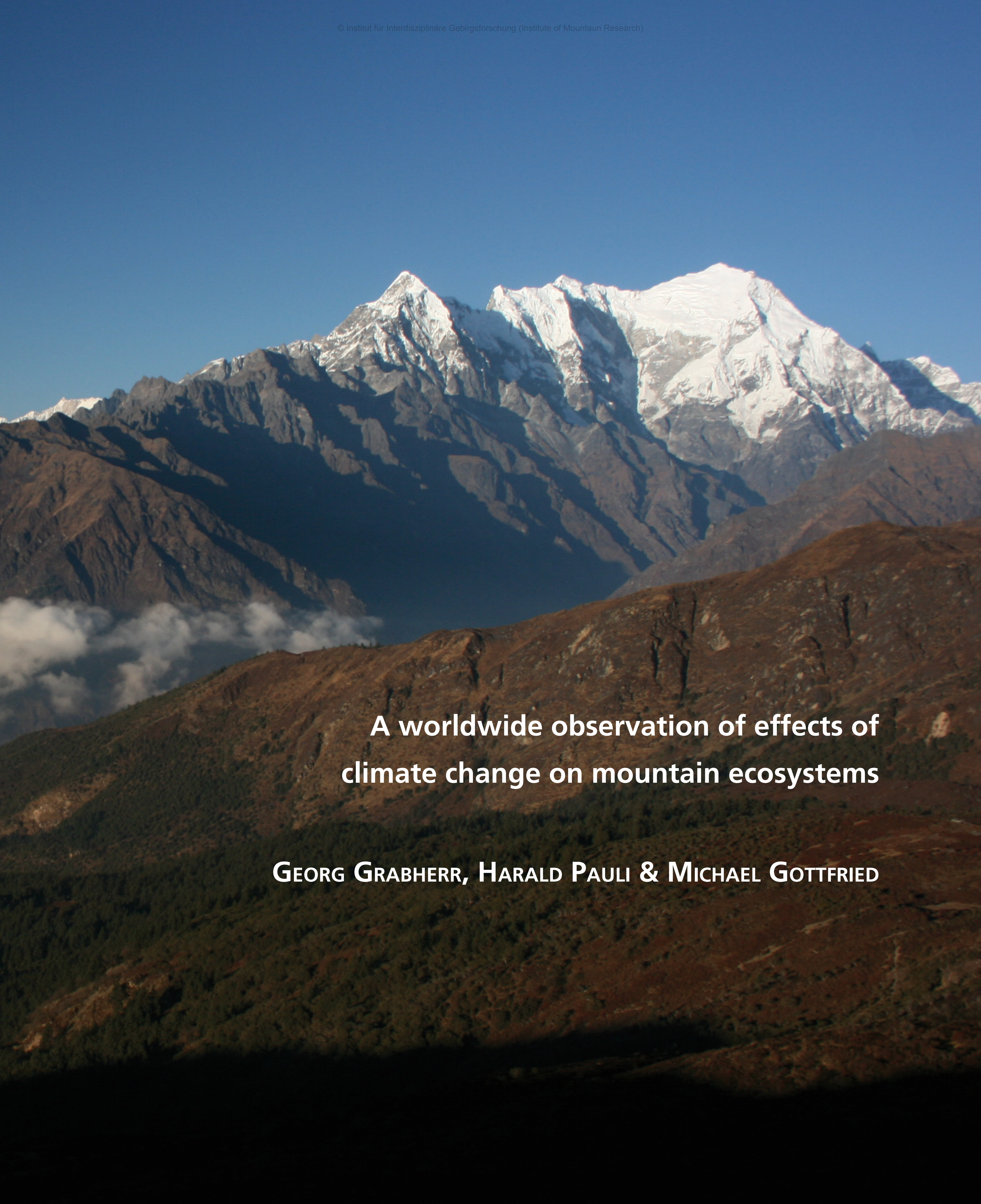

A worldwide observation of effects of climate change on mountain ecosystems

GEORG GRABHERR, HARALD PAULI & MICHAEL GOTTFRIED

Introduction

The general climate warming since the end of the Little Ice Age ca. 150 years ago has left distinct traces in the cryosphere. In high mountain areas across the world, most glaciers lost mass and surface area (Oerlermans 2005), permafrost is thawing and increases the instances of mass movements (Häberli et al. 2006), the zone of "good winters", i. e. those with a continuous snow cover of 100 days, has withdrawn into higher altitudes (Breiling & Charamza 1999).

Fig 1: Change in the treeline ecotone in a wilderness region of the Southern Urals within the previous century. The annual mean temperature increased by about 2 °C within the period from 1929 to 1999. Photographs by Moiseev & Shiyatov, Yekaterinburg.

How does life in high mountains, particularly that living near the low-temperature limits, respond to such changes? Initial indications of warming-induced migration of species, especially in the nival zone, date back to the beginning of the 20th century (Klebelsberg 1913). In the 1950s, Braun-Blanquet confirmed an increase in species richness on selected summits above 3000 m in the Rhaetian Alps (Braun-Blanquet 1958). Grabherr et al. (1994) showed this to be a general trend in this region and beyond, even if some of the 25 summits studied, for which old and reliable records existed, presented no pronounced increase in species richness. Walther et al. (2005) reported that in the recent, very warm, decades the process of upward movement has accelerated. Meanwhile, effects of climate warming on alpine plants have been recorded for other mountain regions as well.

The current status of evidence-based climate impact research on mountain vegetation at cold-determined ecotones can be summarized as follows:

- the treeline ecotone has become denser (e. g. Urals; Moiseev & Shiyatov 2003; Fig. 1) and its upper limits are moving up; this trend had been reversed during cooler periods (1960s / 1970s) as Kullmann (2007) showed for the treeline of birch forests in the Scandinavian mountains;
- the total number of species on mountain summits, especially in the nival zone, has risen and implies an upwards move of species (e. g. Alps; Grabherr et al. 1994; Fig. 2; Walther et al. 2005);
- overall, reliable old species inventories are rare and missing for most of the high mountain areas; this makes it difficult to use high mountain areas as otherwise ideal sites for comparative studies of cold habitats across the world;
- life at the low-temperature limits, especially vascular plants, are excellent indicators for an ecological assessment of the impact of climate change, even if the vegetation reacts with some delay; this means that the responses of high mountain plants reflect

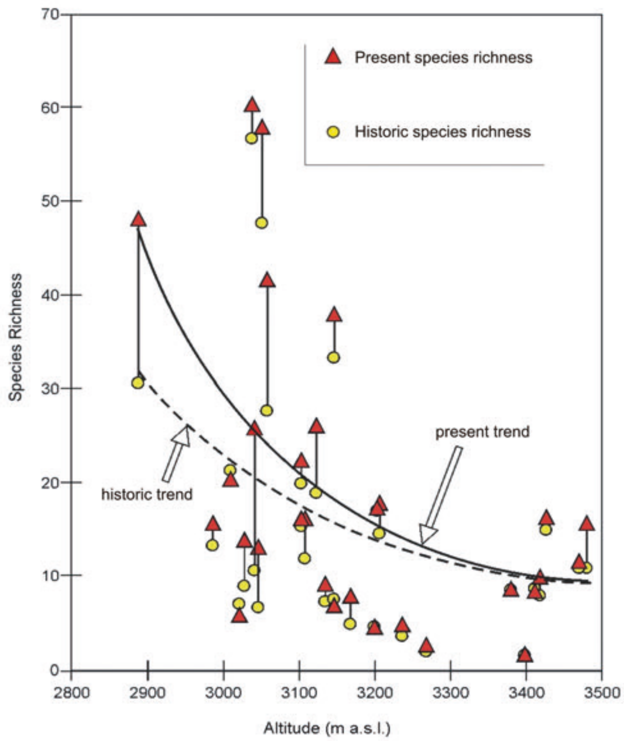

Fig 2: Increase in species richness on summits of the Central Alps within the previous century (Grabherr et al. 1994, updated).

trends of climate change rather than short-term vacillations;

- historical inventories are only usable if an exact localization is possible and a reliable identification of species combined with suitable quantitative measures;
- many high mountain areas are virtually free of human influence and even where there is some impact, there are always undisturbed and difficult to access places and peaks; i.e. high mountain areas are among the few regions on earth where the climate signal can be captured without interference.

These considerations are the basis for the monitoring network designed and set up by the authors. Today this GLORIA network, the Global Observation Research Initiative in Alpine Environments, is established as a long-term programme at the IGF and implemented across the world. It focuses on the well-documented indicatory value of alpine and nival plants and plant communities. Below we outline the concept and methodology of GLORIA, describe its status and present the major results to date.

Concept and methodology of GLORIA

GLORIA builds on the general hypothesis that a warming climate will trigger migration processes which must ultimately lead to a shift in the distribution of species across altitudinal zones (Gottfried et al. 2002). This hypothesis is to be corroborated by standardized monitoring of permanent plots ranging from the treeline ecotone to the upper limits of plant life. The appearance of new species in the plot and the loss of species can indicate longer-term migration processes, while changes in the abundance and cover species can provide short-term signals of a shift in species composition. Since the GLORIA pilot phase (Pauli et al. 2004), it has become clear that an assessment purely in terms of presence/absence is insufficient and that the scientific community expects precise monitoring of quantitative effects in order to be able to evaluate climate impact. This also includes taking into account observer error which affects the statistical power of the data at any comparison of repeat surveys (Vittoz & Guisan 2007) as has clearly been confirmed by our own tests with different groups of observers. In principle, however, the following criteria are still valid for the basic approach:

- simplicity of method but at the same time as scientifically sound as possible; it should be applicable even under expedition conditions;
- comparability of observations for as great a number of reference regions as possible plus a representative distribution;
- low cost, so that it can be implemented by researchers with small budgets;
- integration with scientific institutions (universities, research units) of a certain permanence;
- maximum naturalness of the monitoring sites to capture as clear a climate signal possible.

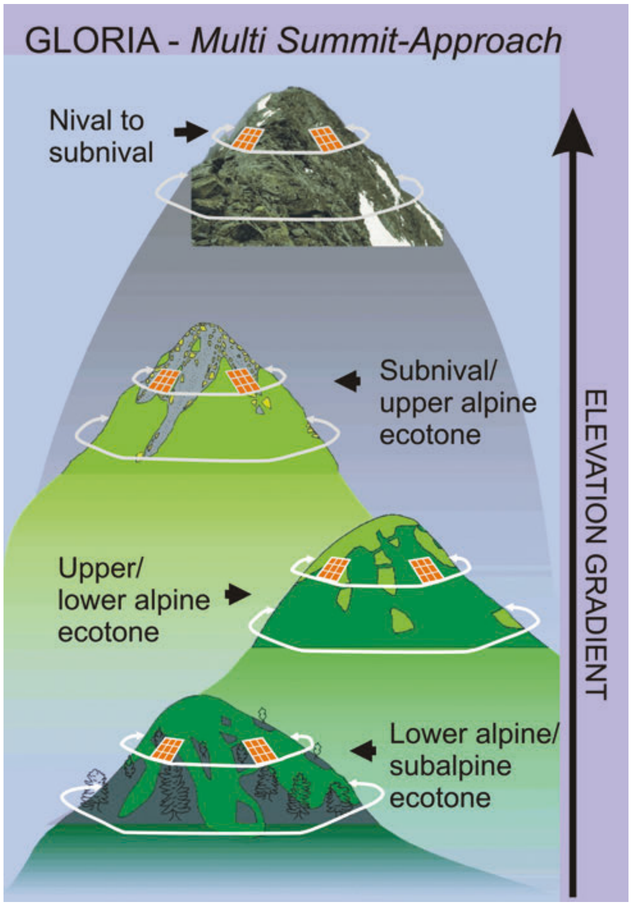

Fig. 3: Multi-summit approach of the GLORIA programme (Pauli et al. 2004).

Based on these criteria, we followed several approaches in the planning phase of GLORIA: the transect approach along more or less homogenous mountain slopes (single mountain approach), the multi-summit approach (Fig. 3) involving plots in the summit areas of mountains of different altitude within a climatically homogenous target region and the master site approach at research stations. The multi-summit approach emerged as the most suitable for an implementation on the global scale. On summits, all aspects are represented within a small area, shadow-effects from neighbouring land features are minimized and such sites are prominent landmarks that can be easily found again. While some mountains are frequented by tourists and others trampled on by grazing animals, in our experience each target region includes summits that are largely free of direct anthropogenic disturbances.

The sampling design (Pauli et al. 2004) is aligned along the main geographical directions around the summit and consists of permanent plots on different scales at the following spatial levels: 0.1×0.1 m², 1×1 m², and 10×10 m² and of larger summit area sections of variable size covering the area down to the 10 m contour line (Fig. 4). In each main direction, a 3×3 m² plot cluster is established with four 1 m² permanent quadrats in the corner positions. The detailed species cover sampling within the quadrats provides the baseline for detecting changes in species composition. Frequency counts within the same quadrats, carried out using a grid frame divided into 100 dm² cells, are used to detect changes in vegetation patterns.

A 10×10 m² square in each cardinal direction that includes the area of the 3×3 m² cluster is established for line-pointing with 400 points. This more recently implemented method should provide additional data to measure cover changes of the more common species. Eight summit area sections cover the entire summit site and are used for surveying the species pool of the whole summit area.

Continuous measurements of soil temperature at 10 cm below the surface in the centre of each 3×3 m² cluster serve to compare temperature and snow regimes. A detailed description of the design and recording methods is given in the GLORIA field manual and its update documents (see www.gloria.ac.at/?a=20).

Status of the network

The first major step in the implementation of GLORIA was reached through a European Union FP5 project (GLORIA Europe) with the establishment of 70 summit sites in 18 target regions across Europe in 2001. Since then, the European network has grown and now includes 36 active target regions. The additional sites were funded by local or national grants. A method testing campaign in 2007 and the first repeat survey of the

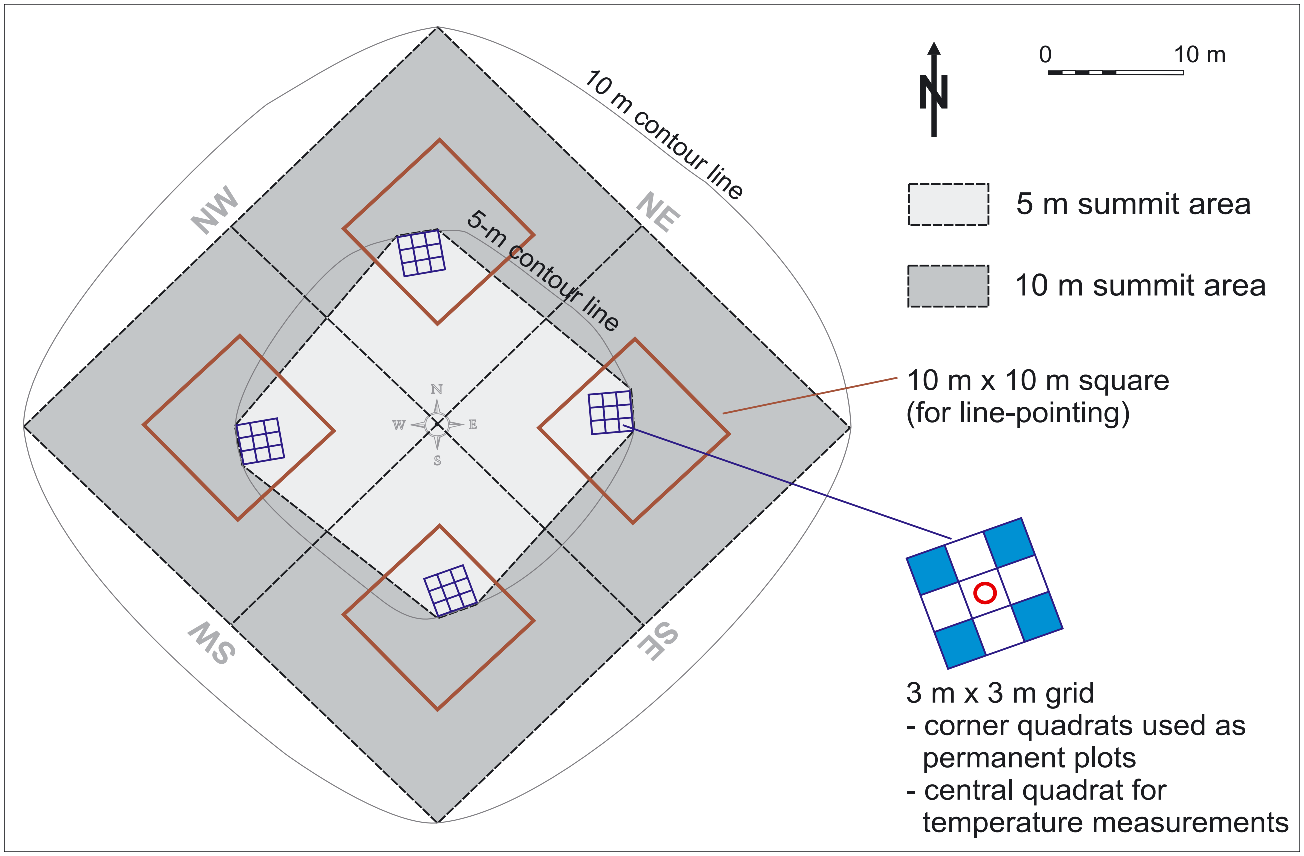

Fig. 4: Sampling design of the GLORIA multi-summit approach (top view), (for further details see: www.gloria.ac.at/?a=20).

sites from 2001 carried out in 2008 was mainly financed by the Swiss MAVA Foundation for Nature Conservation and by the Austrian Federal Ministry of Science and Research.

Globally, GLORIA is currently represented in 77 mountain regions across five continents (Table 1 and Fig. 5). In 12 further regions, site setup is in a concrete planning phase.

In North America, the first sites were set up in Montana (Glacier National Park) and California in 2003 and 2004. Both are now also considered GLORIA master sites. Currently, sites are active in 16 target regions in North America (USA, including Alaska and Canada). All funding came from North-American sources. More sites are planned for 2010 and 2011.

In South America, GLORIA experienced a rapid growth in the Andes where the first sites in two target regions were set up with support from UNESCO-MAB in 2005. Currently, 12 target regions are active across all Andean countries. Funding and support came from various sources such as the Proyecto Paramo Andino and the Consortium for Sustainable Development of the Andean Eco-region (CONDESAN), Herbario Nacional de Bolivia, Conservation Internacional and the European Union (EU) FP6 project ALARM. More recently, the Comunidad Andina de Naciones (CAN), the Agencia Española de Cooperación Internacional para el Desarrollo (AECID) and The Nature Conservancy have added their support. Inter-Andean GLORIA workshops were held in 2007 (Bolivia) and in 2008 (Ecuador); the next one is planned for April 2011 in Argentina.

In Asia, active sites exist in 10 regions: Altai / Russia (Katunskiy Biosphere Reserve) supported by

UNESCO-MAB, four regions in Yunnan / China (led by Missouri Botanical Garden, the Nature Conservancy and Zhongdian Botanical Garden); Langtang, Nepal (Missouri Botanical Garden and Tribhuvan University), Alborz, Iran (supported by the GLORIA coordination), Taiwan (funded by the Taiwanese Ministry of Forestry) and Japan (Shinshu University, Matsumoto). Major gaps still remain in the mountains of central Asia.

Sites in New Zealand and in the Snowy Mountains, Australia, were already set up in 2004.

In Africa, plans for the High Atlas, Morocco, and several expressions of interest for tropical mountains and South Africa have been reported.

Table 1: Number of active GLORIA target regions per continent.

	Europe	North-America	South-America	Asia	Austral-asia	Africa
2008 (Nov)	30	14	8	6	3	0
2010 (April)	36	16	12	10	3	0

Results

Contributions to floras, biodiversity gradients and vegetation patterns

Even the basic surveys in the GLORIA target regions provide new biogeographical and ecological findings. Some GLORIA teams have published their data and all data sets are compiled in the network's central database (see www.gloria.ac.at). These data represent a reliable record on alpine species for the selected summit areas from five continents. In remote or less studied mountain regions, e.g. in the Andes of southern Peru (Halloy, pers. comm.) or in the high mountains of the Iran (Noroozi, pers. comm.), we expect to discover hitherto unknown species.

The data of the pilot project GLORIA Europe confirm the general hypothesis that phytodiversity (only vascular plants) at lower latitudes is higher than at high latitudes (Virtanen et al. 2003). The GLORIA summit floras at mid-latitudes (Alps, Pyrenees, Caucasus) devi-

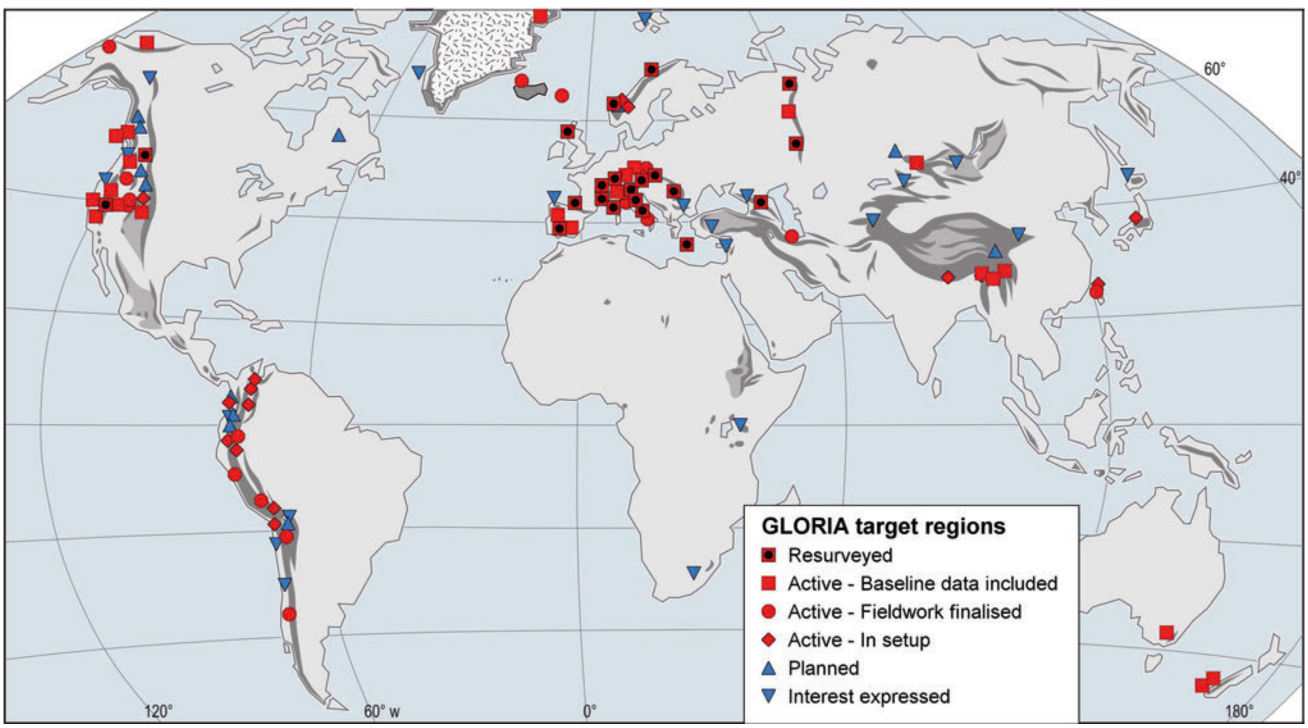

Fig. 5: Current status (May 2010) of the GLORIA network (77 target regions in total).

Fig. 6: Transplanting an alpine Carex firma *sward (from ca. 2 000 m), in a "shock experiment" to lowland climate at the Botanical Garden of Vienna.*

ate from this pattern by being the species-richest. The Mediterranean mountains (Sierra Nevada, Apennines, Lefka Ori (Crete) are home to the most endemic species. For the target regions Sierra Nevada (Spain) and Hochschwab (Austria), Pauli et al. (2003) found that the proportion of endemic species increases with altitude. A generally warmer and drier climate (Sierra Nevada) should eventually lead to the loss of this unique mountain flora. Salick et al. (2009) and Grabherr (2009) estimate that this is also true for medicinal plants. In the Himalayas, Tibetan doctors use 76% of alpine species for medicinal purposes. However, Gottfried et al. (1999) have shown through spatially explicated modelling that microrefugia may support a longer survival. Some vegetation types, such as subalpine Krummholz of *Pinus mugo* in the Limestone Alps, may be highly resistant against warming-driven impacts even in the longer term (hundred years and more) (Dullinger et al. 2004). We may expect many different reactions and some surprises.

The modern view of the altitudinal zonation of high mountain areas, which Humboldt already presented in a comparative approach, is a sequence of vegetation belts that are connected through narrower ecotones (Nagy & Grabherr 2009). By far the most conspicuous ecotone is the transition between closed montane forest and the treeless alpine zone. So far, attempts to describe this treeline ecotone in a general way have failed owing to the high level of individual forms dependent on the particular mountain area (Holtmeier 2009). Nor has the debate about the ecological causes of the treeline been concluded (Körner 2003; Butler et al. 2009). We do not yet have comparative analyses of GLORIA summits at the treeline ecotone. With now 77 target regions in place across a wide geographic and climatic range, the standardized GLORIA data will allow a comparison of the role of different plant functional types (cf. Halloy & Mark 1996) that should reveal interesting ecological aspects.

Less distinct than the treeline ecotone is the transition from the alpine to the nival zone. Some authors understand this zone where the closed alpine grassland disintegrates into an open patchy vegetation as an altitudinal belt, the subnival zone; others see it as an alpine-nival ecotone (Nagy & Grabherr 2009). In the nival zone, the number of species is decreasing considerably (Grabherr et al. 1995; Körner 2003), but there are a number of species with their centre of distribution in this upper zone. These nival species are mainly characterized by a high tolerance of long snow cover, as Gottfried et al. (2002) were able to show through comparative samplings in the area of the GLORIA master station Schrankogel. Snow cover also prevents frost damage from cold spells in summer (Larcher et al. 2010).

On the whole, high mountain research has paid much less attention to the alpine-nival ecotone than to the treeline ecotone. A clear definition along abiotic and biotic criteria is still missing as is a detailed understanding of the processes involved in the dissolution of the vegetation and the exclusion of large numbers of alpine species in the nival zone. Most of all, we lack a global view. Here we can expect suitable data material for documentation and to generate hypotheses from the GLORIA summits that reach into the nival zone.

Early monitoring results

After an initial testing phase, the first permanent GLORIA plots on mountain summits were set up on Hochschwab, Austria, in 1998 and in the Sierra Nevada, in southern Spain, in 1999. In 2001 GLORIA started on a continent-wide scale as part of an EU FP5 project in 18 target regions across Europe (www.gloria.ac.at). In subsequent years, new target regions were added on four other continents.

A high frequency of monitoring cycles does not work in alpine vegetation. Alpine and nival species are long-lived perennials (Nagy & Grabherr 2009), some form clonal populations that can reach an age of several thousand years (Grabherr 1997). We can confidently assume that there is no massive inter-annual variability in the presence of the species as was confirmed by repeat photographs from permanent plots and by transplanting experiments in the Botanical Garden of Vienna (Friedmann & Grabherr 2009; Fig. 6). A frequent reinvestigation of the plots would, moreover, cause damage by trampling. In 2008, a concerted repeat survey of the GLORIA Europe plots was carried out and the comparative data analysis is about to be completed. For the reasons quoted above and because of the generally moderate warming within the last 7 years, we do not expect dramatic impacts on a Europe-wide scale. On the GLORIA summits in the Dolomites, South Tyrol, Italy, however, species richness has increased by around 10% between 2001 and 2006 (Erschbamer et al. 2009). At the master site Schrankogel, we also registered significant changes when comparing 1994 with 2004. A detailed description can be found in the chapter by Pauli et al. 2010 in this volume.

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