

Research Article

Plant diversity and floristic characters of the alpine subnival belt flora in the Hengduan Mountains, SW China

^{1,2}Bo XU ³Zhi-Min LI ¹Hang SUN*

¹(Key Laboratory of Biodiversity and Biogeography, Kunming Institute of Botany, Chinese Academy of Sciences, Kunming 650201, China)

²(University of Chinese Academy of Sciences, Beijing 100049, China)

³(Life Science School, Yunnan Normal University, Kunming 650031, China)

Abstract There have been few studies of the alpine subnival belt flora in the Hengduan Mountains (HM), which host remarkable biodiversity. To extend knowledge of this flora, we examined published floras, herbarium specimens, and field observations (and material) collected by both ourselves and others. In total, 942 seed plant species have been recorded in the belt, representing 168 genera and 48 families. Twenty-four large families (with ≥ 10 species) are present, represented by 873 species (92.68% of the total). These include Asteraceae, Saxifragaceae, and Brassicaceae (146, 82, and 71 species, respectively). There are also 27 large genera (represented by ≥ 10 species), collectively contributing 587 species (62.31%) to the flora, including *Saxifraga*, *Corydalis*, and *Saussurea* (75, 55, and 49 species, respectively). Areal elements represented by the highest numbers of genera are the North temperate, Sino-Himalaya, and Old World temperate elements (39.88%, 14.29%, and 12.50%, respectively), while the Hengduan Mountains, Sino-Himalaya, and Qinghai-Tibetan Plateau elements are most species-rich (355, 281, and 161 species, respectively), collectively accounting for 84.61% species of the known flora. Of these, 295 species (31.32%) are endemic to the Sino-Himalayan alpine subnival belt and 151 (16.03%) strictly endemic to the alpine subnival belt of the HM. These findings indicate that the flora is young, strongly differentiated, probably developed as a result of the plateau's uplift, and speciation has been accelerated by the harsh environment and strong heterogeneity of niches.

Key words alpine subnival belt, floristic characters, Hengduan Mountains, plant diversity.

The alpine subnival belt, below the permanently snow-covered zone, is the highest of all terrestrial ecosystems inhabited by seed plants. The growing season in this belt is short, the vegetation composition is characteristically simple, and it is mainly comprised of cryophilous and xerophilous perennial plants distributed in clustered pioneer communities (Li et al., 1981; Liu et al., 1984; Wu et al., 1987).

Several influential monographs have described the biodiversity patterns and associated factors in arctic–alpine zones, their ecosystems, and both physiological and morphological characteristics of the plants (e.g., Hedber, 1963; Mark & Adams, 1979; Hadley, 1987; Chapin & Körner, 1995; Körner & Spehn, 2002; Körner, 2003). However, these studies have mainly focused on the flora and ecosystems of mountainous regions in Europe, America, and Africa. Much less attention has been paid to the flora of the Himalaya, the Hengduan Mountains (HM), and other high-altitude parts of the Qinghai–Tibetan Plateau (QTP), due to their

inaccessibility, harsh natural environments, and short life-cycles of the plants. There have been a few published studies of cushion plants and the flora of the alpine subnival belt in Tibet (Li et al., 1981, 1985, 1987), Wu et al. (1987) have presented a preliminary classification of alpine scree plant communities in Yunnan, Deng & Zhou (2004) have examined the diversity of alpine scree plants in NW Yunnan, and Peng et al. (2012) have studied reproductive ecology in the subnival belt of the HM. However, knowledge of the alpine flora and biodiversity in the region is still poor. Indeed, several new taxa have been found recently, notably the new genera *Baimashania*, *Shangrilaia* (Al-Shehbaz et al., 2004), and *Parasyncalathium* (Zhang et al., 2011a), the species *Solms-laubachia angustifolia*, *S. calcicola*, *S. grandiflora*, *S. sunhangiana* (Yue et al., 2008), *S. zhongdianensis* (Yue et al., 2005), and 12 new *Corydalis* species from the alpine subnival of the HM (Lidén, 1996; Su, 1997; Su & Lidén, 1997; Wang & Lidén, 2006; Lidén & Su, 2007; Gao et al., 2008; Zhang et al., 2008). Furthermore, according to Zhang & Sun (2008), only one to two specimens of species, on average, are available from alpine zones of the HM in herbaria.

Received: 8 April 2013 Accepted: 26 May 2013

* Author for correspondence. E-mail: hsun@mail.kib.ac.cn. Tel.: 86-871-65215002. Fax: 86-871-65215002.

Due to the paucity of knowledge, fundamental aspects of the flora of the alpine subnival belt of the Himalayas and QTP remain to be elucidated, including the numbers of seed plant species in the region, their taxa, the composition of the flora, the geographical distributions and floristic relationships of the taxa, and the diversity of adaptive morphological structures for the harsh environment. This paper addresses these issues, focusing on the flora of the HM.

1 Material and methods

1.1 Study region

The HM lie in the southeastern region of the QTP, which covers an area of 364 000 km² stretching from 24°40' N, 96°20' E to 34°00' N, 104°30' E (Li, 1987). The HM contain the most abundant biological diversity in the India–Burma area and the region is thus regarded as one of the 10 most important biodiversity hot spots in the world (Myers et al., 2000; Boufford et al., 2004).

The alpine subnival belt is the transitional zone between the upper alpine belt and the nival belt (Nagy & Grabherr, 2009), characterized by low annual average cumulative temperature, large temperature differences between day and night, intense ultraviolet radiation, and strong winds. The climate in the alpine subnival belt is severely cold and may change dramatically in just a few hours. In addition, as a result of the intense glaciations and strong congelifraction, the surface rock is flaked into gravels of various sizes, with a few infertile soil-filled crevices. The harsh climatic conditions prohibit the survival of most species in the belt; only a few species with particular biological characteristics can establish. Thus, the vegetation coverage is very low, less than 5%, with small populations of plants scattered in the crevices (Wu et al., 1987).

The elevation range of the alpine subnival belt flora is usually between 4300 (4000–) and 5200 m, with fluctuations that may vary by hundreds of meters, depending on the slopes of the mountains and the topography of the mountaintops. On the steep slopes, usually with shifting or semi-consolidated screes, it can stretch 200–500 m down to alpine meadows or even alpine shrublands, whereas on gentle slopes, usually with stable or semi-consolidated screes, alpine subnival belt plants often grow together with alpine gravel meadows and alpine cushion plants. Thus, in this report, the alpine subnival belt flora refers not only to alpine subnival belt plants, but also plants of the neighboring sparse alpine gravel meadows and alpine cushion plants, which have a similar elevational range or

overlapping distribution with alpine subnival belt plants.

1.2 Data collection and methods

We obtained an initial checklist of the seed plants in the alpine subnival belt of the HM from published floras, then consulted related herbarium specimens, checked and improved the list, and consulted plant taxonomists with relevant expertise to enhance the precision and reliability of the data. In addition, we included information obtained by examining material and photographs that we, and others, had collected in field investigations.

The taxonomy and nomenclature followed the *Flora of China* (Wu & Raven, 1994–2011). Information on the plants' distribution was mainly acquired from the following published floras: *Vascular Plants of the Hengduan Mountains* (Wang, 1993–1994), *Flora of China* (Wu & Raven, 1994–2011), *Flora Reipublicae Popularis Sinicae* (Editorial Committee of *Flora Reipublicae Popularis Sinicae*, 1959–2004), *Flora Yunnanica* (Wu, 1977–2010), *Flora Xizangica* (Wu, 1983–1987), *Flora Qinghaiica* (Liu, 1996–1999), and *Flora Sichuanica* (Fang, 1981–2011). However, the authors also consulted some influential monographs describing the flora in neighboring regions, such as *Flora of British India* (Hooker, 1872–1897), *An Enumeration of the Flowering Plants of Nepal* (Hara et al., 1978–1982), and *Flora of Bhutan: Including a record of plants from Sikkim* (Grierson et al., 1983–1994).

The herbaria we mainly consulted were Kunming Institute of Botany (KUN), Beijing Institute of Botany (PE), Northwest Institute of Plateau Biology (HNWP), Chengdu Institute of Biology (CDBI), all of which are affiliated to the Chinese Academy of Sciences (CAS), and Harvard University, USA (A). The field observations and material we consulted included (inter alia) records of investigations by: G. Forrest (housed at the Royal Botanic Garden, Edinburgh, the Royal Botanic Garden Kew, London, KUN, and PE); T. T. Yü (housed at PE and KUN), J. F. Rock (housed at A and elsewhere), K. M. Feng (housed at KUN and PE); the Qinghai-Xizang Expedition (housed at KUN, PE, and HNWP), and David E. Boufford et al. (housed at A, KUN, PE, HNWP, and CDBI).

2 Results and Discussion

2.1 Species diversity

Under the influence of the warm, wet southwesterly monsoon from the Indian Ocean coupled with the

unique terrain of SW China, the alpine subnival belt of the HM is home to probably the most abundant subnival flora in the world, hosting 942 species, subspecies, and varieties of seed plants, belonging to 168 genera from 48 families (The Angiosperm Phylogeny Group, 2009). Currently, there is little available research material or published reports purely about subnival flora; the plants are usually included in work about the alpine belt (the mountain area above the treeline), where the elevation range and gradients are much larger than those in alpine subnival areas. However, the subnival flora of the HM includes two to six times more plant species than any other known alpine belt or subnival region globally (Körner, 2003; Noroozi et al., 2008, 2011), clearly demonstrating the richness of the region's flora.

There are some similarities between the dominant families in the HM and other high mountain regions around the world. Inter alia, the most abundant, in species numbers, are Asteraceae, Brassicaceae, Ranunculaceae, Caryophyllaceae, Rosaceae, Poaceae, and Cyperaceae (represented by 146, 71, 46, 44, 25, 24, and 20 species, respectively; Fig. 1). However, some families are unusually well represented in this region (Wu, 1988), or have not been recorded in the flora of any other mountainous region, such as Saxifragaceae (82 species), Papaveraceae (69 species), Gentianaceae (37 species), and Orobanchaceae (*Pedicularis*, 36 species; Fig. 1), indicating that the Himalaya–Hengduan Mountains have served as a distribution and differentiation center for them. Each of these families is represented by at least 10 species, and they are collectively represented by 873 species in the subnival flora, 92.68% of the total number.

The total number of genera that have been recorded in the alpine subnival belt of the HM is 168, approximately 12.68% of the 1325 (Li & Li, 1993) found in the HM region. However, some major genera whose differentiation center is the HM are most strongly represented in this belt (Zhang et al., 2009). Examples include *Saxifraga*, *Saussurea*, *Corydalis*, *Arenaria*, *Cremanthodium*, *Meconopsis*, *Solms-laubachia*, *Rhodiola*, *Kobresia*, and *Androsace*. According to Wang (1993–1994), these species are respectively represented by 75, 55, 49, 31, 28, 12, 13, 14, 12, and 10 species in the belt, out of 147 (51.02%), 94 (58.51%), 103 (47.57%), 57 (54.39%), 41 (68.29%), 16 (81.25%), 12 (100.00%), 36 (38.89%), 39 (30.77%), and 29 (34.48%) species of the respective genera found in the HM region. Thus, more than 30% of the species in these genera have established in the alpine subnival belt, further indicating that this region has served as part of the differentiation and evolutionary center for some groups, despite the extreme environment. Twenty-seven genera dominate the belt's flora, being represented by at least 10 species, 587 species in total (Fig. 2), which account for 16.07% of the genera and 62.31% of species recorded in the alpine subnival belt of the HM. Of these, 266 species are endemic to the HM.

Apart from the genera listed above, only one or two species of most genera have been found growing in the alpine subnival belt. There are 89 such genera (61 represented by a single species), collectively accounting for 52.98% of the total number of recorded genera. Furthermore, although the differentiation centers of some of these genera are located in the HM, the alpine subnival belt is at the margin of their distributions. For

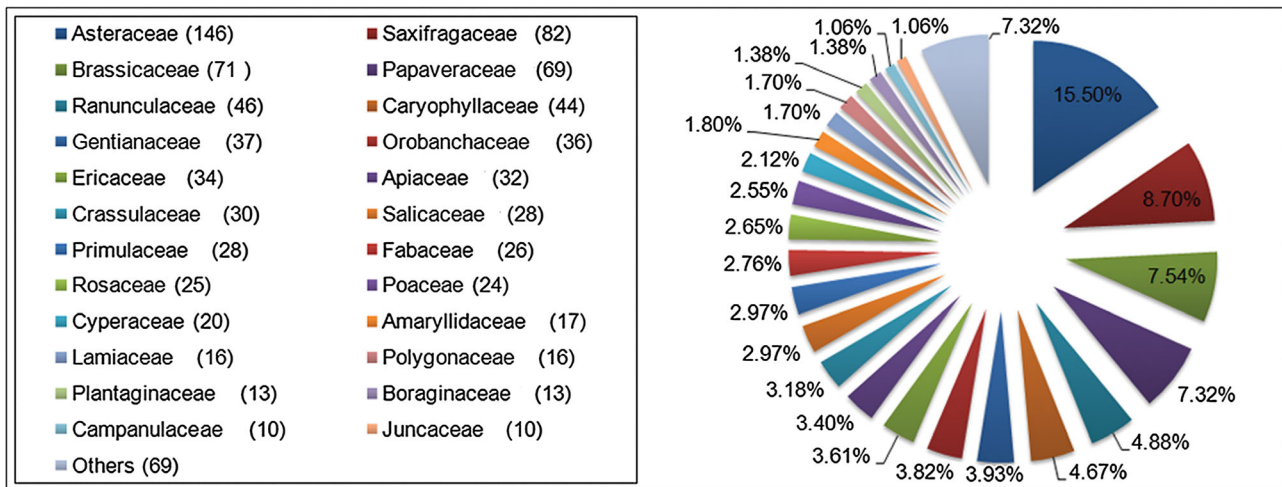


Fig. 1. Numbers of recorded species of the 24 families represented by at least 10 species in the alpine subnival belt of the Hengduan Mountains, and corresponding percentages of the total number of species in the alpine subnival belt of the Hengduan Mountains region.

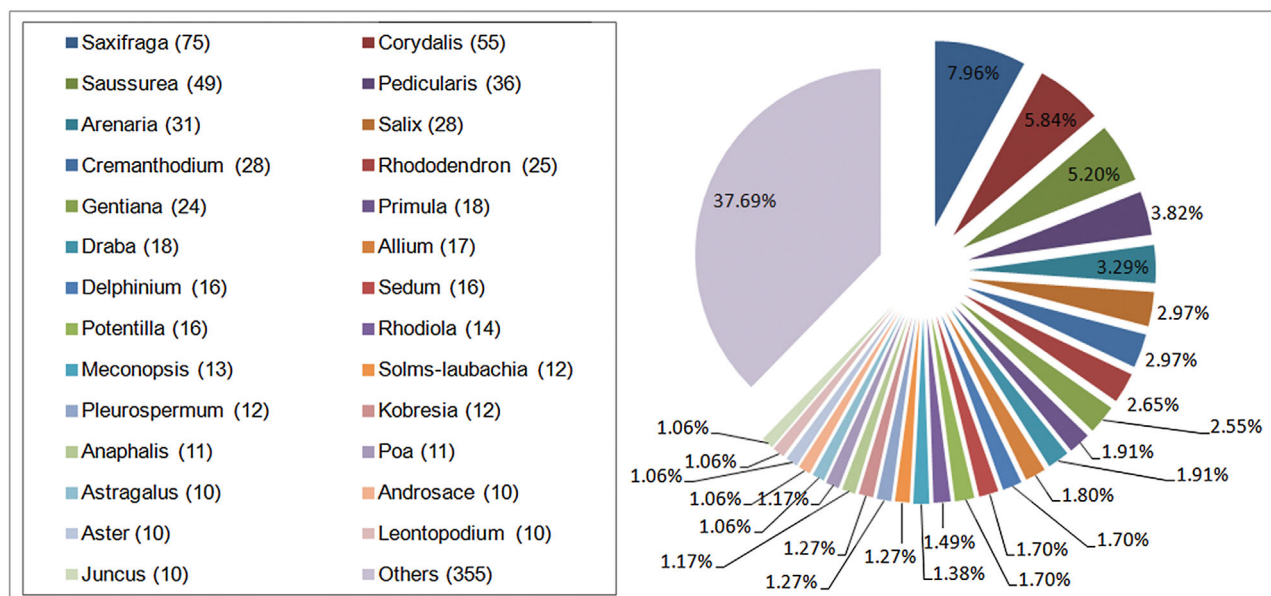


Fig. 2. Numbers of recorded species of the 27 genera represented by at least 10 species in the alpine subnival belt of the Hengduan Mountains, and corresponding percentages of the total number of species in the alpine subnival belt of the Hengduan Mountains region.

instance, *Incarvillea* includes 16 species whose differentiation center is the HM or Sino-Himalaya region, but only two of those species (*Incarvillea compacta* and *Incarvillea younghusbandii*) have dispersed into the alpine subnival belt. In addition, two species of *Iris* have been found in the alpine subnival belt, *Iris kemaonensis* and *Iris potaninii*, and *Euphorbia* is represented by only one species in the belt, *Euphorbia stracheyi*. These data confirm that the alpine subnival belt is the upper limit of the distribution for most families and genera present in the region.

2.2 Endemism

There are no endemic plant families in the alpine subnival belt of the HM. However, 13 genera are endemic to this belt of the Sino-Himalaya region (*Baimashania*, *Cavea*, *Chionocharis*, *Dipoma*, *Eriophyton*, *Hemilophia*, *Parasyncalathium*, *Przewalskia*, *Shangrilaia*, *Sinolimprichtia*, *Solms-laubachia*, *Soroseris*, and *Syncalathium*), of which four are strictly endemic to the alpine subnival region of the HM, *Baimashania*, *Dipoma*, *Hemilophia*, and *Shangrilaia* (Al-Shehbaz et al., 2004). Furthermore, although the ranges of some endemic genera have expanded to the QTP and the Himalayas, they are mainly confined to the HM area. These genera include *Sinolimprichtia*, *Syncalathium*, and *Parasyncalathium* (Zhang et al., 2011a). All of the 13 endemic genera except *Hemilophia*, *Solms-laubachia*, *Soroseris*, and *Syncalathium* are either monotypic (represented by a single species) or bitypic (represented by two species). The latter include

Baimashania and *Eriophyton*. Analysis of the plants' life-forms shows most of the endemic genera to be perennial herbs, except for the annual or perennial *Syncalathium*.

Syncalathium and *Parasyncalathium* show typical convergent evolution, presumably due to the harsh alpine habitats. Indeed, both genera appeared to be so close morphologically that *Parasyncalathium* was previously thought to be a species (*Syncalathium souliei*) of the *Syncalathium* within the subtribe Crepidinae, until it was recently identified as a monotypic genus within the different subtribe Lactucinae (Zhang et al., 2011a, 2011b). Molecular dating suggests that the divergence ages of *Syncalathium* and *Parasyncalathium* are 4.35 and 6.69 Mya, respectively (Zhang et al., 2011a, 2011b). *Przewalskia* has evolved a highly specialized morphological structure, with a cystic fruit adaptation that allows wind-dispersal of the seeds and probably provides a warm microenvironment that promotes seed development. Recent research suggests that speciation of *Przewalskia* probably occurred in the Miocene period (approximately 5.75 Mya), from a tertiary relict group that adapted to the extreme environment caused by plateau uplift (Tu et al., 2010). Therefore, the apparent speciation patterns of endemic groups provide indications that they originated in the late Miocene, predominantly as a consequence of the sharp uplift of the QTP.

In contrast to the low level of generic endemism, there is markedly higher specific endemism. Four kinds

Table 1 Families with the highest numbers of species endemic to the Hengduan Mountains (HM), the Sino-Himalaya alpine subnival belt, the HM alpine subnival belt, and respective percentages of endemic species within the families in the HM alpine subnival belt

Family	HM (%)	Sino-Himalaya alpine subnival belt (%)	HM alpine subnival belt (%)
Asteraceae	50 (34)	50 (34)	18 (12)
Papaveraceae	49 (71)	35 (51)	27 (39)
Saxifragaceae	35 (43)	35 (43)	17 (21)
Brassicaceae	31 (44)	42 (59)	27 (38)
Orobanchaceae	21 (58)	5 (14)	3 (8)
Caryophyllaceae	18 (41)	24 (55)	11 (25)
Ranunculaceae	17 (37)	20 (43)	9 (20)
Salicaceae	16 (57)	3 (11)	3 (11)
Primulaceae	15 (54)	11 (39)	7 (25)
Fabaceae	13 (50)	6 (23)	4 (15)
Gentianaceae	13 (35)	5 (14)	2 (5)
Ericaceae	12 (35)	4 (12)	3 (9)
Crassulaceae	11 (37)	4 (13)	3 (10)

of endemism are considered here: endemism to China; the HM; the Sino-Himalaya alpine subnival belt; and the HM alpine subnival belt. Approximately 587 of the 942 species recorded in the alpine subnival belt of the HM are endemic to China, of which 355 are only found in the HM (62.31% and 37.69%, respectively). The Asteraceae, Papaveraceae, Saxifragaceae, and Brassicaceae are represented by the highest numbers of species endemic to the HM (Table 1). However, the proportions of these endemics are highest in the Papaveraceae (71%), followed by the Orobanchaceae (58%), Salicaceae (57%), and Primulaceae (54%). In addition, 295 species are endemic to the Sino-Himalaya alpine subnival belt, 31.32% of the flora. Asteraceae is represented by the highest number of this class of endemic species, followed by Brassicaceae, Papaveraceae, and Saxifragaceae (Table 1), but the most highly ranked in terms of percentages of endemics are Brassicaceae (59%), followed by Caryophyllaceae (55%), Papaveraceae (51%), Ranunculaceae (43%), and Saxifragaceae (43%). About 151 species are

endemic to the alpine subnival belt of the HM, accounting for 16.03% of the flora. The families richest in this class of endemic species are Papaveraceae and Brassicaceae, followed by Asteraceae and Saxifragaceae (Table 1), however, the most highly ranked in terms of percentages of endemic species are Papaveraceae (39%), followed by Brassicaceae (38%), Caryophyllaceae (25%), and Primulaceae (25%).

2.3 Distribution patterns and floristic elements

Following the system of areal-types presented by Wu et al. (2006), we assigned the genera to floristic elements as follows: (1) Cosmopolitan (21 genera, 12.50% of the total); (2) Tropical Asia–Tropical Africa–Tropical America (S. America; one genus, 0.60%); (3) Tropical and Subtropical E. Asia and Tropical America Disjuncted (one genus, 0.60%); (4) N. Temperate (including Arctic–Alpine, S. and N. Temperate Disjuncted and Eurasia and Temperate S. America Disjuncted sub-types; 67 genera, 39.88%); (5) E. Asia & N. America Disjuncted (six genera, 3.57%); (6) Old World Temperate (including Eurasia–S. Africa, occasionally in Australia Disjuncted; 15 genera, 8.93%); (7) Temperate Asia (eight genera, 4.76%); (8) Mediterranean–W. Asia–C. Asia (two genera, 1.19%); (9) C. Asia (nine genera, 5.36%); (10) E. Asia (three genera, 1.79%); (11) Sino-Himalaya (24 genera, 14.29%); and (12) Endemic to China (confined to HM and adjacent area; 11 genera, 6.55%; Fig. 3).

Apart from Cosmopolitan, this analysis suggests that the most genus-rich floristic element is the N. Temperate, followed by the Sino-Himalaya, Old World Temperate, and Endemic to China elements. Of these, the N. Temperate element included the N. Temperate element (24 genera) and three subtypes as follows: the Arctic–Alpine element (nine genera), N. Temperate and S. Temperate Disjuncted element (24 genera), and Eurasia and Temperate S. America Disjuncted element (10 genera), according to Wu's division principle

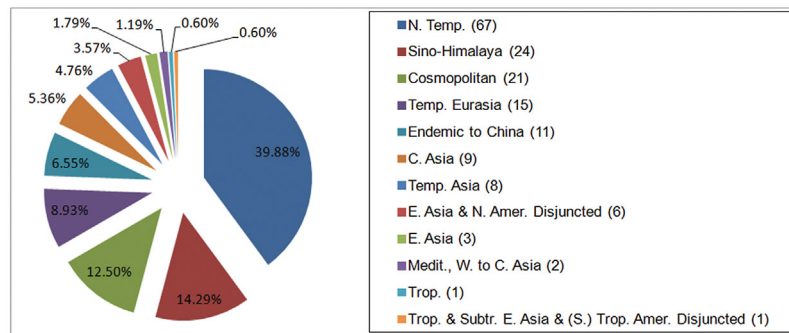


Fig. 3. Areal-types of the genera recorded in the alpine subnival belt of the Hengduan Mountains.

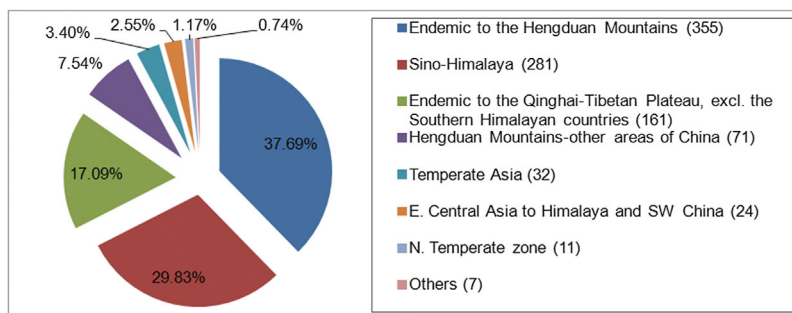


Fig. 4. Areal-types of the species recorded in the alpine subnival belt of the Hengduan Mountains.

(Wu et al., 2006). The results indicate that geological events such as the uplift of the QTP and Quaternary ice age have had profound and lasting effects on the alpine subnival flora of the HM.

The geographical distributions of the 942 species of seed plants recorded in the alpine subnival region of the HM were further divided into seven most important areal-types (Fig. 4), as follows (with examples):

1. Endemic to the Hengduan Mountains, the highest ranked element in term of species numbers. Examples include: *Allium nanodes*, *Corydalis benecincta*, *Meconopsis rudis*, *Saxifraga glacialis*, *Chesneya yunnanensis*, *Salix kangdingensis*, *Gentiana wardii* var. *emergens*, and *Saussurea velutina*.

The distribution of many species of this element is very narrow. Notably, 53 rare species have only been recorded in a single location, or on a particular mountain, and 24 are known solely from type specimens, including: *Shangrilaia nana* (Al-Shehbaz et al., 2004) and *Solms-laubachia zhongdianensis* (Yue et al., 2005), which only grow on Shika Shan in Shangrila, Yunnan; and *Solms-laubachia grandiflora* (Yue et al., 2008), only recorded on Rizhao Shenshan in Xiangcheng, Sichuan.

Most endemic species of this element belong to genera whose differentiation and distribution center is the HM. A number of genera encompass at least 10 such species, including *Corydalis*, *Saxifraga*, *Pedicularis*, *Saussurea*, *Salix*, *Arenaria*, *Cremanthodium*, *Primula*, *Delphinium*, *Solms-laubachia*, *Rhododendron*, and *Sedum*, which respectively include 42, 35, 21, 16, 16, 14, 14, 11, 11, 11, 10, and 10 endemic species, accounting for 76.36%, 46.67%, 58.33%, 32.65%, 57.14%, 45.16%, 50.00%, 61.11%, 68.75%, 91.67%, 40.00%, and 62.50% of the species of the respective genera recorded in the alpine subnival belt of the HM. In addition, some genera (excluding those endemic to the belt) have few species, but a high proportion

of species endemic to the belt. Examples include: *Androsace*, which contributes 10 species to the flora, four of which (40.00%) are endemic; and *Aconitum*, *Lagotis*, and *Silene*, each of which contributes nine species, four of which (44.44%) are endemic. *Ligularia*, *Senecio*, and *Chesneya* each contribute four species, three of which (75.00%) are endemic.

- The Sino-Himalaya element is composed of species that are mostly distributed in the E. Himalaya and HM regions, although some are found in the hinterland of the QTP and even other parts of China. Examples include: *Juniperus squamata*, *Fritillaria delavayi*, *Allium prattii*, *Meconopsis horridula*, *Thalictrum squamiferum*, *Rheum nobile*, *Arenaria densissima*, *Eriophyton wallichii*, *Saussurea medusa*, and *Saussurea obvallata*.
- The Endemic to the Qinghai-Tibetan Plateau element, excluding the southern Himalayan countries, is composed of species endemic to the QTP region of China. Examples include: *Corydalis retingensis*, *Arenaria brevipetala*, *Przewalskia tangutica*, *Marmoritis complanatum*, *Syncalathium kawaguchii*, and *Sinolimprichtia alpina*.
- The Hengduan Mountains-other areas of China element is also composed of species endemic to China. However, their ranges are larger than those of the Qinghai-Tibetan Plateau element, extending to the rest of China. Examples include: *Juniperus pingii* var. *wilsonii*, *Tofieldia divergens*, *Allium ovalifolium*, *Aconitum flavum*, *Stellaria arenarioides*, and *Pleurospermum franchetianum*.
- The Temperate Asia, including central, north, and east Asia, the Himalaya and the Qinghai-Tibetan Plateau element. Examples include: *Ephedra monosperma*, *Ponerorchis chusua*, *Papaver nudicaule*, *Potentilla glabra*, *Sibbaldia tetrandra*, *Draba altaica*, and *Lonicera hispida*.
- The E. Central Asia to Himalaya and SW China element is composed of species whose main

distribution area is located in E. Central Asia to the Himalayas, QTP, and HM. Examples include: *Allium carolinianum*, *Festuca coelestis*, *Biebersteina odora*, *Eutrema heterophyllum*, *Thylacospermum caespitosum*, and *Saussurea gnaphalodes*.

7. The Widespread in the N. Temperate zone (including Eurasia and N. America) element. Examples include: *Festuca rubra*, *Trisetum spicatum*, *Chamerion latifolium*, and *Polygonum viviparum*.

These findings show that endemic species account for a high proportion of the flora in the alpine subnival belt of the HM. Furthermore, the three elements with the highest species richness (the Endemic to the HM, Sino-Himalaya, and Qinghai–Tibetan Plateau, excluding the southern Himalayan countries elements, represented by 355, 281, and 161 species, respectively, are all restricted to the QTP region. Thus, 797 species, or 84.61% of the flora of the subnival belt of the HM, are restricted to the QTP, strongly indicating that geological events such as the uplift of the QTP and the Quaternary ice age have had profound and lasting effects on this flora. The results suggest that the flora is young and strongly differentiated, many species have had too little time to disperse outside the area since their speciation, and that intense island effects have accelerated the evolution of species through strong niche heterogeneity and the extreme environment.

3 Conservation of plant diversity in the alpine subnival belt

The alpine subnival belt of the HM is home to the richest alpine subnival belt flora in the world. However, populations of each species are rather small. In addition, approximately one-third of the plant species are endemic to the alpine subnival belt and most occur only in the HM. They are seriously threatened by increasing human activity, over-exploitation and utilization. Due to their long growth cycles and slow growth, alpine plants are more sensitive to disturbances than those growing at lower elevations (Körne, 2003). Furthermore, these endemic species have narrow distributions, some being restricted to the tops of hills, and are therefore severely endangered by habitat destruction and over-collection, which may cause population degeneration and have severely negative effects on their populations, possibly leading to their extinction. For example, the mean height of *Saussurea laniceps* in NW Yunnan province has decreased by 10 cm and its distribution area has shrunk (Law & Salick, 2005). Similar trends have also been observed in

other alpine subnival belt plant species, such as *Rhodiola* spp. and *Arenaria brevipetala* (Li et al., 2002).

Furthermore, global warming and increases in nitrogen deposition and atmospheric CO₂ concentration are threatening the alpine ecosystem and its biodiversity (Chapin & Körner, 1995; Schächli & Körner, 1996; Diaz & Bradley, 1997; Hughes, 2000; Spurgeon, 2000; Sala et al., 2002; Pockely, 2001). Baker & Mosely (2007) showed that warming of 0.06 °C per year is causing the retreat of glaciers and contributing to an elevational advance of the alpine treeline. A direct negative, short-term effect of rapid warming is habitat loss, leading to species extinction. At the present rate of global warming, by 2050 climate-induced habitat changes are expected to push 30% of species to extinction (Root et al., 2003; Thomas et al., 2004). The alpine subnival belt plants are expected to be particularly severely affected because of their narrow distributions, small populations, and high endemism. The mean annual growing season in alpine areas has already been lengthened by global warming (Menzel & Fabian, 1999), allowing grass species inhabiting sites at lower elevations to invade alpine areas (Dukes & Mooney, 1999). Direct results of species invasion from lower elevations include the gradual shrinkage of habitats of alpine native plants, with consequent effects on the structure and function of alpine ecosystems, including reductions in the diversity of species with special habitat requirements, some of which may be driven to extinction (Boer et al., 1990; Nilsson & Pitt, 1991; Holten, 1993; Sturm et al., 2001). Ongoing climate change is already gradually transforming alpine plant communities, as indicated by recent studies in all major European mountain systems (Gottfried et al., 2012; Pauli et al., 2012). Results of these studies show that the abundance of extremely cold-resistant species is declining and that of less cold-resistant species increasing, suggesting a progressive decline of cold mountain habitats and their biota. Continuation of the trend may shrink the European mountain flora, despite an average increase in summit species richness across the region (Gottfried et al., 2012; Pauli et al., 2012). Unfortunately, we do not know what is likely to happen in the subnival belt of the HM due to the scarcity of permanent observation plots. Such plots have only been established at four sites in NW Yunnan as part of the Global Observation Research Initiative in Alpine Environments network (www.gloria.ac.at). As the HM is a global biodiversity hot spot, we recommend the establishment of more long-term observation sites in the alpine subnival belt of the HM.

Acknowledgements The authors would like to thank D. E. BOUFFORD, Ji-Pei YUE, Lin-Yang CHEN, Jin-Long DONG, Guang-Fu CHEN, Yang YANG, Da-Cai ZHANG, Jia-Hui CHEN, Jian-Wen ZHANG, Wei-Dong ZHU, and others for their assistance during fieldwork and Xin-Hui LI for meaningful discussion about the division of species areal-types. Furthermore, the authors thank Bo SONG and others for the preparation of material for conservation of plant diversity. We also thank Sees-editing Ltd. for linguistic assistance, and staff of the herbaria of the Kunming Institute of Botany, Beijing Institute of Botany, Northwest Institute of Plateau Biology, Chengdu Institute of Biology (all CAS) and Harvard University, USA, for assistance with examining specimens. The study was supported by the Strategic Priority Research Program (B) of the Chinese Academy of Sciences (Grant No. XDB03030112), the National Natural Science Foundation of China (Grant Nos. 40930209 and 31100179), and the Hundred Talents Program of the Chinese Academy of Sciences (Grant No. 2011312D11022 to H. SUN).

References

- Al-Shehbaz IA, Yue JP, Sun H. 2004. *Shangrilaia* (Brassicaceae), a new genus from China. *Novon* 14: 271–274.
- Baker BB, Mosely RK. 2007. Advancing treeline and retreating glaciers: Implications for conservation in Yunnan, P.R. China. *Arctic, Antarctic and Alpine Research* 39: 200–209.
- Boer MM, Koster EA, Lundberg H. 1990. Greenhouse impact in Fennoscandia: Preliminary findings of European workshop on the effects of climate change. *Ambio* 19: 2–10.
- Boufford DE, Dijk PPV, Zhi L. 2004. Mountains of southwest China. In: Mittermeier RA, Robles-Gil P, Hoffman M, Pilgrim J, Brooks T, Mittermeier CG, Lamoreux J, da Fonseca Gustavo AB eds. *Hotspots revisited: Earth's biologically richest and most endangered ecoregions*. 2nd ed. Mexico: Cemex. 159–164.
- Chapin FS III, Körner Ch. 1995. Arctic and alpine biodiversity: Patterns, cause and ecosystem consequences. Berlin: Springer-Verlag. 1–332.
- Deng M, Zhou ZK. 2004. Seed plant diversity on screes from northwest Yunnan. *Acta Botanica Yunnanica* 26: 23–34.
- Diaz HF, Bradley R. 1997. Temperature variations during the last century at high elevation sites. *Climatic Change* 136: 253–279.
- Dukes JS, Mooney HA. 1999. Does global change increase the success of biological invaders? *Trends in Ecology and Evolution* 14: 135–139.
- Editorial Committee of Flora Reipublicae Popularis Sinicae. 1959–2004. *Flora Reipublicae Popularis Sinicae*. Beijing: Science Press.
- Fang WP ed. 1981–2011. *Flora Sichuanica*. Chengdu: Sichuan People's Publishing House, Sichuan Science and Technology Press, and Sichuan Nationalities Publishing House.
- Gao XF, Peng YL, Lidén M, Wang YW. 2008. Three new species of *Corydalis* (Fumariaceae) from northwestern Sichuan China. *Novon* 18: 330–335.
- Gottfried M, Pauli H, Futschik A, Akhalkatsi M, Barančok P, Alonso JLB, Coldea G, Dick J, Erschbamer B, Calzado MRF, Kazakis G, Krajčič J, Larsson P, Mallaun M, Michelsen O, Moiseev D, Moiseev P, Molau U, Merzouki A, Nagy L, Nakhutsrishvili G, Pedersen B, Pelino G, Puscas M, Rossi G, Stanisci A, Theurillat J-P, Tomaselli M, Villar L, Vittoz P, Vogiatzakis I, Grabherr G. 2012. Continent-wide response of mountain vegetation to climate change. *Nature Climate Change* 2: 111–115.
- Grierson AJC, Long DG, Noltie HJ. 1983–1994. *Flora of Bhutan: Including a record of plants from Sikkim*. Vols. 1–3. Edinburgh: Royal Botanic Garden.
- Hadley KS. 1987. Vascular alpine plant distributions within the central and southern Rocky Mountains, USA. *Arctic and Alpine Research* 19: 242–251.
- Hara H, Stearn WT, Williams LHJ, Chater AO. 1978–1982. An enumeration of the flowering plants of Nepal. Vols. 1–3. London: Trustees of British Museum (natural history).
- Hedberg O. 1963. The phytogeographical position of the afroalpine flora. *Recent Advances in Botany* 1: 914–919.
- Holten JJ. 1993. Potential effects of climate change on distribution of plant species, with emphasis on Norway. In: Holten JJ, Paulsen G, Oechel WC eds. *Impacts of climate change on natural ecosystems*. Trondheim: Norwegian Institute for Nature Research. 84–105.
- Hooker JD. 1872–1897. *Flora of British India*. Vols. 1–7. London: L. Reeve & Co.
- Hughes L. 2000. Biological consequences of global warming: Is the signal already apparent? *Trends in Ecology and Evolution* 15: 56–61.
- Körner C. 2003. *Alpine plant life: Functional plant ecology of high mountain ecosystems*. New York: Springer-Verlag.
- Körner C, Spehn EM. 2002. *Mountain biodiversity: A global assessment*. New York: Parthenon Publishing Group Ltd.
- Law W, Salick J. 2005. Human-induced dwarfing of Himalayan snow lotus, *Saussurea laniceps* (Asteraceae). *Proceedings of the National Academy of Sciences USA* 102: 10218–10220.
- Li BS, Wang JT, Li SY. 1987. The floristic features and geographic distribution of the cushion plant in Xizang. *Mountain Research* 15: 14–20.
- Li BS, Zhang JW, Wang JT. 1985. The alpine cushion vegetation of Xizang. *Acta Botanica Sinica* 27: 311–317.
- Li BS, Zhang JW, Wang JT, Chen WL. 1981. A preliminary study of the subnival vegetation in Xizang. *Acta Botanica Sinica* 23: 132–139.
- Li BY. 1987. On the boundaries of the Hengduan Mountains. *Mountain Research* 5: 74–82.
- Li LY, Zhan D, Wei YF, Zhong GY, Qin SY, Ciren BZ, Gesang BZ. 2002. Conservation of endangered species resources of Tibetan medicine in China. *China Journal of Chinese Materia Medica* 27: 561–563.
- Li XW, Li J. 1993. A preliminary floristic study on the seed plants from the region of Hengduan Mountain. *Acta Botanica Yunnanica* 15: 217–231.
- Lidén M. 1996. New taxa of tuberous *Corydalis* (Fumariaceae). *Willdenowia* 26: 23–35.

- Lidén M, Su ZY. 2007. New species of *Corydalis* (Fumariaceae) from China II. *Novon* 17: 479–496.
- Liu LH, Yu YD, Zhang JH. 1984. The division of vertical vegetation zone in Hengduanshan. *Acta Botanica Yunnanica* 6: 205–216.
- Liu SW ed. 1996–1999. *Flora Qinghaiica*. Vols. 1–4. Xining: Qinghai People's Publishing House.
- Mark AF, Adams NM. 1979. *New Zealand alpine plants*. 2nd ed. Wellington: A.H. & A.W. Reed Ltd.
- Menzel A, Fabian P. 1999. Growing season extended in Europe. *Nature* 397: 659.
- Myers N, Mittermeier RA, Mittermeier CG, da Fonseca GAB, Kent J. 2000. Biodiversity hotspots for conservation priorities. *Nature* 403: 853–858.
- Nagy L, Grabherr G. 2009. *The biology of alpine habitats*. New York: Oxford University Press.
- Nilsson S, Pitt D. 1991. *Mountain world in danger: Climate change in the forests and mountains of Europe*. London: Earthscan Publications.
- Noroozi J, Akhiani H, Breckle S-W. 2008. Biodiversity and phytogeography of the alpine flora of Iran. *Biodiversity and Conservation* 17: 493–521.
- Noroozi J, Pauli H, Grabherr G, Breckle SW. 2011. The subnival-vascular plant species of Iran: A unique high-mountain flora and its threat from climate warming. *Biodiversity and Conservation* 20: 1319–1338.
- Pauli H, Gottfried M, Dullinger S, Abdaladze O, Akhalkatsi M, Alonso JLB, Coldea G, Dick J, Erschbamer B, Calzado RF, Ghosn D, Holten JI, Kanka R, Kazakis G, Kollár J, Larsson P, Moiseev P, Moiseev D, Molau U, Mesa JM, Nagy L, Pelino G, Puşcaş M, Rossi G, Stanisci A, Syverhuset AO, Theurillat J-P, Tomaselli M, Unterluggauer P, Villar L, Vittoz P, Grabherr G. 2012. Recent plant diversity changes on Europe's mountain summits. *Science* 336: 353–355.
- Peng DL, Zhang ZQ, Xu B, Li ZM, Sun H. 2012. Patterns of flower morphology and sexual systems in the subnival belt of the Hengduan Mountains, SW China. *Alpine Botany* 122: 65–73.
- Pockely P. 2001. Climate change transforms island ecosystems. *Nature* 410: 616.
- Root TL, Price JT, Hall KR, Schneider SH, Rosenzweig C, Pounds JA. 2003. Fingerprints of global warming on wild animals and plants. *Nature* 421: 57–60.
- Sala OE, Chapin FS III, Armesto JJ, Berlow E, Bloomfield J, Dirzo R, Huber-Sanwald E, Huenneke LF, Jackson RB, Kinzig A, Leemans R, Lodge DM, Mooney HA, Oesterheld M, Poff NL, Sykes MT, Walker BH, Walker M, Wall DH. 2002. Global biodiversity scenarios for the year 2100. *Science* 287: 1770–1774.
- Schäppi B, Körner C. 1996. Growth responses of an alpine grassland to elevated CO₂. *Oecologia* 105: 43–52.
- Spurgeon D. 2000. Global warming threatens extinction for many species. *Nature* 407: 121.
- Sturm M, Racine C, Tape K. 2001. Increasing shrub abundance in the Arctic. *Nature* 411: 546–547.
- Su ZY. 1997. New taxa of *Corydalis* from China. *Acta Botanica Yunnanica* 19: 227–235.
- Su ZY, Lidén M. 1997. *Corydalis* in China I: Some new species. *Edinburgh Journal of Botany* 54: 55–84.
- The Angiosperm Phylogeny Group. 2009. An update of the Angiosperm Phylogeny Group classification for the orders and families of flowering plants: APG III. *Botanical Journal of the Linnean Society* 161: 105–121.
- Thomas CD, Cameron A, Green RE, Bakkenes M, Beaumont LJ, Collingham YC, Erasmus BFN, de Siqueira MF, Grainger A, Hannah L, Hughes L, Huntley B, van Jaarsveld AS, Midgley GF, Miles L, Ortega-Huerta MA, Peterson AT, Phillips OL, Williams SE. 2004. Extinction risk from climate change. *Nature* 427: 145–148.
- Tu TY, Volis S, Dillon M, Sun H, Wen J. 2010. Dispersals of Hyoscyameae and Mandragoreae (Solanaceae) from the New World to Eurasia in the early Miocene and their biogeographic diversification within Eurasia. *Molecular Phylogenetics and Evolution* 57: 1226–1237.
- Wang WT ed. 1993–1994. *Vascular plants of the Hengduan Mountains*. Vols. 1–2. Beijing: Science Press.
- Wang YW, Lidén M. 2006. *Corydalis panda* (Fumariaceae), a new species from Sichuan, China. *Annales Botanici Fennici* 43: 478–480.
- Wu ZY ed. 1977–2010. *Flora Yunnanica*. Vols. 1–22. Beijing: Science Press.
- Wu ZY ed. 1983–1987. *Flora Xizangica*. Vols. 1–5. Beijing: Science Press.
- Wu ZY. 1988. Hengduan Mountain flora and her significance. *Journal of Japanese Botany* 63: 1–31.
- Wu ZY, Raven PH eds. 1994–2011. *Flora of China*. Beijing: Science Press; St. Louis: Missouri Botanical Garden Press.
- Wu ZY, Zhou ZK, Sun H, Li DZ, Peng H. 2006. The areal-types of seed plants and their origin and differentiation. Kunming: Yunnan Science and Technology Press. 146–451.
- Wu ZY, Zhu YC, Jiang HQ. 1987. *Yunnan vegetation*. Beijing: Science Press.
- Yue JP, Al-Shehbaz IA, Sun H. 2005. *Solms-laubachia zhongdianensis* (Brassicaceae), a new species from the Hengduan Mountains of Yunnan, China. *Annales Botanici Fennici* 42: 155–158.
- Yue JP, Sun H, Li JH, Al-Shehbaz IA. 2008. A synopsis of an expanded *Solms-laubachia* (Brassicaceae) and the description of four new species from western China. *Annals of the Missouri Botanical Garden* 95: 520–538.
- Zhang DC, Sun H. 2008. Distribution of specimens and species richness of seed plants above timber line in the Hengduan Mountains, southwest China. *Biodiversity Science* 16: 381–388.
- Zhang DC, Zhang YH, Boufford DE, Sun H. 2009. Elevational patterns of species richness and endemism for some important taxa in the Hengduan Mountains, southwestern China. *Biodiversity and Conservation* 18: 699–716.
- Zhang JW, Boufford DE, Sun H. 2011a. *Parasyncalathium* J. W. Zhang, Boufford, H. Sun (Asteraceae, Cichorieae): A new genus endemic to the Himalaya-Hengduan Mountains. *Taxon* 60: 1678–1684.
- Zhang JW, Nie ZL, Wen J, Sun H. 2011b. Molecular phylogeny and biogeography of three closely related genera, *Sorosotis*, *Stebbinsia*, and *Syncalathium* (Asteraceae, Cichorieae), endemic to the Tibetan Plateau, SW China. *Taxon* 60: 15–26.
- Zhang ML, Su ZY, Lidén M. 2008. *Corydalis*. In: Wu ZY, Raven PH eds. *Flora of China*. Beijing: Science Press; St. Louis: Missouri Botanical Garden Press. 7: 295–428.