

## The 29°N latitudinal line: an important division in the Hengduan Mountains, a biodiversity hotspot in southwest China

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This paper aimed to explore the division of the southern and northern Hengduan Mountains based on gradients in species similarity and richness, and to analyze species richness in each sub-region. The Hengduan Mountain region was divided into nine latitudinal belts using one degree of latitude to define the belt after which distribution of seed plants within each latitudinal belt was recorded. Latitudinal patterns of species similarity were measured using the Jaccard similarity index for each pair of adjacent latitudinal belts. Non-metric multidimensional scaling (NMDS) was also used to analyze the similarity in species composition among the nine latitudinal belts. The latitudinal pattern of species similarity and the NMDS ordination both showed a great change in species composition across the 29°N latitudinal line, essentially dividing the Hengduan Mountain region into southern and northern sub-regions. Species richness, shown by the *c*-value of the species–area power function, and species–area ratio along a latitudinal gradient both showed a sharp decrease across the latitudinal belt from 29°0′ to 29°59′N. The southern sub-region occupied 40% of the total area of the Hengduan Mountain region, but contained more than 80% of all the seed plants in the region. The higher species richness and endemism in the southern sub-region showed it to be the core of the Hengduan biodiversity hotspot, a result not unexpected because of the greater extremes of topography and wider diversity of habitats in the southern portion.

Species richness, endemism and degree of threat from human activities are among the main factors in the designation of biodiversity hotspots (Myers 1988, Mittermeier et al. 1998, Myers et al. 2000). Based on these criteria, the Hengduan Mountain region in southwestern China has been designated one of the world's biodiversity hotspots (Boufford and Dijk 2000, Myers et al. 2000, Boufford et al. 2004). Nationally, the southern and northern sub-regions of the Hengduan Mountains have been recognized as being among the 11 key regions of terrestrial biodiversity in China (SEPA 1998). Until now, however, these areas have been poorly described, and their delimitation has been insufficiently analyzed. In particular, species richness and endemism among the sub-regions have never been analyzed and compared.

The latitudinal gradients in topography and climate have already been noted, and the differences in vegetation and climate between the southern and northern Hengduan Mountains have been discussed by Yu et al. (1989) and Zhang et al. (1997). As a region of high biodiversity, however, species richness and endemism have received considerable attention by biologists (Prendergast et al. 1993, Kier and Barthlott 2001, Hobohm 2003). Among the questions raised are whether a latitudinal gradient in species richness and similarity exists to denote the division of the southern and northern Hengduan Mountains, and

whether this division coincides with the division of vegetation. In this study, we analyze the patterns of seed plant species richness and similarity in species composition across a latitudinal gradient to determine the dividing line between the southern and northern Hengduan Mountains, provide details of seed plant species richness in each sub-region, and demonstrate the differences in species richness and endemism between the sub-regions.

Variation in species richness along an environmental gradient is not linear. Abrupt changes in species richness can indicate boundaries between different sub-regions (Koleff and Gaston 2001, Vetaas and Grytnes 2002, Brayard et al. 2005). To compare differences in species richness among sites of varying sizes, the effect of area should be eliminated. Simple species–area ratio, assumed to have a linear species–area relationship, has been used by Myers et al. (2000) and Fattorini (2006) to designate biodiversity hotspots. Species–area relationships are best described, however, by the power function,  $S = cA^z$ , where *S* equals species richness, *A* equals area size, and *c* and *z* are constants (Connor and McCoy 1979, Wright 1981). The *c*-value has been calculated to detect differences in species richness among sites of varying sizes, with a higher *c*-value indicating an increase in species richness (Ovadia 2003, Fattorini 2006). We here describe the latitudinal patterns of species richness by both species–area

ratio and c-value to determine if they are consistent and if they show a sharp change at the same latitudinal belt indicative of a division between the southern and northern sub-regions.

A similarity index of species composition is a quantitative assessment of the affinity of species among sites. Higher values indicate greater consistency in species composition (Magurran 2004). Similarity indexes of species have also been used to partition biotic areas. A low value of species similarity between areas can be used to determine boundaries of biotic areas, with each biotic area showing high affinity in species composition (Whittaker 1972, Ibarra-Manríquez et al. 2002, Primo and Vázquez 2004, Xie et al. 2004).

Can changes in species richness and similarity indicate boundaries between the southern and northern Hengduan Mountains? If both species richness and similarity change sharply at the same latitude, that will indicate a clear division between the southern and northern Hengduan Mountains. Such a division will not only distinguish species richness in each sub-region, but will also show each sub-region to be a separate biogeographic unit. The primary aims of this study, therefore, are to 1) describe the variation in species richness and similarity along a latitudinal gradient in the Hengduan Mountains; 2) explore the division between the southern and northern sub-regions based on latitudinal gradients in species richness and similarity in species composition, and to analyze species richness and endemism in each sub-region.

## Material and methods

### Study area

The Hengduan Mountains include western and north-western Yunnan, western Sichuan, eastern and southeastern Tibet (Xizang), southeastern Qinghai and southwestern Gansu, an area of 364 000 km<sup>2</sup> stretching from 24°40' to 34°00'N and from 96°20' to 104°30'E (Li 1987) (Fig. 1). Six mountain chains and rivers cross the region from north to south. They contrast with other Chinese mountains and rivers, which run from west to east. The average elevation within the region decreases from west to east and from north to south. Annual mean temperature ranges from 12 to 15°C in the south and from 9 to 12°C in the north. Annual mean precipitation is higher in the south, southeast and southwest (1000–1300 mm) than in the center and north (600–800 mm) (Zhang et al. 1997). The vegetation in the region can be broadly categorized into two types separated by a curved line joining Kangding, Muli, Zhongdian ('Shangri-La') and Baxoi (Yu et al. 1989) (Fig. 1). To the south, the vegetation at low elevations consists of broadleaved forest with a mixture of evergreen and deciduous species, e.g. *Castanopsis*, *Cyclobalanopsis*, *Lithocarpus*, *Quercus*, *Michelia*, *Schima*, *Betula* and *Acer*. In the north, the vegetation is less varied than in the south and is represented by the Qinghai-Xizang plateau alpine vegetation consisting mainly of coniferous trees (Liu et al. 1984, 1985, Yu et al. 1989). Along the elevational gradient, vegetation in the south is more varied than in the north, but coniferous forests, consisting mainly of species of *Picea*, *Abies*, *Pinus*, *Larix*

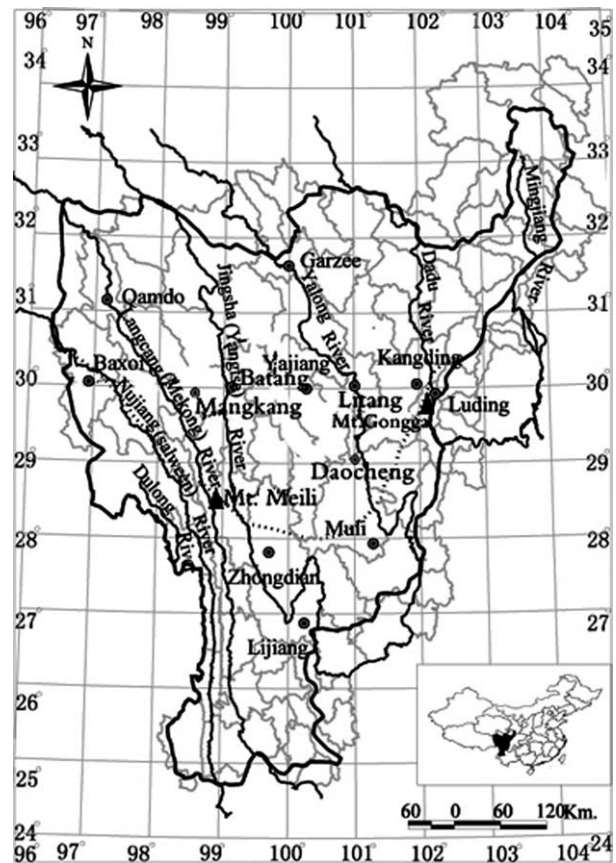


Figure 1. Location of the Hengduan Mountains in southwest China, and its boundary. The broken line indicates the limit between evergreen broad-leaved forest and Qinghai-Xizang plateau alpine vegetation.

(Pinaceae) and *Juniperus* (Cupressaceae), occupy the same elevational range, from 3100–4100 m a.s.l., within the entire region (Liu et al. 1984).

### Sources of data

Data from publications, online databases, field investigations and specimens in herbaria were compiled into a database. 'The vascular plants of the Hengduan Mountains' (Wang 1993, 1994) is the most important publication for information on the distribution of species within the region. This work presents the distributions of species in the region based on 21 082 specimens of vascular plants collected during a systematic survey of the plants of the Hengduan Mountains by members of the Chinese Academy of Sciences. The online database, 'Biodiversity of the Hengduan Mountains and adjacent areas of south-central China' data sets (<<http://hengduan.huh.harvard.edu/fieldnotes>>) lists over 13 500 specimens identified to species, each record giving name, location, habitat, geographic coordinates, elevation and date of collection and collectors. Observations from field investigations and specimens deposited in the herbarium of the Kunming Inst. of Botany (KUN) of the Chinese Academy of Sciences provided additional data that was added to the database.

## Area data

The digital elevational model (DEM) from the China State Bureau of Surveying and Mapping was used to calculate the area of each 1° latitudinal belt within the region using ESRI's Arcview 3.1. We interpolated the DEM for each 1° latitudinal belt and rasterized at 1 × 1 km grid cells, then counted the number of grid cells to sum up the area.

## Analysis of data

The Hengduan Mountains region was divided into nine latitudinal belts, starting with the first belt at 24°40' to 25°59'N, each one degree of latitude marked the northern boundary of succeeding belts, with nine latitudinal belts labeled I to IX from south to north. Based on specimens and data from publications, the distribution of each species within a latitudinal belt was recorded, and a matrix of present (1) or absent (0) for species in each latitudinal belt was constructed. We calculated the Jaccard similarity index for each pair of adjacent latitudinal belts using EstimateS 7.51 software (Colwell 2005). The latitudinal pattern of species similarity was determined by variation in species similarity between adjacent latitudinal belts from south to north. We analyzed the latitudinal pattern of species similarity for all seed plants in the Hengduan Mountains, and separately for endemic species, trees and species occurring at mid elevations, from 3100–4100 m a.s.l., in coniferous forests. We also selected 16 genera to test the universality of these patterns using the following criterion: temperate genera with the number of species in the region exceeding 100 (*Aconitum*, *Corydalis*, *Pedicularis*, *Primula*, *Rhododendron*, *Salix*, *Saxifraga* and *Saussurea*); sub-tropical to temperate genera with the number of species in the region exceeding 40 (*Euonymus*, *Ilex*, *Impatiens*, *Indigofera* and *Rabdosia*); and widespread Northern Hemisphere genera, with the number of species in the region exceeding 100, including *Astragalus*, *Carex* and *Gentiana*. Non-metric multidimensional scaling (NMDS) ordination, performed in PC-ORD 4.0, was used to analyze patterns of species composition among the nine latitudinal belts based on pairwise Jaccard similarity indices.

We separately determined the number of total, endemic and tree species within different latitudinal range and calculated the area of the corresponding latitudinal range starting from the southernmost latitudinal belt (24°40'–25°59'N), then for the southernmost two and three latitudinal belts, through the entire region. We used the combination of species richness and area to determine species–area relationships (SAR) for total, endemic and tree species by linear and power models. The regressions showed

a strong relationship between area and species richness for both linear and power models (Table 1). The species–area ratio was calculated by the formula: species–area ratio = number of species/area (100 km<sup>-2</sup>). Based on the z-values of total, endemic or tree species (Table 1), estimated by the power function of SAR, we calculated the c-values for each latitudinal belt. The latitudinal pattern of species richness was revealed by both patterns of species–area ratio and c-value.

A species was defined as endemic if its distribution is limited to the Hengduan Mountain region or only extends slightly into neighboring regions. Endemism is expressed as the percentage of endemic species within each latitudinal belt or region relative to the total number of species within that belt or region. All graphic representation was performed in SPSS 11.5.

## Results

The total number of seed plants in the Hengduan Mountains is 8590, with 2783 of these species (32.4%) being endemic to this region, 777 species being arborescent, and 4535 species occurring at mid elevations, from 3100 to 4100 m a.s.l. For the total species number in this region and its sub-sets of the endemics, tree species and species at mid elevations, the variation in species similarity between adjacent latitudinal belts along the latitudinal gradient tended to show two inconspicuous peaks. Similarity increased with increasing latitude between 24°40' and 28°N, then declined to a visibly low value around 29°N, then decreased slowly with increasing latitude between 30° and 34°N (Fig. 2a). Low similarity index was found at three latitudes, namely between the southernmost, northernmost and across the 29°N latitudinal belts (Fig. 2a). Species at mid elevations, from 3100 to 4100 m a.s.l., had the highest similarity, and endemics showed the lowest similarity there (Fig. 2a).

Among the 16 selected genera, 9 genera showed a similar latitudinal pattern of species similarity with the total, endemic, tree and species at mid elevations (Fig. 2b–d); 4 genera showed a low similarity between the southernmost and 29°N latitudinal belts, but not between the northernmost belts (Fig. 2e); 3 genera did not show a notable low similarity between the latitudinal belts on each side of 29°N (Fig. 2f).

The NMDS ordinations of the total species, endemic species, tree species and species at mid elevations (3100–4100 m a.s.l.) congruently showed that latitudinal belts I and IX had a low degree of similarity with other latitudinal belts, and similarity between latitudinal belts IV and V was also

Table 1. Regression between species richness and area by linear and power models, and values of parameters. \*denotes a p-value <0.001 and \*\*denotes a p-value <0.05.

Species subset	Linear model		Power model		
	R <sup>2</sup>	Slope	R <sup>2</sup>	c-value	z-value
Total species	0.85*	0.014	0.92*	72.1	0.3772
Endemic species	0.80*	0.006	0.88*	1.0	0.6271
Trees	0.76**	0.001	0.92*	19.1	0.2932

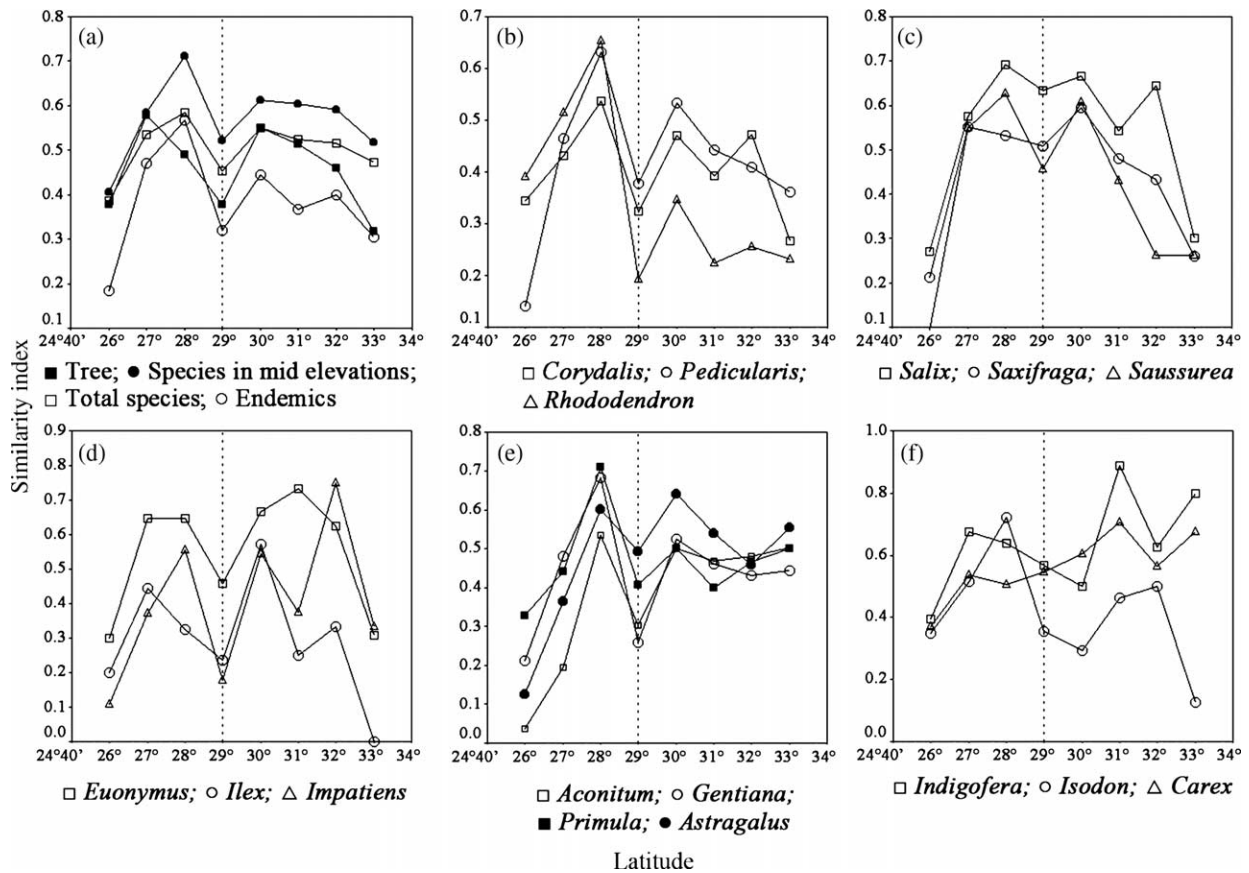


Figure 2. Similarity between adjacent 1° latitudinal belts along a latitudinal gradient in the Hengduan Mountains in southwest China. The reference line indicates a site where the species similarity exhibits a visibly low value (a)–(e) or not (f). (a)–(d) similarity between the southernmost, northernmost or across the 29°N latitudinal belts, presented a visibly low value, (e) similarity between southernmost or across the 29°N latitudinal belt was notably low, (f) the latitudinal pattern of similarity differed from that of (a)–(e).

low (Fig. 3). Combining the locations, the nine latitudinal belts can be divided into two groups; latitudinal belts I–IV clustered into one group while latitudinal belts V–IX clustered into one other group (Fig. 3).

For total species, endemic species and tree species, the latitudinal patterns of species richness shown by c-values

were consistently unimodal and peaked at latitudinal belt III (27.0°–27.9°N) (Fig. 4a). The species–area ratio of the total species and tree species on average decreased monotonously with increasing latitude, but the species–area ratio for endemic species showed a unimodal pattern, peaking at latitudinal belt III (27.0°–27.9°N) (Fig. 4b). Patterns of

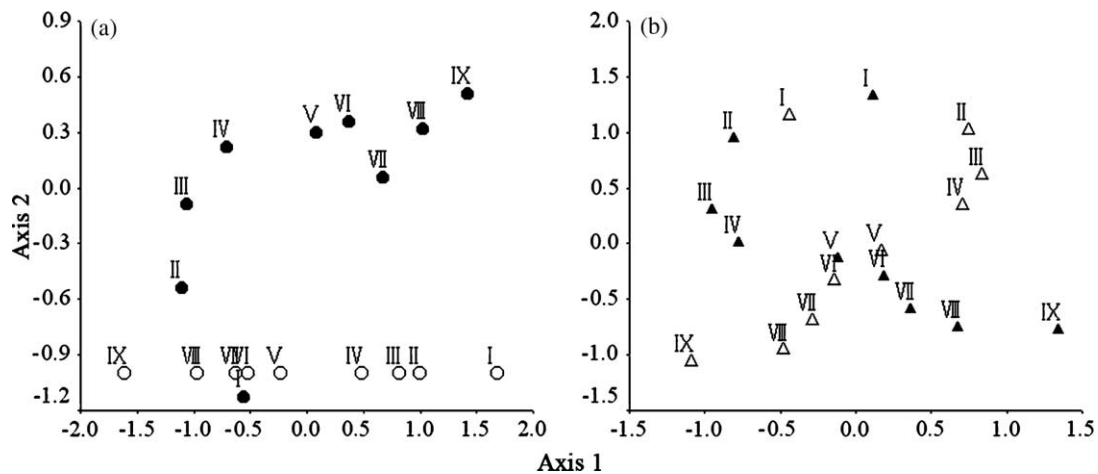


Figure 3. NMDS ordination of nine latitudinal belts in the Hengduan Mountains, based on the Jaccard similarity index. (a) for total species (●) and trees (○), (b) for endemic species (△) and species in mid elevations from 3100–4100 m a.s.l. (▲). The ordination of trees was one-dimensional, and a fixed value on Axis 2 (–1) was assigned to all plots.

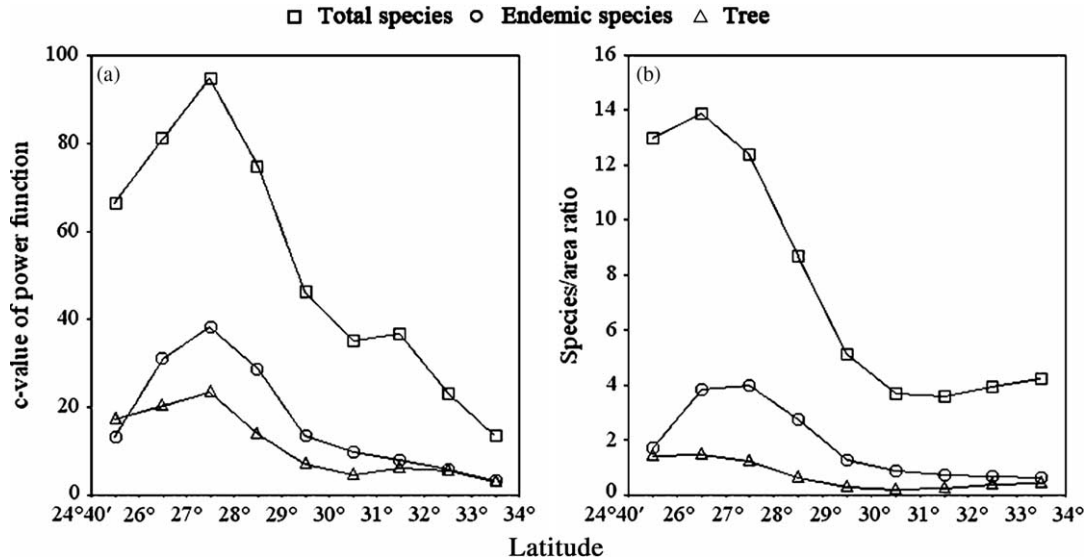


Figure 4. Latitudinal pattern of species richness in the Hengduan Mountains. (a) pattern of *c*-value of the power function was unimodal and peaked at the latitudinal belt from 27.0°N to 27.9°N for total species, endemic species and tree species, (b) the pattern of species–area ratio (100 km<sup>-2</sup>) tended to decrease with increasing latitude for total species and trees and, in addition, tended to be unimodal for endemics, peaking at the latitudinal belt from 27.0°N to 27.9°N.

species richness shown by *c*-values and species–area ratios were strongly correlated ( $R^2 = 0.78$  for total species, 0.96 for endemics and 0.84 for trees), and both showed a sharp decrease at latitudinal belt V (29.0°–29.9°N) (Fig. 4).

Variation in endemism of total species and tree species along the latitudinal gradient also presented a unimodal pattern, peaking at latitudinal belts III and IV (27.0°–28.9°N) (Fig. 5).

According to the latitudinal patterns of species richness and similarity, the Hengduan Mountain region can be divided into a southern and a northern sub-region along the 29°N latitudinal line. Species richness and degree of endemism between the sub-regions differ greatly. The southern sub-region occupies 40% of the total area, but has more than 80% of the total, endemic and tree species.

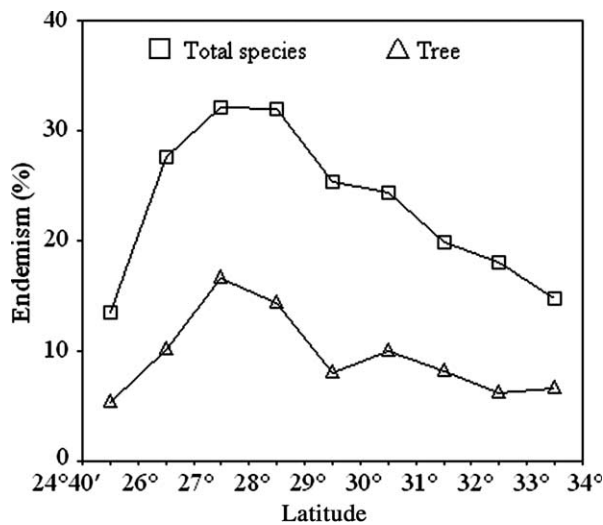


Figure 5. Variation in endemism of total species and tree species along the latitudinal gradient showing an unimodal pattern peaking at the latitudinal belt from 27.0°N to 27.9°N.

More than 50% of the total species and 60% of the endemic and tree species have their distribution only in the southern sub-region; and endemism in the southern sub-region is higher than in the northern sub-region (Table 2).

## Discussion

### Latitudinal pattern of species similarity

The latitudinal pattern of similarity for all species within the Hengduan Mountain region coincides with the patterns for endemic species, tree species and species at mid elevations (3100–4100 m a.s.l.), and for the species in most of the selected genera. There is a visibly low value of similarity between the belts on each side of the 29°N latitudinal line (Fig. 2a–d). The Hengduan Mountains comprise a natural floristic region bordering the Yunnan plateau flora region in the south and the Tangut flora region in the north (Wu and Wu 1996). The composition of the species in the southernmost and the northernmost latitudinal belts is therefore characterized partly by the adjacent floristic region, explaining the observed low similarity between the southernmost and the northernmost latitudinal belts. Furthermore, the dissimilarity in species composition between the southernmost or northernmost latitudinal belts coincides with the southern and northern boundaries of the Hengduan Mountains.

Topography is an important limiting factor in the distribution of species (Bruun 2000, Takyu et al. 2005, Ding et al. 2006) and the great change in topography near 29°N can well explain the low degree of similarity between the latitudinal belts across 29°N. There is a series of high mountains and plateaus along a line coinciding roughly with the 29°N latitudinal line in this region. Mt Gongga, the highest mountain in the region (7556 m a.s.l.), and 28 other mountains with rising above 6000 m a.s.l.

Table 2. Comparison of species richness, endemism and area between the southern and northern Hengduan Mountains. <sup>a</sup> = all seed plants in the southern or northern sub-region, <sup>b</sup> = species distributed only in the south or north by subtracting species shared by the two sub-regions from the total species in southern or northern sub-region.

Region	Entire region	Southern sub-region		Northern sub-region	
		Total <sup>a</sup>	Sub-total <sup>b</sup>	Total <sup>a</sup>	Sub-total <sup>b</sup>
Total species					
Number of species	8590	7146	4477	4113	1444
% relative to total	100.0	83.2	52.1	47.9	16.8
% endemism	32.4	32.0	38.9	25.3	34.1
Endemic species					
Number of species	2783	2290	1742	1041	493
% relative to endemics	100.0	82.3	62.6	37.4	17.7
Trees					
Number of species	777	685	507	270	92
% relative to trees	100.0	88.2	65.3	34.7	11.8
% endemism	15.7	15.3	18.3	10.7	18.5
Area					
Area (km <sup>2</sup> ) and %	364 000	148 000 (40.7%)		216 000 (59.3%)	

around Mt Gongga are located in the east (Li 1989). The Litang–Daocheng Plateau is located in the middle of this region, and the peaks on the plateau frequently exceed 5500 meters a.s.l. Meili Snow Mountain and the Mangkang Plateau are located to the west (Zhang et al. 1997). The high mountains and plateaus form a significant obstacle for the dispersal of species across the region, reflected by the greatly different species composition in the latitudinal belts north and south of 29°N. Species similarities in the genera *Indigofera* and *Rabdosia* do not show a low value between the latitudinal belts across 29°N (Fig. 2f), since the species in these genera are mainly distributed in the valleys. Variation in topography near 29°N therefore has little influence on their distribution. The lower species similarity between adjacent latitudinal belts across 29°N defines the boundary between the southern and the northern Hengduan Mountains.

Species similarity is used to quantitatively classify the communities (Shokri et al. 2004, Su et al. 2004), so that variation in the vegetation in this region, occurring within the latitudinal range from 28°N to 30°N, where broad-leaved forests are gradually replaced by temperate coniferous forests (Fig. 1) (Yu et al. 1989), coincides with the pronounced change in species composition at 29°N. But the variation in vegetation and species composition does not completely coincide. Coniferous forest covers the same elevational range throughout the entire Hengduan Mountain region, but its species composition greatly changes around 29°N (Fig. 2a).

### Species–area ratios and c-values of power function

Latitudinal patterns of species richness shown by species–area ratios and c-values of power function are strongly correlated ( $R^2 = 0.78–0.96$ ), and consistently present a sharp decrease at latitudinal belt V (29.0°–29.9°N) (Fig. 4), such that both patterns are indicative for determining the dividing line between the southern and northern sub-regions. The latitudinal pattern of species richness shown by species–area ratios, however, is more consistent with the often reported latitudinal pattern of species richness, which

decreases monotonously with increasing latitude (Kerr 1999, Hillebrand 2004). One may argue that a power function can best describe SAR, therefore, species–area ratios have received criticism because of the non-linear relationship of species and area (Ovadia 2003). The typical z-value of the power function for mainland curves (0.18) has been used to estimate c-values for different regions (Ovadia 2003), and it assumes that all regions have the same SAR. However, SAR is scale-sensitive, or at least the parameters are different among regions (Lyons and Willig 2002), and our data also show that the z-values for the total, endemic and tree species differed greatly (Table 1). Furthermore, there may be multiple types of SAR in each latitudinal belt or region, so the c-value of the power function may not well describe species richness on a broad scale.

### The difference in species richness and endemism between the southern and northern sub-regions

The consistent pronounced change in species richness, the ordination of the nine latitudinal belts and the low similarity in species composition between the belts on each side of 29°N all support the rationality of dividing the Hengduan region into two parts. The difference in species composition and richness between the sub-regions is clear. The southern sub-region has a far greater concentration of species than the northern sub-region (Table 2) and is the core of this biodiversity hotspot. Energy availability and diversity of habitats are strongly correlated with species richness (Guégan et al. 1998, Engle and Summers 1999, Triantis et al. 2003, Brayard et al. 2005). Temperature, a surrogate of energy, along the latitudinal gradient in the Hengduan Mountains, affected by latitude and elevation, decreases sharply towards higher latitudes (Zhang et al. 1997). The composition of the vegetation in the southern sub-region, reflecting more favorable conditions, is more complicated than that in the northern sub-region (Liu et al. 1984, 1985). The greater energy levels and more diverse habitats in the southern sub-region result in a greater abundance of species. Additionally, the Quaternary glaciations covered only a small part of the southern sub-region of

the Hengduan Mountains (Li et al. 1991), so this sub-region was likely a core refugium for temperate species during glacial periods. Perhaps partly because of the glacial episodes, rapid evolution of new species has occurred in the southern sub-region and most species are of recent origin (Wu 1988, Sun 2002, Wang and Liu 2004, Liu et al. 2006), and this sub-region is one of the major centers of endemism in China (Li 1994). In contrast, the lower temperatures, less favorable climate, more extensive glaciation during the Pleistocene and less dramatic topography have resulted in lower species richness and lower endemism in the northern sub-region.

## Conclusions

The globally recognized Hengduan biodiversity hotspot can be broken down into southern and northern sub-divisions. The recognition of the great differences in species richness and endemism between the southern and northern sub-regions shows the urgent need to separately examine both sub-regions when making decisions for land use and conservation. The spatial patterns of species richness and similarity play an important role in the quantitative measurement and comparison of species composition and richness among different geographic units.

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