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Diversity of the alpine vegetation in central Taiwan is affected by climate change based on a century of floristic inventories

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ABSTRACT. Floristically, Taiwan is a very rich island due to her varied geography, topography and habitats. Through extended historical research involving past and present botanical inventories of the central mountains, particularly of the Hehuanshan area of Taiwan, we are now able to examine the floristic composition of four elevation zones, 2,000-2,500 m, 2,500-3,000 m, 3,000-3,500 m, and 3,500-3,950 m. We selected four study sites, namely Shinjenkan (SJK) at 2,250-2,585 m, Shihmenshan (SMS) at 3,000 m, Hehuan East Peak (HEP) at 3,401 m, and Hehuan Major Peak (HMP) at 3,408 m, and determined their α, β, and γ diversities along with their Simpson's diversity indices. Our results clearly showed that the species richness (α diversity) was significantly high and decreased as the altitude increased. Coincidently, Simpson's diversity index at 2,250 m was significantly high at 0.85, drastically decreased to 0.17 at 3,145 m, and continued to decrease to 0.10 at both sites at 3408 m. On the other hand, by comparing plant distribution data collected over a century for the Hehuanshan, Alishan and Yushan areas, we were able to predict that plants would migrate mostly from a lower to a higher elevation when the global temperature increases. For instance, in the Hehuanshan area, 16 species would move towards higher elevations and seven species would remain in their original zone. In the Alishan area, seven species would migrate and four would remain in their original zone, and in Yushan, 15 species would migrate out of their zone and five would remain. Of all of the species, at least six risk extinction, since their expected migration would take them far beyond the limits of the land available above 3,950 m. It is concluded that the alpine vegetation will be redistributed, many plant species will move towards a higher elevation and, eventually, at least six plant species (*Anaphalis morrisonicola, Artemisia morrisonensis, Swertia randaiensis, Hypericum nagasawai, Angelica morrisonicola,* and *Cirsium arisanensis*) will become extinct.

Keywords: Alishan; Alpine vegetation; α, β, γ diversity; Global warming; Hehuanshan; Plant migration; Simpson's diversity index; Yushan.

INTRODUCTION

Chen (1995) proposed that Taiwan has been affected by at least four ice ages, and that these have caused significant changes to the island's vegetation. Past PAGES (Past Global Changes, IGBP) studies on the effect of climate change on vegetation in natural forests in Taiwan, including pollen analyses and geological variation (Tsukada, 1966; Su, 1984a, 1984b, 1985; Chen, 1995), have all suggested that climate change will lead to vegetation succession.

Botanical inventories of the entire island, but particularly of the mountainous areas, were initiated by Japanese botanists in 1895. Pioneer Japanese botanists, namely Hayata, Kudo, Sasaki, Masamune, Yamamoto, Sato, etc. (Huang, 1993), paid great attention to mountainous regions such as Alishan, Yushan and Hehuanshan, all of which are above 2,000 m. A great number of specimens were collected and deposited in the herbaria of Tokyo University, Kyoto University (Chen, 1995) and Taihoku Empire University (the present National Taiwan University) before World War II. After the war, Taiwanese botanists continued the inventory. Taiwan is located in the subtropical and tropical region with great topographic variation ranging from sea level to 3,950 m above sea level (asl), and with more than 200 mountain peaks above 3,000 m. Due to the

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variable climate and habitats, Taiwan possesses great plant diversity. Of the more than 4000 vascular plant species registered, more than 25% are endemic. The large amount of data accumulated over the past 100 years concerning the flora and climatic conditions in Taiwan now make the study of floristic changes related to climatic conditions possible.

We used the following indices of diversity to understand changes in plant communities: α (alpha) diversity, β (beta) diversity and γ (gamma) diversity. Alpha diversity refers to the number of species in a certain community; beta diversity represents the variability of species composition along an environmental or geographical gradient; and gamma diversity applies to larger geographical scales, referring to the number of species in a large region (Primack, 1998). These concepts are useful when studying biological diversity in relation to conservation biology in a community or region, such as in natural reserves or national parks. Combining botanical inventories and climatic information, we can use diversity indices to understand vegetation change relative to climatic or topographic changes.

Several recent international conferences on biodiversity informatics and the impact of climate change on life have taken place in different parts of the world (Dan BIF conference, 2008; ISGMB, 2008; ISGBHHW, 2009). Many important questions were asked concerning the extent to which global warming will affect Earth's biodiversity, including the natural systems that sustain human societies. It is very difficult to apply traditional experimental approaches to investigate the large-scale and long-term nature of the issues without involving biodiversity data and employing statistical analysis. Data from the Global Biodiversity Information Facility, GBIF, have made it possible to assess the change in biodiversity as affected by climate change. It is beyond doubt that the substantial floristic documents covering a century of exploration from several data banks in Taiwan and Japan, as well as the climatic data from the Central Weather Bureau of Taiwan, which has been registered since the 1900s, allow us to investigate the aforementioned questions. In addition, the senior author initiated a national thematic research program to address these issues in 2006 (2006-2009).

In fact, there has been an increasing awareness and evidence of global warming over the last century (Prabhakar and Shaw, 2008; CCSC, 2009), which is leading to climate change and temperature increases in the range of 0.6-1.5°C in many parts of the world. Negative impacts of climate change on ecosystems have also been demonstrated in Taiwan (Chou, 2009). The Intergovernmental Panel on Climate Change (IPCC) has proposed different scenarios (A1, A2, B2, etc.) that predict the future change in global temperature. In Taiwan, we have observed and analyzed climatic changes since the 1900s using data obtained from the Central Weather Bureau of Taiwan. If global warming occurs in Taiwan, it is hypothesized that some plant species might migrate to higher elevations. Pearson and Raxworthy (2008) presented a case study on the extreme vulnerability of tropical mountain endemic species due to climatic change, and concluded that endemic species in Madagascar distributed close to summits may be especially vulnerable to extinction due to their upward movement. Few studies have addressed how climate change, and in particular changes in temperature and precipitation, affect the diversity of vegetation in mountain areas (Beerling and Woodward, 1994). We therefore attempt herein to assess the correlation between climate change and plant diversity in Taiwan based on one century of weather data and botanical records. However, it is rather difficult to address the subject in the lower elevations in Taiwan due to the many socio-economic factors affecting the natural vegetation. Therefore, our analyses concentrate on remote areas, particularly in the central mountains above a 2,000-m elevation, such as Alishan, Hehuanshan and Yushan, with a special emphasis on the Hehuanshan region.

MATERIALS AND METHODS

Study sites

Taiwan is located to the southeast of China (21°53'50"-25°18'20" N; 120°01'00"-121°59'15" E), and with the tropic of Cancer passing through Chia-Yi in southern Taiwan; it is both subtropical and tropical. The topography of Taiwan ranges from sea level to 3,950 m above sea level, and has more than 200 peaks reaching above 3,000 m. The average temperature is 28°C in summer and 14°C in winter. The average annual precipitation is 2,515 mm, but the rain is often concentrated in the few months from July to September. A dry period from November to April is particularly pronounced in southern Taiwan.

It is impossible to survey the floristic diversity of the entire alpine region; thus, we selected the Hehuanshan area (Nantou County) for detailed study. Four sites were selected along highway 14A at elevations of 2,550-3,500 m above sea level:

1. Shinjenkan (SJK) is located at 21.5 K ~ 22 K, Highway 14A, situated at 121°12'52.8" East and 24°06'46.5" North. The sampling site for shrubs is located at 2,585 m asl (above sea level) at 121°12'53" East and 24°06'49.3" North.
2. Shihmenshan (SMS) is located at 34 K, Highway 14A, at 3,145 m asl, 121°17'03.5" East and 24°08'48.1" North.
3. Hehuan East Peak (HEP) is located at 3,401 m asl, 121°16'54.0" East, 24°08'11.3" North.
4. Hehuan Major Peak (HMP) is located at 3,408 m asl, 121°16'17.7" East, 24°08'30.6" North.

Botanical inventory of alpine vegetation from data banks in Taiwan

Several botanical databases are available from the Biodiversity Research Center of Academia Sinica, Taipei (BRC/AS) (http://dbIn.Sinica.edu.tw/textdb/hast_labelquery.php), National Taiwan University (http://tai2.

ntu.tw/webtaiprog/web.query-aspx), and Taiwan Forestry Research Institute (http://taif.tfri.gov.tw:8080/spec-query.aspx). We surveyed plant species distributed in the Hehuanshan area, arbitrarily divided into 4 elevation zones (2,000-2,500 m, 2,500-3,000 m, 3,000-3,500 m, and above 3,500 m) and listed the plant species, genera, and families found within each zone. The plant species nomenclature follows *Flora of Taiwan* (2nd edition, Huang et al., 2002); in addition, a list of rare and endangered species was obtained from the database of the Council of Agriculture, Taiwan (Chou et al., 2009, unpublished report).

Diversity measurement

We determined the α, β, and γ diversity of vegetation and used Simpson's diversity index to make a comparison between sampling sites and time. The equation of Simpson's diversity index was described by Simpson (1949).

At the study sites, plants were sampled based on the botanical survey of quadrates (10 × 10 m each) and on and transect sampling (20 m long) at an interval of 100 m along Highway 14A from an elevation of 2,250 to 2,750 m.

Examination of plant specimens in herbaria in Japan and Taiwan

From the databases mentioned above, we downloaded relevant information for each species found at our selected study sites. We consulted the herbarium of Tokyo University to add any information from early documents and recent findings that had not been uploaded to the databases. For the 367 plant species that were recorded in the Hehuanshan area, we carefully checked all vouchers deposited in the herbaria and the contents of several databases in Taiwan. We obtained a list of species found at the Shinjenkan site in different years and at different elevations (Chou et al. 2009, unpublished report, or see Supplementary Table 1).

Checking climatic data from the last century in Taiwan

Since 1895, weather stations have been established in most areas in Taiwan. Weather data from the last century were obtained from the Central Weather Bureau of Taiwan; however, the data from the Hehuanshan are incomplete due to the lack of a weather station there at the beginning of the 20th century. Instead, we obtained data from nearby stations at Alishan and Yushan, which are relatively close to the Hehuanshan site. The average annual temperature and precipitation since 1930 are presented in Figure 1.

Statistical analysis

All species are listed in an Office Excel 2007 table according to altitude, and the elevations of each species' distribution vs. year of each species' recording were analyzed statistically using standard deviation (SD) as described by Gomez and Gomez (1976). An adjusted SD was obtained according to the formula which was used by Jump et al. (2006):

$$\text{Adjusted SD} = \frac{\text{Each Elevation - Mean Elevation of Each Species}}{\text{SD Elevation}}$$

The expected elevation of migrated species was represented by M (mean elevation in meter) plus SD (standard deviation). For example, *Acer serrulatum* was documented at the first time in 1984 at 2,200 m asl and was later documented in 1999 at 2,400 m asl. From the two data, we obtained a mean elevation of 2,300 m and a standard deviation (SD) of 141.42 m. From the mean and SD, it was deduced that the plant might move upwards to an expected elevation of 2,441 m. Following this computing process, we were able to assess the migration of each plant to a certain altitude.

Estimation of available land area in the Hehuanshan area

Using ArcView software and a digital geographic model (Digital Terrain Model, DTM), and through communication with Prof. Chen at the National Pingtung University of Science and Technology, Taiwan, the land area of Hehuanshan above 2,000 m was estimated by dividing into five elevational zones (2,000-2,250 m, 2,250-2,500 m, 2,500-2,750 m, 2,750-3,000 m, and above 3,000 m). The estimated available land area is expressed as a percentage (Chou et al., 2009, unpublished report).

RESULT AND DISCUSSION

Botanical diversity in the alpine area of Taiwan

We attempted to study the botanical diversity of alpine plants based on a century of botanical inventories documented in the databases of various Taiwanese institutions. Appropriately 25,000 specimens have been collected in our study area above an elevation of 2,000 m, including 132 families, 557 genera, and 1442 species (Table 1). In the elevation zone of 2,000-2,500 m, we recorded 1266 species, 527 genera, and 131 families; in the 2,500-3,000 zone we recorded 829 species; in the 3,000-3,500 m zone we recorded 561 species; and above 3,500 m we recorded 252 species (Huang et al., 2002). It is clear that the number of plant species decreases with increasing elevation.

At the same time, the available land decreases with altitude. For example, in the Hehuanshan area, the available land in elevation zone C (2,500-2,750 m) corresponds to 94% of the land area in elevation zone D (2,750-3,000 m), and the area in zone E (3,000-3,421 m) is equal to 30% of the area in elevation zone D (2,750-3,000 m) (Table 2). Logistically, under global warming in the region, plant species would migrate upwards to the higher elevations in zone E, where the available land for plant growth is only 30% of the area previously occupied (Table 2); in other words, about 70% of plant species might not survive due to limited space. However, most endemic species may not be seriously affected by global warming. In the Hehuanshan area, there are 480 endemic species, about one-third of the total number of species found in the mountainous

Table 1. A summary of the number of plant families, genera, and species distributed in four elevation zones of the Central mountain area of Taiwan based on a century of botanical inventories. Data are synthesized from *Flora of Taiwan* (2002).

Altitude (m)		Pteridophytes	Gymnosperms	Angiosperms		Total
				Dicotyledons	Monocotyledons	
2000-2500	Families	20	5	94	12	131
	Genera	61	13	352	101	527
	Species	159	17	879	211	1,266
2500-3000	Families	19	3	76	9	107
	Genera	45	10	235	72	362
	Species	112	12	550	155	829
3000-3500	Families	15	2	61	7	85
	Genera	28	4	169	55	256
	Species	76	6	367	112	561
3500-3950	Families	5	2	41	6	54
	Genera	9	3	101	31	144
	Species	16	4	181	51	252
Total	Families	20	5	95	12	132
	Genera	67	14	366	110	557
	Species	200	19	965	258	1,442

region. We concluded that some species, even though they can migrate to higher elevations, may become extinct anyway due to the limited space and to the environmental stress in these areas (Chen, 1995). In Taiwan, vegetation is almost absent at elevations above 3,900 m, which is similar to that documented for the island of Madagascar (Pearson and Raxworthy, 2008).

Botanical inventory at the Shinjenkan study site

The Shinjenkan study site, located at a 2,250-m elevation along Highway 14A, is a unique ecotone for alpine vegetation, featuring alpine herbaceous plants, shrubs, and woody plants. This transitional site lends itself to the study of vegetation composition and succession. The senior author has taken students and researchers to this site since 1984 and has made an extensive survey of its botanical composition from 1984-1990 and 2007-2009. A complete list of the species encountered is presented in Supplementary Table 1. In total, 88 species were found at the Shinjenkan site, all of which were found in other parts of the Central Mountain alpine region. Thirty three of these species were recorded over 100 years ago (1905-2010), 25 species were recorded over 90 years ago (1911-2010), 15 species over 80 years ago (1922-2010), two species recorded before 1940, and the remaining species were documented after 1963 (Supplementary Table 1).

Table 2. Estimated available land in the five elevation zones in the Hehuanshan area*.

	Elevation (m)	Estimated area (ha)	Expected available area, × 100%
A	2000-2250	1330	100
B	2250-2500	1380	103 (1380/1330)
C	2500-2750	1593	115 (1593/1380)
D	2750-3000	1500	94 (1500/1593)
E	3000-3421	458	30 (458/1500)
	Total	6261	

*Available land for plant growth as plants migrate upwards.

In addition, a comparison of the botanical compositions of pteridophytes, gymnosperms, and angiosperms (including dicotyledon and monocotyledon) reveals that there were 62 species in 1984, 90 species in 2007, and 83 species in 2008 (Table 3). The number of species appeared to increase from 1984 to 2008, and naturally, we cannot discount the hypothesis that this significant increase is due to global warming.

Botanical composition of the Hehuan East Peak

At the Hehuan East Peak study site, we made an inventory of the seasonal species distribution for 2008 and 2009. Twenty-four species (*Ainsliaea macroclinidioides*, *Carex* spp., *C. satzumensis, Deschampsia flexuosa, Festuca ovina, E. rubra, Gentiana arisanensis, G. davidii* var. *formosana, Hieracium morii, Hypericum nagasawae, Juniperus formosnus, J. squamata, Lycopodium lavatum, L. obscurum, L. pseudoclavatum, L. selago* var. *appressum, L. veitchii, Miscanthus transmorrisonensis, Platanthera brevicalcarata, Rhododendron pseudochrysanthum, Solidago virgaurea* var. *leiocarpa, Trichophorum subcapitatum, Veratrum formosanum* and *Yushania niitakayamensis*) were commonly found both years (Table 4). Of these, five species (*Gentiana arisanensis, L. obscurum, M. transmorrisonensis, Trichophorum subcapitatum* and *Yushania niitakayamensis*) were present every season, indicating their dominance. Some species may have died or were not found in the winter or spring. Thus, the α diversity at the site is about 24, a rather low value for species diversity.

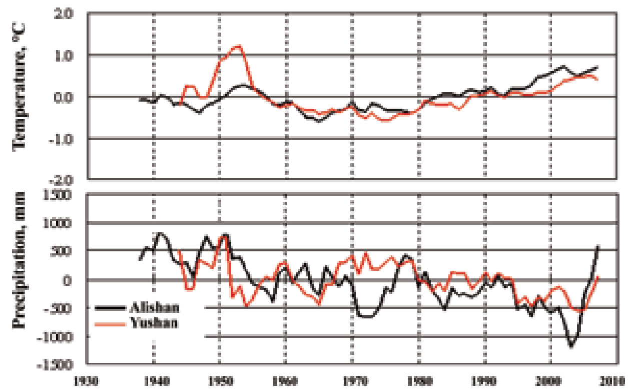

Figure 1. Annual temperature and precipitation after subtracting the average temperature and precipitation for the years 1930-2008. Data obtained from the Central Weather Bureau of Taiwan.

Comparison of species diversity in the Hehuanshan area

A botanical inventory of the Hehuanshan area was performed at four study sites (Shinjenkan, Shihmenshan, Hehuan East Peak, and Hehuan Major Peak). The total number of species and the α, β, γ diversity are presented in Table 5. The alpha (α) diversity is related to the population concept of species richness and can be used to compare the number of species in particular places or ecosystems, such as forests (Primack, 1998). Among the four sites in the Hehuanshan area, the α diversity was significantly higher at the Shinjenkan site as compared with the other three sites; this difference is presumably due to temperature at the lower elevation.

The altitudinal difference between Shinjenkan and Shihmenshan is about 600 meters, while that between Shinjenkan and both the Hehuan East Peak (HHE) and Hehuan Major Peak (HMP) is about 1,000 m. In general, when the elevation increases, the temperature is usually reduced by -0.6°C for every 100 m; thus, theoretically, the temperature difference between Shihmenshan and Shinjenkan is about -3.6°C. The temperature difference would be causative of plant diversity. It is not surprising, then, that the α diversity at the Shinjenkan site was significantly higher than that at the other three sites. Naturally, species richness (α diversity) decreases as elevation increases. Furthermore, γ diversity refers to the total number of species in a region or at larger geographical scales; thus, the γ diversity of each site in the Hehuanshan area is also variable and decreases as elevation increases. In fact, at both the HHE and HHM sites, the number of species in winter and spring is exceedingly low, indicating that plant growth at higher elevations during the cold winter and early spring is difficult. This is reflected by the β-diversity, which is expressed as the value of α/γ, and represents the variability of species composition along an environmental gradient. When the temperature decreases, the β diversity decreases. We observed that the number of species along the elevation of Highway 14A decreases when the elevation increases. In

Table 3. Comparison of the botanical composition at the Shinjenkan site in different inventory years.

Year		Pteridophytes	Gymnosperms	Angiosperms		Total No. of species
				Dicotyledons	Monocotyledons	
1984	Families	4	1	25	3	33
Oct	Genera	6	1	41	7	55
	Species	9	1	45	7	62
2007	Families	7	1	33	3	44
Apr	Genera	7	1	64	6	78
	Species	11	1	72	6	90
2008	Families	10	1	30	4	45
Apr	Genera	10	1	56	5	72
	Species	12	1	65	5	83

Table 4. Dynamics of plant species present at the Hehuan East Peak site.

Botanical composition	2008		2009	
	April	July	April	July
Ainsliaea macroclinidioides (阿里山鬼督郵)	−[1]	−	−	+
Carex spp. (薹屬)	+	−	−	+
Carex satzumensis (油薹)	−	+	−	+
Deschampsia flexuosa (曲芒髮草)	−	+	−	+
Festuca ovina (羊茅)	−	+	−	−
Festuca rubra (紫羊茅)	−	−	−	+
Gentiana arisanensis (阿里山龍膽)	+	+	+	+
Gentiana davidii var. *formosana* (台灣龍膽)	−	+	−	−
Hieracium morii (森氏山柳菊)	−	−	−	+
Hypericum nagasawae (玉山金絲桃)	−	−	−	+
Juniperus formosana (刺柏)	−	+	+	+
Juniperus squamata (玉山圓柏)	+	+	−	−
Lycopodium clavatum (石松)	+	+	+	+
Lycopodium obscurum (玉柏)	+	+	+	+
Lycopodium pseudoclavatum (假石松)	−	−	−	+
Lycopodium veitchii (玉山石松)	+	−	−	+
L. selago var. *appressum* (小杉葉石松)	+	−	+	+
Miscanthus transmorrisonensis (高山芒)	+	+	+	+
Platanthera brevicalcarata (短距粉蝶蘭)	−	+	−	+
Rhododendron pseudochrysanthum (玉山杜鵑)	+	−	−	−
Solidago virgaurea var. *leiocarpa* (一枝黃花)	+	+	−	+
Trichophorum subcapitatum (玉山針藺)	+	+	+	+
Veratrum formosanum (台灣藜蘆)	−	+	−	+
Yushania niitakayamensis (玉山箭竹)	+	+	+	+
Subtotal	12	15	8	20
Total no. of species (α diversity)				24

[1]+, Indicates the presence of the species; −, Indicates that the species was not found.

addition, from a comparison of the inventory data between the 1980s and 2000s, the number of species at the Shinjenkan site appears to increase. Presumably, this is due to the invasion of species from elsewhere and/or is likely due to global warming.

If funds are limited and sites for conservation need to be prioritized, the Shinjenkan site should be considered highest priority, due to its the exceedingly high γ diversity as compared with the other three sites.

Based on α, β, γ diversity, the Shinjenkan site exhibits the greatest mountain biodiversity. It is also interesting to note that when elevation increases the plant diversity in terms of α and γ decreases, indicating that temperature is a causative factor affecting plant populations. According to the IPCC, the temperature of the four sites simultaneously increased by 0.6°C, 1.5°C, and 3°C in the A1, B1 and B2 scenarios, respectively. Consequently, the plants in Shinjenkan would move upwards to the SMS site (3,145 m) and continue to move to the HHM and HHE sites (3,410 m). The migration of species is discussed in detail below.

The average number of species at each site was computed and the average of Simpson's index was obtained by the techniques described by Barbour et al. (1987). The species distributions at the four sites at different elevations in Shinjenkan and Shihmenshan are given in Table 6. These data show that species diversity, as measured by Simpson's index, is significantly higher (0.85) at the SJK site, drastically decreasing to 0.17 at the Shihmenshan site and to 0.10 at both HHE and HHM. A significant negative correlation between elevation and Simpson's index was found (Figure 2). This finding agrees with our previous results (Table 5), concluding that the topographic gradient certainly leads to the temperature change that results in variable plant diversity.

Table 5. Variation of the diversity index of plants distributed at the four study sites with seasons.

Diversity			Study site[1]			
			SJK (2,550 m)	SMS (3,145 m)	HEP (3,401 m)	HHM (3,408 m)
α	1984	October	62	—[2]	—	—
	1993	October	35	—	—	—
	2007	May	90	—	—	—
	2008	April	37	11	10	—
		July	29	16	14	—
	2009	October	—	24	13	—
		April	19	18	7	13
		July	—	27	19	—
β	1984	October	2.35	—	—	—
(α/γ)	1993	October	4.17	—	—	—
	2007	May	1.62	—	—	—
	2008	April	3.95	3.64	2.70	—
		July	5.03	2.50	1.93	—
		October	—	1.67	2.08	—
	2009	April	7.68	2.22	3.86	1.00
		July	—	1.48	1.42	—
γ			146	40	27	13

[1]SJK: Shinjenkan (新人崗); SMS: Shihmenshan (石門山); HHE: Hehuan East Peak (合歡東峰); HHM: Hehuan Major Peak (合歡主峰).
[2]—: Not detected.

Table 6. Comparison of Simpson's diversity index of plants found at 4 sites in the Hehuanshan area.

Study site	Average		
	No. of species	Simpson's index	df
Shinjenkan (SJK) (2,550 m)	51.83 ± 27.82	0.85	6
Shihmenshan (SMS) (3,145 m)	20.16 ± 7.08	0.17	6
Hehuan East Peak (HEP) (3,401 m) + Hehuan Major Peak (HHM) (3,408 m)	12.66 ± 3.82	0.10	6

Migration of plant species in the Central Mountains of Taiwan

According to the IPCC scenario A1, last century's global temperature increased by 0.6°C, which was coincident with the elevation change. An altitude increase of 100 meters is associated with a temperature decrease of -0.6°C. Thus, plants would have to migrate 100 meters or more upwards in order to compensate for the temperature change registered over the past century.

Regarding vegetation distribution in the Hehuanshan area, we arbitrarily divided the vegetation zone into 6 zones, namely zone A (2,250-2,500 m), zone B (2,500-2,750 m), zone C (2,750-3,000 m), zone D (3,000-3,250 m), zone E (3,250-3,500 m), and zone F (3,500-3,750 m). By the aforementioned analyses, those plants expected to migrate upwards, downwards, or to remain in the same zone are listed in Table 7. In zone A, *Acer serrulatum* is expected to migrate upwards only 141 m; thus, it remains in zone A. In zone B, *Eupatorium formosanum* is expected to migrate 419 m; thus, it will invade to 3,038 m asl in zone D, and *Lyonia ovalifolia* will remain in zone B. In zone C, all seven species are expected to migrate upwards. Of these, three species, *Aster taiwanensis*, *Deutzia pulchra* and *Pinus taiwanensis,* will migrate into zone D, while the remaining four species will migrate past zone D to zone E. In zone D, two species, *Rosa transmorrisonensis* and *Hydrocotyle setulosa,* will remain, and the other seven species are expected to migrate upwards to zone E; however, only one species, *Hemiphragma heterophyllum,* will migrate downwards to zone C. In zone E, two species, *Rhododendron rubropilosum* and *Rubus rolfei,* will remain in the same zone, and *Artemisia morrisonensis* will migrate 578 m to reach 3,978 m, which is beyond the highest peak of Yushan. This species is thus expected to become extinct.

Plant distribution results for Alishan, using the same methodology, are given in Table 8. In zone A (2,000-2,250

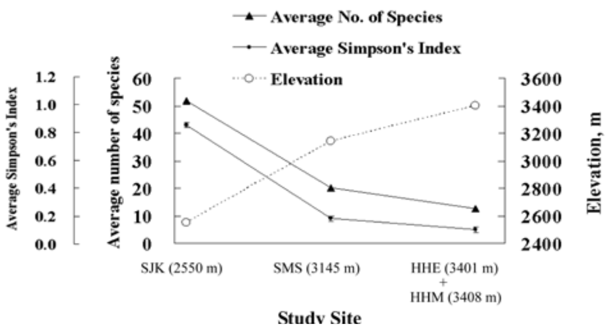

Figure 2. Comparison of the average number of species and Simpson's diversity index against elevation at each experimental site.

m), three species (*Lyonia ovalifolia*, *Rhododendron rubropilosum* and *Sedum morrisonense)* are expected to migrate upwards to the higher zone B, C, and B, respectively; however, *Aster taiwanensis* appears to migrate downwards to zone A, and *Cirsium arisanense* remains in zone A. Regarding species migration in zone B (2,250-2,500 m), two species (*Deutzia pulchra* and *Angelica morrisonicola)* will migrate downwards to zone A, one species *Hemiphragma heterophyllum* will migrate upwards to zone C (2,500-2,750 m), and the remaining three species will not migrate out of zone B. It is interesting to note that no data are available for zone C.

Regarding the species distribution in the Yushan area, six zones, namely, zone A (2,500-2,750 m), zone B (2,750-

Table 7. Plant species expected to migrate to different altitudes in the Hehuanshan area.

Species name	Mean Altitude, m	Standard Deviation, m	Expected migration, m	Migrate into zone
Zone A: 2,250-2,500 m (one species remains)				
Acer serrulatum	2300	141	2441 ↑	Remains
Zone B: 2,500-2,750 m (one species out; one species remains)				
Eupatorium formosanum	2619	419	3038 ↑	D
Lyonia ovalifolia	2650	71	2721 ↑	Remains
Zone C: 2,750-3,000 m (seven species out)				
Aster taiwanensis	2840	187	3027 ↑	D
Cirsium arisanense	2842	626	3468 ↑	E
Deutzia pulchra	2800	265	3065 ↑	D
Pinus taiwanensis	2960	198	3158 ↑	D
Pyrola morrisonensis	2938	477	3415 ↑	E
Pimpinella niitakayamensis	2883	449	3332 ↑	E
*Picris hieracioide*s subsp. *morrisonensis*	2789	551	3340 ↑	E
Zone D: 3,000-3,250 m (eight species out; two species remain)				
Rosa transmorrisonensis	3213	18	3231 ↑	Remains
Spiraea formosana	3180	103	3283 ↑	E
Anaphalis morrisonicola	3055	435	3490 ↑	E
Angelica morrisonicola	3200	283	3483 ↑	E
Luzula taiwaniana Satake	3150	212	3362 ↑	E
*Picris hieracioide*s subsp. *morrisonensis*	3217	202	3419 ↑	E
Sedum morrisonense	3250	71	3320 ↑	E
Swertia randaiensis	3200	141	3341 ↑	E
Hemiphragma heterophyllum	3055	176	2878 ↓	C
Hydrocotyle setulosa	3100	—	—	Remains
Zone E: 3,250-3,500 m (one species out; two species remain)				
Rhododendron rubropilosum Hayata var. *rubropilosum*	3300	141	3441 ↑	Remains
Rubus rolfei	3300	141	3441 ↑	Remains
Artemisia morrisonensis	3400	578	3978 ↑	F and above
Zone F: 3,500-4,000 m (one species remains)				
Dianthus pygmaeus	3900	—	—	Remains

Table 8. Plant species expected to migrate to different altitudes in the Alishan area.

Species name	Mean Altitude, m	Standard Deviation, m	Expected migration, m	Migrate into zone
Zone A: 2,000-2,250 m (four species out; one species remains)				
Lyonia ovalifolia	2200	283	2483 ↑	B
Rhododendron rubropilosum	2228	322	2550 ↑	C
Aster taiwanensis	2100	141	1959 ↓	Below A
Cirsium arisanense	2250	212	2038 ↓	Remains
Sedum morrisonense	2150	212	2362 ↑	B
Zone B: 2,250-2,500 m (three species out; three species remain)				
Deutzia pulchra	2305	134	2171 ↓	A
Spiraea formosana	2350	71	2279 ↓	Remains
Angelica morrisonicola	2350	212	2138 ↓	A
Eupatorium formosana	2400	0	0	Remains
Hemiphragma heterophyllum	2387	160	2547 ↑	C
Picris hieracioides subsp. *morrisonensis*	2350	71	2279 ↓	Remains
Zone C: 2,500-2,750 m (no data available)				

Table 9. Plant species expected to migrate to different altitudes in the Yushan area.

Species name	Mean Altitude, m	Standard Deviation, m	Expected migration, m	Migrate into zone
Zone A: 2,500-2,750 m (two species out)				
Aster taiwanensis	2740	57	2797 ↑	B
Eupatorium formosanum	2550	636	3186 ↑	C
Zone B: 2,750-3,000 m (two species remains)				
Picris hieracioides subsp. *morrisonensis*	3000	0	3000	Remains
Rubus rolfei	2925	106	2819 ↓	Remains
Zone C: 3,000-3,250 m (four species out)				
Rhododendron rubropilosum	3250	354	3604 ↑	E
Spiraea formosana	3250	354	3604 ↑	E
Hemiphragma heterophyllum	3100	566	2534 ↓	A
Rosa transmorrisonensis	3250	354	3604 ↑	E
Zone D: 3,250-3,500 m (five species out)				
Gaultheria itoana	3300	424	3704 ↑	E
Anaphalis morrisonicola	3491	694	4185 ↑	Above F
Artemisia morrisonensis	3475	672	4147 ↑	Above F
Swertia randaiensis	3400	567	3966 ↑	Above F
Triplostegia glandulifera	3275	389	3664 ↑	E
Zone E: 3,500-3,750 m (one species out; one species remains)				
Luzula taiwaniana Satake	3638	54	3692 ↑	Remains
Sedum morrisonense	3650	212	3862 ↑	F
Zone F: 3,750-4,000 m (three species out; two species remain)				
Hypericum nagasawai	3775	247	4022 ↑	Above F
Angelica morrisonicola	3774	315	4089 ↑	Above F
Cirsium arisanense	3875	106	3981 ↑	Above F
Dianthus pygmaeus	3900	0	3900	Remains
Pimpinella niitakayamensis Hayata.	3800	141	3941 ↑	Remains

3,000 m), zone C (3,000-3,250 m), zone D (3,250-3,500 m) and zone E (3,500-3,750 m), and zone F (3,750-4,000 m), were defined, and the details of plant migration are given in Table 9. In zone A, *Aster taiwanensis* is expected to migrate upwards to zone B and *Eupatorium formosanum* will migrate to zone C. In zone B, *Picris hieracioide*s subsp. *morrisonensis* and *Rubus rolfei* will remain in the same zone. In zone C, two species (*Rhododendron rubropilosum* and *Spiraea formosana*) will migrate upwards to zone E, but *Hemiphragma heterophyllum* will migrate downwards to zone A. *Rosa transmorrisonensis* and *Gaultheria itoana* are expected to migrate upwards to the higher zone E. In zone D, three species (*Anaphalis morrisonicola*, *Artemisia morrisonensis* and *Swertia randaiensis*) are expected to migrate into higher elevations above zone F; thus, these species might be expected to become extinct. Two species (*Gaultheria itoana* and *Triplostegia glandulifera)* will migrate into zone E. In zone E, one species, *Luzula taiwaniana* will remain in the same zone, but another species, *Sedum morrisonense*, will migrate upwards to the higher-elevation zone F. Finally, in zone F, two species (*Dianthus pygmaeus* and *Pimpinella niitakayamensis*) will remain in the same zone, but three other species (*Hypericum nagasawai*, *Cirsium arisanense* and *Angelica morrisonicola*) are expected to migrate upwards to higher elevations above 3,950 m; thus, these three species might eventually become extinct. In conclusion, the number of migrating species in the Yushan area is expected to be lower than that in Alishan and Hehuanshan; however, six species are eventually expected to become extinct.

In all cases, plant migration toward higher elevations means a reduction in the land available for plant colonization. Using ArcView software and a digital geographic model, the available land for plant growth above 3,000 m was predicted to be only 30% of that in the 2,750-3,000 m elevation zone (Chou, 2009, unpublished data). At higher elevations, the available habitat decreases, resulting in some species becoming extinct (Chou, 2009, unpublished report). Indeed, there is almost no vegetation distributed in areas above 3,900 m. In consequence, plants migrating to higher elevations above 3,900 m are likely to become extinct eventually. Similarly, Peason and Raxworthy (2008) indicated that upslope displacement of species is one of the expected biological responses to climate change. They further reported that locally endemic species in Madagascar such as amphibians and reptiles would be pushed up to summits and would be vulnerable to extinction as they reach the tops of mountains. Guisan (2008) also predicted the effect of climate change on alpine flora in the Swiss Alps and in other mountain ranges in Europe, and forecast the change of alpine species distribution and diversity.

Jump et al. (2006) suggested that a rapid increase in global temperature is likely to impose strong directional selection on plant populations, which was demonstrated by a unique study of *Fagus sylvatica* conducted in Spain. Evidence of the evolutionary effects of climate change on natural populations was reviewed by Thomas (2005) and Jump and Penuelas (2005). We used similar approach to study the molecular adaptation of *Alnus formosana* and *Pinus taiwanensis*.

In addition to global warming, precipitation is also one of major factors that determine vegetation change. Although a weather station was not present in the Hehuanshan area, we were able to use weather data from nearby stations at Alishan and Yushan. During the past century, the rainfall pattern has varied significantly in the mountainous area below an elevation of 2,000 m. Liu et al. (2009) showed that the frequency of small or medium rainfall (< 40 mm/each) significantly reduced but that of heavy rainfall (> 400 mm/each typhoon) increased by 50%. Liu et al. (2009) further indicated that the frequency of heavy rainfall will increase by 25% when the global temperature increases by 1°C. If that occurs in Taiwan, resulting disasters such as landslides in areas of heavy rainfall will severely impact forest communities. Fortunately, this has not occurred very often in the Hehuanshan (HHS) area due to the dominant and dense vegetation growing there, such as *Yushania niitakayamensis* (bamboo plant) and *Miscanthus transmorrisonensis* (grassland vegetation). In addition, a well-protected ecological conservation area has been defined in the Hehuanshan area as part of the Taroko National Park; thus, the Hehuanshan region has only been slightly affected by rainfall. Furthermore, Lin et al. (2010) developed a yearly warning index to assess the climatic impact on the water resources in Taiwan, which indicated that the water resources will increase in the unpopulated eastern region but will decrease over other densely-populated and densely-industrialized regions. However, they did not mention a change in the Hehuanshan area. Presumably, the rainfall pattern has not changed significantly in the area above 2,000-m elevation over the last century; however, the greatest indication of climate change in the Hehuanshan region may be the temperature increase caused by global warming.

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Supplementary Table 1. Species distributed at the Shin-Jen-Kan site and species collected and deposited in herbaria of Tokyo University, National Taiwan University and Academia Sinica.*

Scientific Name	Chinese name	Initial document date	Up to date, year
Hypericum nagasawai	玉山金絲桃	1905/11/2	105
Dianthus pygmaeus	玉山石竹	1906/10/20	104
Gaultheria itoana	高山白珠樹	1906/10/18	104
Rhododendron rubropilosum	紅毛杜鵑	1906/11/27	104
Pinus taiwanensis	台灣二葉松	1906/11/25	104
Deutzia pulchra	大葉溲疏	1906/1/1	104
Pyrola morrisonensis	玉山鹿蹄草	1906/10/20	104
Sedum morrisonense	玉山佛甲草	1906/10/19	104
Artemisia morrisonensis	細葉山艾	1906/10/19	104
Aster taiwanensis	台灣馬蘭	1906/1/1	104
Spiraea prunifolia var. *pseudoprunifolia*	笑靨花	1906/10/12	104
Angelica morrisonicola	玉山當歸	1906/10/1	104
Hydrocotyle setulosa	阿里山天胡荽	1906/11/9	104
Cirsium arisanense	阿里山薊	1906/10/20	104
Pimpinella niitakayamensis	玉山茴芹	1906/10/20	104
Picris hieracioides subsp. *morrisonensis*	玉山毛蓮菜	1906/11/25	104
Triplostegia glandulifera	三萼花草	1906/10/20	104
Rubus rolfei	高山懸鉤子	1906/10/19	104
Spiraea formosana	台灣繡線菊	1906/10/15	104
Luzula taiwaniana S	台灣地楊梅	1906/11/18	104
Acer serrulatum	青楓	1907/9/28	103
Lyonia ovalifolia	南燭	1908/8/10	102
Swertia randaiensis	巒大當藥	1908/8/9	102
Lepisorus monilisorus	擬芨瓦葦	1908/9/1	102
Miscanthus transmorrisonensis	高山芒	1908/8/9	102
Gentiana flavomaculata	黃斑龍膽	1908/8/9	102
Eupatorium formosanum	台灣澤蘭	1909/2/9	101
Hemiphragma heterophyllum	腰只花	1909/10/8	101
Rosa transmorrisonensis	高山薔薇	1909/10/9	101
Anaphalis morrisonicola	玉山抱莖籟蕭	1909/10/7	101
Galium formosense	圓葉豬殃殃	1909/10/9	101
Polygala japonica	瓜子金	1910/3/24	100
Viola adenothrix	喜岩堇菜	1910/4/15	100
Lilium formosanum	台灣百合	1911/1/23	99
Boenninghausenia albiflora	臭節草	1911/11/12	99
Veronica persica	阿拉伯婆婆納	1911/4/10	99
Lonicera acuminata	阿里山忍冬	1912/1/24	98
Dryopteris hypophlebia	深山鱗毛蕨	1912/1/1	98
Viburnum propinquum	高山莢迷	1914/4/28	96
Salix fulvopubescens	褐毛柳	1913/5/7	96
Sonchus oleraceus	苦滇菜	1915/5/10	95
Artemisia indica	艾	1916/10/15	94
Euonymus spraguei	刺果衛矛	1916/3/1	94
Coriaria japonica subsp. *intermedia*	台灣馬桑	1917/3/30	93
Berberis kawakamii	台灣小檗	1918/10/1	92
Stellaria media	繁縷	1918/10/1	92

Supplementary Table 1. (Continuing)

Scientific Name	Chinese name	Initial document date	Up to date, year
Elaeagnus thunbergii	鄧氏胡頹子	1918/3/4	92
Adenophora triphylla	輪葉沙參	1918/1/4	92
Senecio nemorensis var. *dentatus*	黃菀	1918/7/29	92
Photinia serratifolia	石楠	1918/11/9	92
Prunus taiwaniana	霧社山櫻花	1918/3/3	92
Pedicularis verticillata	馬先蒿	1919/7/5	91
Astilbe longicarpa	落新婦	1919/5/29	91
Gnaphalium affine	鼠麴草	1919/8/5	91
Gnaphalium involucratum var. *simplex*	細葉鼠麴草	1919/8/7	91
Acer morrisonense	台灣紅榨楓	1919/8/1	91
Photinia niitakayamensis	玉山假沙梨	1919/8/14	91
Rubus niveus	白絨懸鉤子	1919/8/4	91
Geranium robertianum	漢紅魚腥草	1922/6/27	88
Alnus formosana	台灣赤楊	1922/1/26	88
Lepisorus pseudo-ussuriensis	擬烏蘇里瓦葦	1923/12/19	87
Epilobium amurense	黑龍江柳葉菜	1925/9/15	85
Salvia arisanensis	阿里山鼠尾草	1925/6/3	85
Solidago virgaurea var. *leiocarpa*	一枝黃花	1925/10/8	85
Asplenium trichomanes	鐵角蕨	1925/8/14	85
Diplopterygium glaucum	裏白	1927/10/7	80
Cheilanthes farinosa	深山粉背蕨	1927/10/13	83
Eurya crenatifolia	假柃木	1928/11/3	82
Viola senzanensis	尖山堇菜	1928/10/1	82
Cyclobalanopsis stenophylloides	狹葉櫟	1928/8/15	82
Clinopodium laxiflorum	疏花塔花	1929/8/21	81
Crassocephalum crepidioides	昭和草	1929/11/1	81
Youngia japonica	黃鵪菜	1930/7/7	80
Potentilla matsumurae var. *pilosa*	高山翻白草	1931/7/14	79
Poa acroleuca	白頂早熟禾	1940/4/20	70
Cardamine flexuosa	焊菜	1963/12/31	47
Bromus catharticus	大扁雀麥	1969/8/5	41
Crypsinus quasidivaricatus	玉山茀蕨	1979/10/8	31
Conyza sumatrensis	野茼蒿	1982/11/1	28
Clematis lasiandra	小木通	1983/7/15	27
Tricyrtis formosana var. *stolonifera*	山油點草	1983/1/30	27
Pteridium aquilinum subsp. *wightianum*	巒大蕨	1983/9/22	27
Arabis lyrata subsp. *kamtschatica*	玉山筷子芥	1984/6/20	26
Stellaria saxatilis	疏花繁縷	1985/7/3	25
Woodsia polystichoides	岩蕨	1989/10/9	21
Cotoneaster horizontalis	平枝鋪地蜈蚣	1994/9/25	16
Galinsoga quadriradiata	粗毛小米菊	1998/6/22	12
Lepisorus morrisonensis	玉山瓦葦	1999/7/16	11

*Plant specimens collected before 1945 were obtained by Japanese botanists and vouchers were deposited in the herbarium of Tokyo University, while specimens collected after 1946 were obtained by local botanists and vouchers were deposited in the herbaria of the National Taiwan University or Academia Sinica, Taipei.

台灣中部高山植物之植物歧異度受氣候變遷之影響

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由於台灣地理位置、地形及棲地的變化造成豐富的植物歧異度，從過去百年及現今的植物調查，特別是在中央山脈的合歡山地區，我們得以了解植物的組成。在合歡山地區分爲四個高度帶，即 2,000 ~ 2,500 公尺、2,500~ 3,000 公尺、3,000 ~ 3,500 公尺及 3,500 ~ 3,950 公尺，以了解其植物的組成，並選擇新人崗（2,250 公尺）、石門山（3,000 公尺）、合歡山東峰（3,500 公尺）及合歡山主峰（3,500 公尺）的樣區（10×10 公尺），分別調查其植物組成，並由其數據計算其 α、β、γ 及辛普森（Simpson's）歧異度指數以比較上述研究地之植物歧異度。其結果顯示 α、β、γ 植物歧異度隨海拔高度之增加而遞減。但在新人崗實驗地，其 α 歧異度隨年代而增加，辛普森指數隨海拔高度亦遞減，顯示氣候對合歡山地區的植物歧異度有顯著的影響，從百年來的紀錄分析得知，在合歡山地區有 16 個物種會往較高的海拔移出；7 個物種留在同一海拔高度帶。在阿里山地區則有 7 個物種移出，4 個物種留在同一海拔高度帶；在玉山地區則有 15 個物種移出，5 個物種留在原海拔帶，但至少有 6 種因移出的高度太大已超越 3,950 公尺，故可能會滅絕。此結果顯示，若全球暖化發生於台灣則台灣高山植物將會有遷移的現象，會有相當多的物種往更高的地區移動，最後導致至少 6 種植物種的滅絕。

關健詞：阿里山；高山植被；α、β、γ 歧異度；全球暖化；合歡山；植物遷移；辛普森歧異度；玉山。