region were only partly glaciated and remained more isolated than northern European ones, which were extensively ice-covered and whose margins were more connected to surrounding areas (Hughes & Woodward [2008](#)). The isolation in Mediterranean high mountain environments, caused by the orographic discontinuity of cold areas (Chapin & Körner [1994](#); Körner [2003](#)), gave rise to a peak of cryophilic endemic plants (Catonica & Manzi [2002](#)). Indeed, on these mountains, cryophilic species are restricted to low open-vegetation on the highest summits, where they

account for almost 90% of the total plant cover (Pauli et al. [2003](#); Casazza et al. [2005](#); Petriccione [2005](#); Stanisci et al. [2005](#), [2010](#); Fernández-Calzado et al. [2012](#); van Gils et al. [2012](#)).

In the last 50 years, the mountain areas have experienced an increase in global average temperatures per decade of  $0.13 \pm 0.03^\circ\text{C}$  and are projected to go through a higher rate of climate warming than most other regions of the world (IPCC [2013](#)). In addition, the decade 2001–2010 was the warmest one of the last century. Such climatic changes are affecting the flora and fauna at different spatial and temporal scales (Parmesan [2006](#)). Concerning vascular plants, an increment in species richness in high mountain ecosystems is expected. Indeed, several studies have documented the upward shifting of thermophilic plants distribution both through long-term (Grabherr et al. [2001](#); Theurillat & Guisan [2001](#); Korner [2003](#); Walther et al. [2005](#); Nagy [2006](#); Cannone et al. [2007](#); Holzinger et al. [2008](#); Parolo & Rossi [2008](#); Britton et al. [2009](#); Engler et al. [2011](#); Palombo et al. [2013](#)) and short-term time periods (e.g. Pauli et al. [2007](#), [2012](#); Erschbamer et al. [2011](#)). Simultaneously, a decline of cryophilic endemic species is expected because of their specific habitat requirements, narrow distribution ranges and low capacity to modify their geographic distribution (Erschbamer et al. [2009](#)). In particular, plant endemics of southern European high mountains, being distributed in small populations with low genetic diversity, are highly sensitive to global warming (Schwartz et al. [2006](#); Dirnböck et al. [2011](#); Fernández-Calzado et al. [2012](#)).

Even if the analysis of changes in plant communities floristic composition (e.g. total species, focal species and key species) over time represents a sound indicator and predictor of environmental change, including climate warming, further plant structural and ecological parameters could be successfully used for the same purpose (Chiarucci & Bonini [2005](#); Carranza et al. [2012](#); Gottfried et al. [2012](#); Matteodo et al. [2013](#)). For instance, the variation over time of life forms (Raunkiaer [1934](#)) may provide a signal of ongoing ecological processes across different biogeographic and bioclimatic zones. In the context of climate change, identifying the life forms of expanding and contracting plant species is essential for predicting future changes in alpine vegetation (Illa et al. [2006](#); Vittoz et al. [2008](#); Epstein et al. [2013](#); Matteodo et al. [2013](#)). In addition, the usefulness of plant species as ecological indicators of global warming has been demonstrated (Gottfried et al. [2012](#)). Indeed, plants represent integrated expressions of the values of environmental variables that may strongly fluctuate in time and space (Dieckmann [2003](#)). In particular, in order to quantify the warming effect or “thermophilization”, the analysis of the natural distribution of plant species along an altitudinal gradient (altitudinal ranks, ARs) could be very informative (Gottfried et al. [2012](#)). Warming effect could be driven by two main mechanisms: filling process, given by an increment in the abundance of thermophilic outpost species, and moving processes (Grabherr et al. [1995](#)), due to the immigration of thermophilic species from the lower altitudinal belts. Moreover, the thermophilization could also derive from the disappearance of cold-adapted species (for details, see Gottfried et al. [2012](#)).

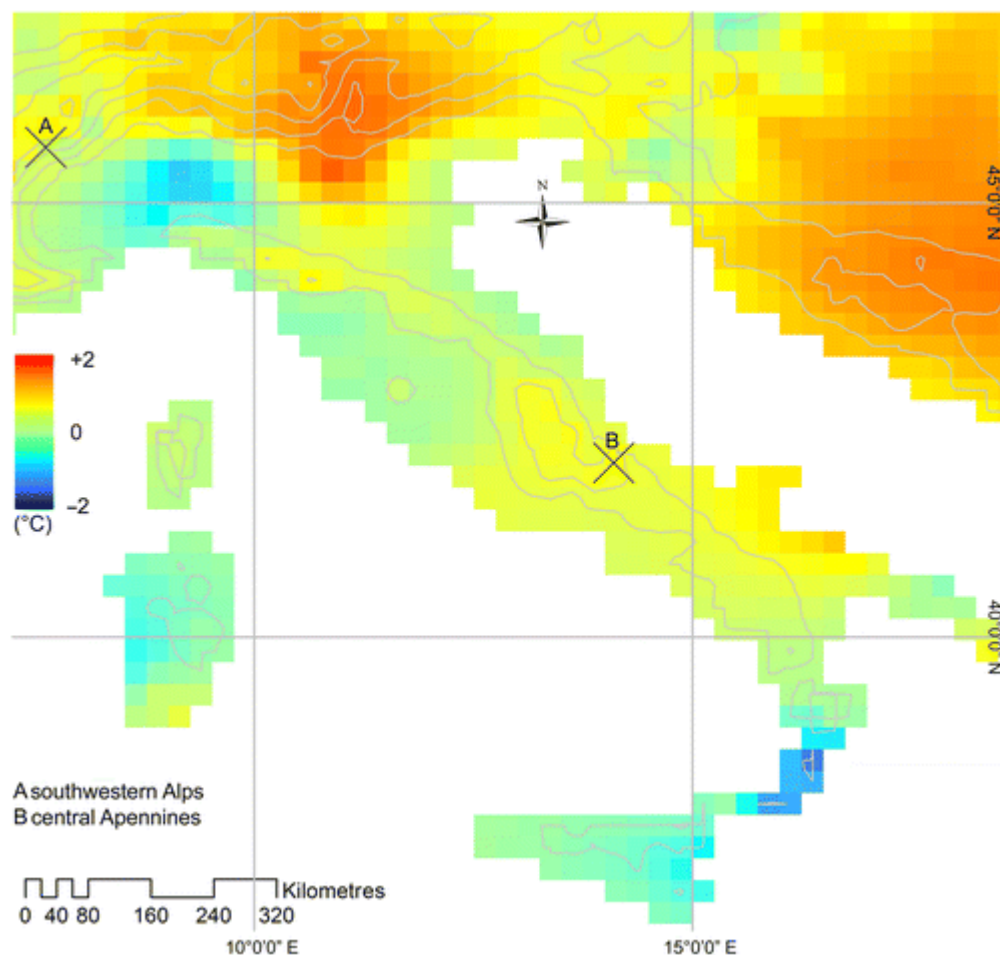
In consideration of the factors noted above, the present work analysed the short-term changes occurring on biodiversity, structure and ecological patterns of plant communities on several Italian high-elevation summits. In particular, using the data series available from two monitoring sites belonging to the GLORIA network (GLORIA environments – <http://www.gloria.ac.at/>), we focused on changes of floristic (endemics), structural (life forms) and ecological (AR values and thermic vegetation indicator) variables. The results of 10-year monitoring of the Italian summits should clarify the following questions: (i) Has the endemic species frequency changed during the last 10 years? (ii) Has the frequency of life forms changed and, if so, are some of them more affected than others? (iii) Have plant communities revealed a “thermophilization” effect? (iv) Is there any evidence of expansion of lower elevation species (montane and treeline species) or, on the contrary, of the contraction of species of higher belts (alpine and nival)?

# Material and methods

## Study area

The study area has been set up within the GLORIA project network and is now also part of the European Long-Term Ecological Research (LTER) network (<http://www.lter-europe.net>). It includes two mountain sites (central Apennines and southwestern Alps – <http://www.lteritalia.it>), where the alpine vegetation has been monitored during the last decade. The temperature change between 2001 and 2012, downscaled to the investigated sites, was 0.61°C for central Apennines and 0.55°C for southwestern Alps (E-OBS database – Haylock et al. 2008) (Figure 1).

Figure 1 Location of the investigated high mountain GLORIA and LTER sites (crosses). The map represents the change in mean annual temperatures between 2001 and 2012. Temperature data were derived from E-OBS database with a resolution of 0.25 × 0.25 geographical degrees.



The Apennine site includes the alpine belt (from 2400 to 2790 m a.s.l.) of the Majella National Park. In the year 2001, three summits were selected to be monitored: Mt Femmina Morta at 2405 m a.s.l., Mt Macellaro at 2635 m a.s.l. and Mt Mammoccio at 2737 m a.s.l. This site is geologically characterized by a large limestone summit plateau, shaped by periglacial phenomena and by tectonic-karst depressions and surrounded by deep slopes (Giraudi 1998). The vegetation of the lower two summits is characterized by open grasslands with scarce vegetation cover (26% of the total surface) dominated by *Sesleria tenuifolia*, *Carex kitaibeliana*, *Helianthemum oelandicum* subsp. *alpestre*, *Androsace villosa*, *Iberis saxatilis*, *Arenaria grandiflora* and *Minuartia verna*. The vegetation cover of the highest summit is very low (15%) and the

most frequent species are *Galium magellense*, *Cerastium thomasii*, *Viola magellensis* and *Alyssum cuneifolium*. The regional endemic species on the central Apennines represent 23% of the total sampled species. The dominant life form is hemicryptophytes, followed by chamaephytes, which progressively increase along the altitudinal gradient (Stanisci et al. [2005](#)).

The Alps site is located in Aosta Valley (Mont Avic Natural Park – Champdepraz and in Valtournenche – Matterhorn Valley). In 2002, four summits were selected at the alpine belt: Col de la Croix at 2340 m a.s.l., Lago Balena at 2584 m a.s.l., Pra Pelat at 2790 m a.s.l. and Cime Bianche at 3014 m a.s.l. The Champdepraz area is characterized by the Piedmont Greenstone Calc schist, with outcrops of Greenstone alternate with volcanic sedimentary sequences while the Valtournenche area is formed by garnetiferous micaschists and calcschists. The vegetation of the lower summits consists of alpine open grasslands with the occurrence of shrubs, and some rare trees and the mean plant cover is low (39%). The most common species are *Carex fimbriata*, *Festuca varia*, *Juniperus communis* subsp. *alpina*, *Vaccinium uliginosum* subsp. *microphyllum*, *Carex curvula*, *Festuca halleri*, *Kobresia myosuroides*, *Leucanthemopsis alpina* and *Minuartia verna*. In the highest summits, the vegetation is distributed in patches that cover < 14% of the total surface mainly occupied by debris. The dominant species are *Festuca quadriflora*, *Armeria maritima* subsp. *alpina*, *Silene acaulis* subsp. *bryoides*, *Minuartia sedoides*, *Saxifraga bryoides* and *Saxifraga oppositifolia*. In the site, the regional endemic species amounted to the 13% of the total species pool. Hemicryptophytes are dominant, followed by chamaephytes and geophytes (Geo; Aeschmann et al. [2012](#)).

#### Data collection

On both the LTER sites, vegetation is monitored according to the GLORIA multi-summit standardized method (Pauli et al. [2004](#)). The first data sampling was carried out in 2001 for central Apennines and 2002 for southwestern Alps and in 2012 both sites were re-visited (Table S1). For each summit, a 3 × 3 grid was established for each cardinal direction, at 5 m below the summit peak. In the four 1-m<sup>2</sup> corner plots (quadrants) of the grid, the species frequency was determined using a “frequency frame” divided into 100 subplots. In total, 7 summits and 112 permanent plots of 1 m<sup>2</sup> were surveyed. Species identification and nomenclature follow the Flora Europaea (Tutin et al. [1964–1980](#)). In order to minimize error linked to species identification, we filtered potentially misidentified species from the list, as described by Pauli et al. ([2012](#)).

#### Data analysis

We compared high summits vegetation between the two sampled dates, focusing on floristic information, structural parameters and ecological features. In order to investigate floristic changes, we analysed the frequency of endemic species; here, we considered as endemic only those species which are exclusive to a single mountain system (Pauli et al. [2012](#)). Changes in the vegetation structure over time were examined using life forms. The following categories were revealed in the sampled flora: fruticose chamaephytes (ChF), reptant chamaephytes (ChR), suffruticose chamaephytes (ChS), cushion chamaephytes (ChC), succulent chamaephytes (ChSc), Geo, caespitose hemicryptophytes (HC), hemicryptophytes with rosette (HR), stalked hemicryptophytes (HS), biennial hemicryptophytes (HB), phanerophytes and nano-phanerophytes (Ph) and therophytes (Th). For the identification of endemic plant species and for the attribution of life forms, we referred to Pignatti ([2005](#)), Conti et al. ([2005](#)) and Aeschmann et al. ([2004](#)). Finally, ecological features were measured following the approach proposed by Gottfried et al. ([2012](#)) for the analysis of the response of mountain vegetation to climate change in Europe. We used vascular plant species as bio-indicators of thermophilization (*sensu* Gottfried et al. [2012](#)). For each plant species, the AR value was assigned according to their specific altitudinal distribution. ARs vary from 1 to 6 as follows: AR 1, species with nival distribution centre; AR 2, alpine to nival species that do not descend under the treeline; AR 3, alpine centred species which do not descend to the montane belt; AR 4, alpine centred species that descend to the montane belt and species indifferently distributed from the treeline to the alpine; AR 5, species centred in the treeline ecotone or indifferently distributed from the montane to the alpine belts; AR

6, species which are montane centred or indifferently distributed from the montane belt to the treeline. Then, we calculated a thermic vegetation indicator ( $S$ ) for each plot as follows: given  $p_{ij}$  as the frequency of species  $i$  in plot  $j$ , and  $AR_i$  the AR value of the species  $i$ , the thermic vegetation index is

$$S = \frac{\sum_{i=1}^n AR_i \times p_{ij}}{\sum_{i=1}^n p_{ij}}$$

It is important to note that an increment of  $S$  values (thermophilization) could be expected when the frequency of species with high AR values (e.g. mountain species or thermophilic) increase or the frequency of species with low AR values decline (e.g. nival or cryophilic). In order to better investigate this ecological trend on each site, changes in AR frequency values were also assessed.

To analyse changes in the investigated parameters (endemics, life forms,  $S$  and AR values), we compared their frequencies in permanent plots between the two sampled dates (2001/2002 vs. 2012) using a paired test (Sokal & Rohlf [1981](#)). Data were first tested for normality using a Shapiro–Wilk test (Sokal & Rohlf [1981](#)). As the parameters (endemics, life forms,  $S$  and AR values) were not normally distributed, we chose the non-parametric Wilcoxon signed-rank test for paired samples (Wilcoxon [1945](#)). The Wilcoxon signed-rank test (paired) uses the sign and the magnitude of the rank of differences between specific pairs of measurements and was used to determine whether the differences found between the median values of the first and the second data were significantly different from zero. Significance was evaluated at a 95% confidence level. All the analyses were performed by using the statistical software PAST (Hammer et al. [2001](#)).

## Results

During the last decade, the structure and ecology of high summits vegetation on the two Italian GLORIA and LTER sites changed significantly. Although the decline in the frequency of regional endemic flora was moderate (from 1541 to 1298 for central Apennines and from 1043 to 929 for southwestern Alps), structural and ecological parameters significantly varied for both of the analysed sites. A significant increase in HC frequencies was evident on both the mountain sites (Figure [2](#)). In the southwestern Alps, HC total frequency significantly increased from 2589 to 2878 (+11%;  $p = 0.0045$ ,  $z = 2.836$ ), while in the central Apennines it increased from 963 to 1269 (+32%;  $p = 0.0086$ ,  $z = 2.625$ ). Moreover, in central Apennines, a significant increment of frequencies was found for ChS: they grow from 1701 to 2227 (+31%,  $p = 0.011$ ,  $z = 2.539$ ). On the southwestern Alps, significantly higher frequency values were evident for HR (Figure [2](#)) ( $p = 0.001$ ,  $z = 3.254$ ) by about 20% (from 930 to 1114). On the other hand, a significant reduction of Geo, from 823 to 682 (– 17%) was also observed on the southwestern Alps ( $p = 0.0278$ ,  $z = 2.200$ ). The thermic vegetation indicator ( $S$ ) showed significantly higher values in 2012 as compared with the older data (Figure [3](#)). For central Apennines,  $S$  increased from 3.61 to 3.72, with a mean increment of 0.11 ( $p = 0.001$ ,  $z = 3.056$ ), while for southwestern Alps  $S$  changed from 2.90 to 2.99 with a mean increment of 0.09 ( $p = 0.031$ ,  $z = 2.148$ ). In the central Apennines, the frequency of plant species with wide distribution (AR 4) and montane species (AR 6) showed a significant increase (AR 4:  $z = 3,101$ ,  $p = 0.001$ ; AR 6:  $z = 2,117$ ,  $p = 0.047$ ) (Table [1](#)), while in the southwestern Alps the frequency of timberline species (AR 5) ( $z = 2.668$ ,  $p = 0.007$ ) increased.

Figure 2 Changes in life form frequencies between the two analysed dates for both the investigated GLORIA and LTER sites. HS, stalked hemicryptophytes; HC, caespitose hemicryptophytes; HR, rosette hemicryptophytes; HB, biennial hemicryptophytes; ChR, reptant chamaephytes; ChS, suffruticose chamaephytes; ChC, cushion chamaephytes; ChSc, succulent chamaephytes; ChF, fruticose chamaephytes; Th, therophytes; Geo, geophytes; Ph, phanerophytes and nano-phanerophytes. Asterisks indicate significant differences ( $p < 0.05$ ) according to the Wilcoxon signed-rank test (paired).

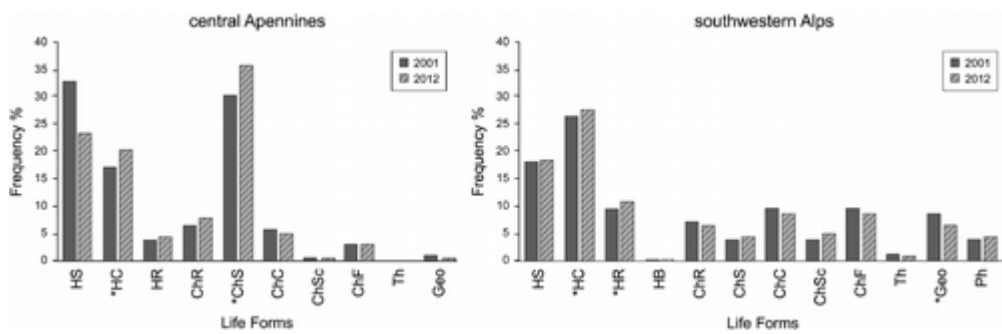


Figure 3 Box and whisker plots of the thermic vegetation indicator *S*. T1, first data sampling (2001–2002); T2, re-survey performed in 2012. Significant differences between the compared dates (Wilcoxon signed-rank test,  $p < 0.05$ ) were evident for both the LTER sites.

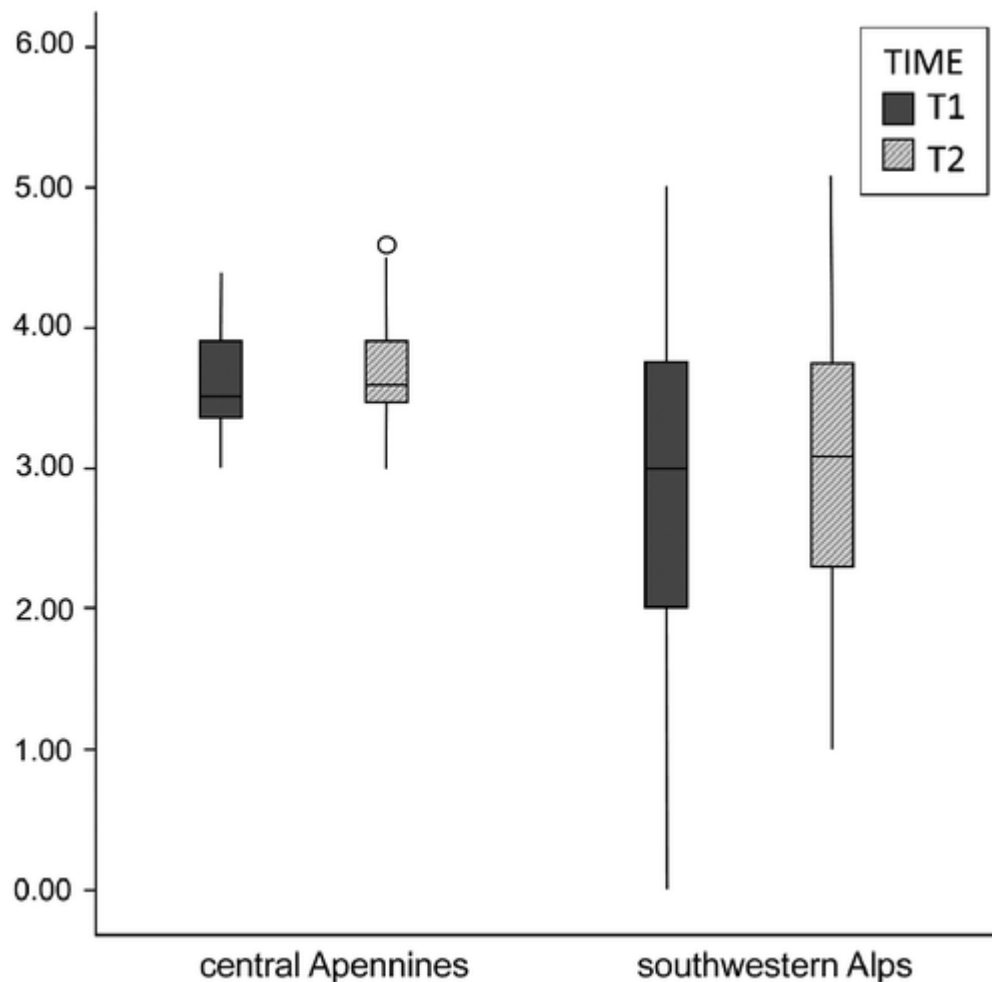


Table 1 Changes in AR frequencies between the two analysed dates for both the investigated GLORIA and LTER sites.

AR	Central Apennines			South-Western Alps		
	Trend	<i>z</i>	<i>p</i> -Value	Trend	<i>z</i>	<i>p</i> -Value
1	–	0.457	0.665	–	1.010	0.321
2	+	0.145	0.892	+	1.939	0.052
3	–	1.623	0.104	+	1.677	0.094
4	+	3.101	<b>0.001</b>	+	1.026	0.031
5	+	1.430	0.158	+	2.668	<b>0.007</b>
6	+	2.117	<b>0.047</b>	+	1.000	0.317

Note: Significant *p*-values ( $p < 0.05$ ), according to the Wilcoxon signed-rank test (paired), are in bold; +, increase; –, decrease.

## Discussion

The weak short-term variation in regional endemics of the examined sites seems to be in line with the general theory according to which high-elevation endemics are expected to decline under a warmer climate (e.g. Grabherr et al. 1995; Pauli et al. 2003; Schwartz et al. 2006; Dirnböck et al. 2011; Fernández-Calzado et al. 2012). Anyway, the weakness of the signal could be related to two main issues: (i) the homogeneous (micro-topographical and microclimatic) conditions which characterize the monitored sites and (ii) the limited inter-specific competitive pressure on the sampled harsh environment (Dullinger et al. 2007; Cavieres et al. 2014). Note that we have monitored only ridge and summit habitats vegetation, while the abovementioned theory is based on the entire flora present in the high-elevation mosaic (micro-topographical and microclimatic). Indeed, it is well documented that, beside the ridges, also scree and cliffs ecosystems host a rich pool of endemic species (Pauli et al. 2003; Casazza et al. 2005; Bragazza 2009; Stanisci et al. 2010; Fernández-Calzado et al. 2012). Taking into account that the manner in which endemic species respond to climate warming depends on their abilities to cope with micro-topographical situations (Gottfried et al. 1999), further studies addressing the behaviour of the endemic species on dolines, screes, cliffs, plateau and slope habitats are needed. Second, the weak variation of endemic species frequencies on ridge and summits could also be due to the extremely harsh environmental conditions (high wind speed and extreme temperature fluctuations) which, in these habitats, limit the inter-specific competitive pressure (Körner 2003; Gutiérrez-Girón & Gavilán 2010). At least for a short-term period of observation, the only endemic taxon showing a strong decline on central Apennines ridges is the steno-endemic *Viola magellensis*. Further studies are necessary to verify its trend over time in other high-elevation habitats where it was previously recorded, such as the stable scree on mild slopes (Blasi et al. 2005; Stanisci et al. 2010; van Gils et al. 2012).

As concerns vegetation structure, different “fingerprints” of the climate warming may be clearly detected across the GLORIA/LTER Italian summit habitats. The observed increase in HC frequencies is due to the expansion of graminoid species, characteristic of open grassland communities present in areas between the timberline and the alpine zone. Matteodo et al. (2013) detected similar trends, in a long-term analysis of the Swiss Alps and indicated the HC as particularly prone to face the ongoing processes of climatic change. Indeed, these graminoids have likely been favoured by their efficient vegetative reproduction and by their well-adapted leaves to support dry environmental conditions (Aeschmann et al. 2012). In addition, the observed rise in HR frequencies in the southwestern Alps site is probably due to their phenological characteristics. Indeed, as documented in an alpine area of Sweden, species with delayed flowering (e.g.



HR) respond positively to global warming (Molau et al. [2005](#)). Moreover, even though five types of chamaephytes are present in the central Apennines (ChR, ChS, ChC, ChF, ChSc), only the ChS show a significant increase. Such results pinpoint this life form as the most suitable one among the chamaephytes to face the warming effects. The observed increase in ChS is due to the expansion of the smallest woody plants in the area, such as *Arenaria grandiflora*, *Iberis saxatilis*, *Edraianthus graminifolius* and *Vitaliana praetutiana*. A similar increase in chamaephytes, mainly dwarf-shrubs, was also observed in the alpine grasslands (Vittoz et al. [2008](#)) and in the arctic tundra (Myers-Smith et al. [2011](#); Epstein et al. [2013](#)). The potential ability of ChS to respond in a warmer world should be verified through further comparative analysis including other LTER Mediterranean high summits. Overall, the observed trends of dominant perennial life forms (hemicytrophytes and chamaephytes) agree with the expected increment of vascular plant biomass described for arctic and alpine habitats (Cornelissen et al. [2001](#)). In addition, our findings are supported by short-term models that forecast a general increase in dwarf shrubs and in competitive clonal graminoids in alpine ecosystems (Erschbamer et al. [2009](#)). Such structural changes may also have implications for other taxonomical groups, such as invertebrates and birds which have precise habitat breeding and foraging requirements (Nagy et al. [2003](#)). Finally, in the southwestern Alps, the Geo significantly decrease. Note that only three species belong to this group (*Carex fimbriata*, *Lloydia serotina* and *Polygonum viviparum*) and they are present only at lower altitudes. Moreover, previous long-term research carried out in the Alps (Matteodo et al. [2013](#)) evidenced very weak variations of Geo. To explain our results, we can simply speculate, at the present time, that Geo, being typical of wet microhabitats (Aeschmann et al. [2012](#)), decreased during the last decade probably because summit habitats have become drier. Further research on the behaviour of Geo in the alpine belt ecosystems under different scenarios of global change is necessary.

The observed increment of the thermic vegetation indicator *S*, for both the investigated sites, is higher than the mean increment of *S* value recorded for all the European summits in the period 2001–2008 (Gottfried et al. [2012](#)). This increase mostly reflects a filling process of thermophilic species already present at the alpine belt, rather than immigration of species from lower elevations. For example, in the central Apennines, the frequency of many species with wide distribution between timberline and alpine belt (AR 4) (e.g. *Sesleria tenuifolia* and *Arenaria grandiflora*), as well as montane species (AR 6) (e.g. *Carex humilis*) significantly increased. Similar results were reported by Petriccione ([2005](#)) using short-term phytosociological data. In particular, dry grasslands communities dominated by *Sesleria tenuifolia* and *Carex humilis* are favoured by the current climate warming, and are filling an increasing area on summit habitats. Such filling process could be related with the ability of this dry grasslands communities to live on windy ridges habitats above the timberline (Blasi et al. [2005](#); Di Pietro et al. [2008](#)), where eolic sedimentation of fine particles give origin to shallow soils. At the same time, in the southwestern Alps, timberline species group (AR 5) (e.g. *Festuca varia* and *Juniperus alpina*) showed a consistent increase. Here, alpine grassland communities, dominated by *Festuca varia* and *F. halleri*, and alpine juniper shrubland have strengthened their presence in the last decade. Although a decline of cold adapted species could be expected, the current observed thermophilization is only due to the increase in thermophilic species frequencies. Similar evidence has emerged from previous studies concerning high-elevation ecosystems of Alps (e.g. Grabherr et al. [2001](#); Walther et al. [2005](#); Cannone et al. [2007](#); Pauli et al. [2007](#), [2012](#); Parolo & Rossi [2008](#); Erschbamer et al. [2011](#)). Erschbamer et al. ([2009](#)) argued that increasing temperatures and prolonged growing seasons enhanced soil development and consequently promote the expansion of species from the lower altitudes.

## Conclusion and final remarks

The analyses of short-term changes on biodiversity, structure and ecological patterns of plant species in Italian high-elevation summits suggest a rapid response of the alpine vegetation to the ongoing climate

warming. Such findings agree with recent short-term studies at both continental (Gottfried et al. [2012](#); Pauli et al. [2012](#)) and local scales (e.g. Cannone et al. [2007](#); Erschbamer et al. [2009](#); Vittoz et al. [2010](#)). While studies based on centuries data series (e.g. Grabherr et al. [2001](#); Erschbamer et al. [2011](#); Matteodo et al. [2013](#)) can help to identify large-scale patterns of change and can offer a benchmark for making global predictions over time (Matteodo et al. [2013](#)), short-term analyses of ecological indicators with smaller spatial and temporal resolutions are still necessary to improve our understanding concerning species behaviour in a changing climate. The short-term analysis of LTER Italian summits clearly shows the ongoing increment of thermophilic and perennial plant species. This process is expected to further accelerate according to climate warming predictions.

It would be advisable to test our findings throughout the southern Europe mountain LTER sites, as they are excellent observatories to investigate the ecological responses to climate warming. Moreover, in order to increase our knowledge concerning the ecological processes caused by climate change in the high-elevation ecosystems, it could be useful to analyse the floristic structural and ecological features of each habitat of the high-elevation landscape mosaic, because the micro-topographical and micro-climatic heterogeneity may influence the specific dispersal pattern of each sensitive plant species, as well as their resilience and resistance.

## **Supplemental data**

Table S1. List of recorded species in the two dates (2001/2002 and 2012) for both the GLORIA sites (central Apennines and south-western Alps). Life forms, altitudinal rank and species frequency are also provided.

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