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Conservation biogeography of the snake family Colubridae of China

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Abstract. The areal distribution of the snake family Colubridae in China was analyzed quantitatively with the aims of determining the zoogeographic regions, areas of endemism, priority areas for conservation and important environmental factors. A presence/absence data matrix of 141 Colubridae species was analyzed by the two-way indicator analysis (TWINSPAN) for regionalization, parsimony analysis of endemicity for areas of endemism, and linear programming for priority areas selection. Ecological niche modeling was integrated into priority areas selection to achieve the objective of protecting species potential suitable habitats. The Bioclim True/False model was used because of its conservatism property. Results indicated there are nine major zoogeographical regions based on Colubridae species, some of which had been documented by previous zoogeographical regionalizations of East Asia. Four endemic areas were identified by parsimony analysis of endemicity: One in Yunnan, one in Taiwan, and another two in Tibet Province. Optimal priority areas set identified thirty-five grid cells based on species' suitable habitat ranges.

Key words: Colubridae species, zoogeographic regionalization, conservation priorities, areas of endemism

Introduction

The snake family Colubridae (Squamata: Serpentes) is the largest family of reptilia globally, in which 36 genera inhabit the mainland of China and Taiwan. Their distribution patterns are the most diverse and representative in East and South Asia when compared with other families. Many papers associated with snake species in the Asian area have only focused on distribution reports and checklists of the snake species. Quantitative analyses of species distributional patterns at large spatial scales are still not available, even though current data published are sufficient to delimit zoogeographical regions, reveal species distribution patterns and identify areas of endemism for ophidian biogeography, as well as selecting priority areas for systematic conservation.

The goals of historical and ecological biogeography are to diagnose the areas of endemism and delimitation of zoogeographical regions. They have common missions because both are to understand the geographical relations that species occupied. Areas of endemism constitute basic units in historical biogeography (Morrone & Crisci 1995), while zoogeographic regions could be useful in revealing the ecological associations among different geographical areas.

Classification of global terrestrial animal divisions could be dated back to mid-19th century, while for zoogeographical regions of China, the research could be traced back to mid-20th century (Xie et al. 2004). However, previous faunal region divisions were mostly based on experts' knowledge, and quantitative methods are seldom employed (Chen 2008).

Zoogeographic regionalization is commonly analyzed by classification or ordination methods such as cluster analysis, TWINSPAN (Hill 1979) and principle component analysis. In our study, we employed the TWINSPAN technique because it can find representative species for each zoogeographic region. This allowed us to interpret each region easily. For areas of endemism identification, there are a suite of phylogenetic, multivariate or optimal methods that have recently been proposed. For example, the phenetic clustering method, optimization criterion method, biotic element analysis, nested areas of endemism analysis, and parsimony analysis of endemicity. All of the above tools have been discussed comparatively by Morrone (1994), Linder (2001), Szumik et al. (2002), Hausdorf & Henning (2003), Deo & DeSalle (2006) and Moline & Linder (2006). Among these approaches parsimony analysis has been most commonly used because of its simplicity and reliability.

In this study we analyzed the geographical distributions of the Colubridae species living in China in order to elucidate further underlying knowledge of East Asian fauna. The distributional data were analyzed by combined approaches from the fields of community ecology, biogeography and conservation biology. Hence, the present study could produce multiple results and could be interpreted in multi-faceted aspects. Zoogeographical regions, the areas of endemism and priority areas for conservation would be discussed synthetically (Chen 2008). Few previous studies have been able to integrate these sorts of methods together in their species/areas analysis (Chen & Bi 2007, Chen 2008).

Materials and methods

Data

We considered all available data on the geographical distribution of Colubridae species in China, including Taiwan. There are more than 8000 raw distribution records for the 141 Colubridae species in the data set (which is available from the author upon request). Original resources of the distributional data and species nomenclatures were obtained from the species service website (CSIS-China Species Information Service; http://www. chinabiodiversity.com) and Fauna Sinica-Reptilia Vol. 3 Squamata: Serpentes (Zhao et al. 1998), and data were validated by the EMBL reptile database (http://www.embl-heidelberg.de/~uetz/LivingReptiles.html), UNEP-WCMC species database (http://www.unep-wcmc.org/species/index.htm) and Species 2000 (http://www.sp2000.org/).

The geographical area of mainland China (including Taiwan) is situated in the region lying between 18-54º N and 73-135º E. For carrying out the quantitative analysis, the territory was divided into 1º×1º cells. The presence (1) or absence (0) of each Colubridae species in each cell was recorded to form a basal matrix (available from the authors upon request), in which 366 cells corresponded to 141 species. The geographical map of China in East Asia used is shown in Fig. 1.

Methods

TWINSPAN, a multivariate community classification technique, was used to divide the zoogeographic regions of Colubridae species. The program WinTWINS 2.3 (Hill & Šmilauer 2005) was used to perform TWINSPAN. The Cornell condensed format of the original data was transformed by the program TransTWIS developed by the author, which is available upon request. TWINSPAN produces a dichotomous classification of sites (in this study, 'cells') on the basis of their species composition. The

TWINSPAN was set to: maximum level of divisions-9; minimum group size for division-5; maximum number of indicators per division-10.

Parsimony analysis of endemicity (PAE), a technique that has been widely employed to select areas of endemism (e.g. Costa et al. 2000; Christman et al. 2005), was used to designate the most important areas for Colubridae species (Morrone 1994). PAE was implemented using WinClada (Nixon 1999). The settings were 500 replications, with saving 2000 trees maximally. A strict consensus tree was generated, each clade of which was marked with homoplasious (white dots) and non-homoplasious (black dots) species.

Priority areas for conservation considering species' suitable habitat ranges

One straightforward criterion of determining the conservation status of species is its range size. The potential suitable habitat ranges for species could be used as an important index of selecting priority areas. We used ecological niche modeling as an index of quantifying species potential (maximal) habitat ranges. More areas were predicted as potential suitable ranges in ecological niche modeling denoted the species have wide ecological niches and can adapt different environmental conditions (Hirzel et al. 2002; Hirzel & Arlettaz 2003). Species that have narrow predicted potential ranges will be regarded as constrained species, which can be paid more attention in conservation planning. To construct this

Figure 1. 141 Geographical map and names of study locations

index quantitatively, we used the formula as follows:

$IC = Is/Im$

Where Is is the number of cells (10′×10′) (the minimal resolution used in the ecological niche model) from which the species have been predicted to occur, and Im is the number of cells occupied by the species with widest potential suitable geographical range.

The median of all ICs was selected as the standard to classify the ICs into two groups: high ICs and low ICs. Species that have high ICs will be assigned 1 representative time, while species that have low ICs will be assigned 2 times. This assignment could assist us in achieving one of our *a priori* objectives: species inhabiting narrow suitable ranges should be considered preferentially in conservation planning. The Bioclim True/False model was implemented in DIVA-GIS software (http://www.diva-gis.org) with setting of suitable percentile 0.025.

Linear programming was used to select the optimal priority areas. It can avoid the suboptimal problem that annual simulation or heuristic methods might encounter (Yip et al. 2006; Chen 2007).

The formulae were illustrated as follows:

$$\text{Min} \sum_{j=1}^{n} X_j \qquad \text{(I)}$$

where n was the number of grid cells variable X_j was 1 if cell j was selected and 0 if otherwise.

Subject to the constraints:

$$\sum_{j=1}^{n} a_{ij} X_j \geq \min(r_i, s_i) \qquad \text{(II)}$$

$$X_j \in \{0,1\} \quad j=1, 2, \ldots, n \qquad \text{(III)}$$

where n was the number of species (in our study n=141), a_{ij} was 1 if species i was present in cell j and 0 if otherwise. s_i depicts the total number of cells with records of species i; r_i denotes species i should be present at least r_i times in the priority set. High IC group species r_i =1, low IC group species r_i =2.

To obtain different combinations of optimal solutions and prevent a set (S) of s cells that have already been selected from being selected again, the following constraint was added successively (Rodrigues et al. 2000; Yip et al. 2006).

$$\sum_{j \in S} X_j \leq s - 1 \qquad \text{(IV)}$$

The software Lindo version 6.1 (LINDO System, Inc., http://www.lindo.com) was used to perform the analysis.

Results

Zoogeographical regions

The resulting visual map of TWINSPAN is shown in Fig. 2. The detailed outputs of the analysis are available from the authors upon request.

Nine zoogeographical regions were established based on the results of TWINSPAN (Fig. 3).

These nine major zoogeographical regions were as follows:

I, Southwest region: contained Yunnan province, east to the eastern Qinghai-Tibetan plateau and included the southern foot of the Himalayas. Indicator species were *Ahaetulla prasina* Reinwardt, *Boiga multomaculata* Reinwardt, *Dendrelaphis pictus* Gmelin, *Elaphe carinata* Günther, and *Elaphe porphyracea* Cantor.

II, South region: ranging from coastal areas of the three southern provinces, Fujian, Guangdong and Guangxi, with Hainan Island, reaching to Vietnam and Laos. Representative species were *Amphiesma boulengeri* Gressitt, *Amphiesma modesta* Günther, *Amphiesma octolineat*a Boulenger, *Atretium yunnanensis* Anderson, and *Dinodon septentrionalis* Günther.

III, Middle region: part of Yun-Gui plateau, north to Gansui and Shanxi provinces. East to the western part of Hubei province. Supportive species were *Amphiesma stolata* Linnaeus, *Boiga kraepelini* Stejneger, *Calamaria septentrionalis* Boulenger, *Dinodon flavozonatum* Pope, and *Elaphe bimaculata* Schmidt.

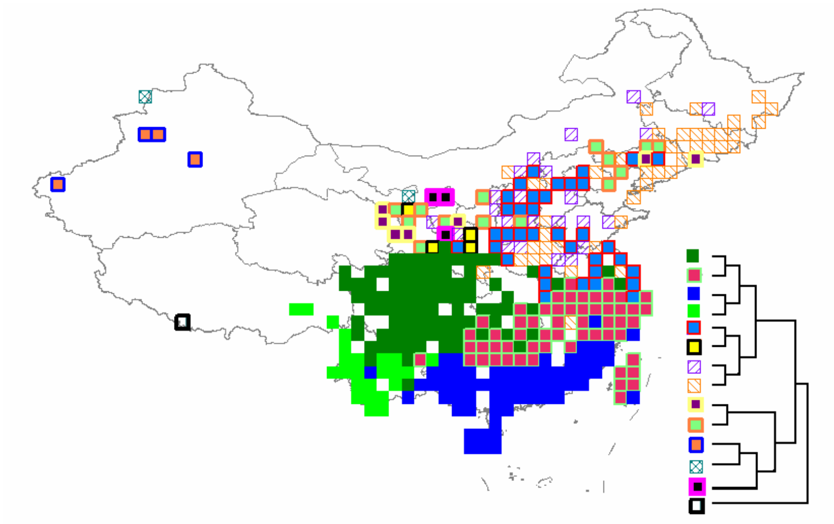

Figure 2. Map of classification of cells generated by TWINSPAN.

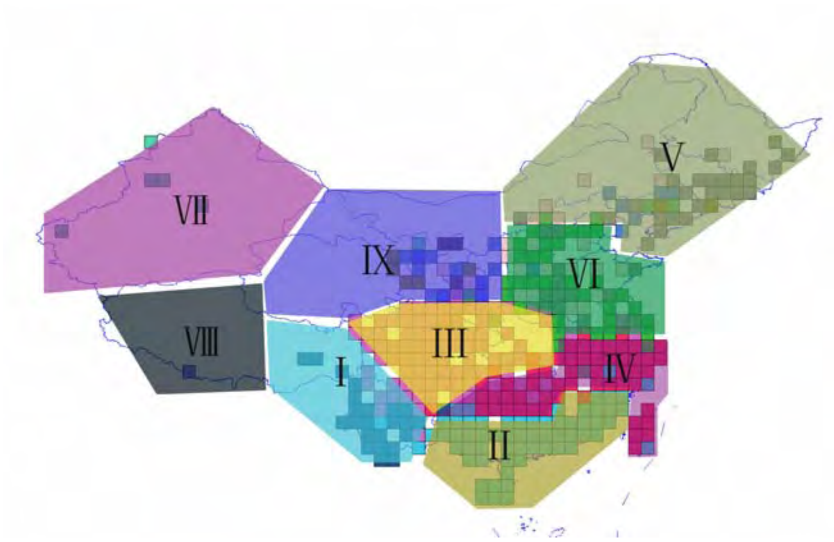

Figure 3. Nine zoogeographical regions delimited by TWISPAN.
The regions are delimitated based on the classification of Fig. 2.

IV, East region: upon the northern part of Guangxi and Guangdong, along the Yangtze River, containing Hunan, the eastern part of Hubei to Zejiang and Jiangshu. Representative species were *Achalinus spinalis* Peters, *Amphiesma craspedogaster* Boulenger, *Amphiesma sauteri* Boulenger, *Cyclophiops major* Günther, and *Dinodon rufozonatum* Cantor.

V, Northeast region: east to the western desert in Inner Mongolia, and mainly contained three northeastern provinces: Liaoning, Jilin and Heilongjiang, connecting to Manchuria and Korea. Denotative species were *Amphiesma vibakari* Boie, *Elaphe anomala* Boulenger, *Elaphe dione* Pallas, *Elaphe schrenckii* Strauch and *Rhabdophis tigrinus* Boie.

VI, North region: north to Liaoning, and the southern tip crossed the Yellow River, including Shandong Peninsula. Indicator species were *Coluber spinalis* Peters, *Dinodon rufozonatum* Cantor, *Elaphe bimaculata* Schmidt, and *Elaphe mandarina* Canto.

VII, West region: contained Qaida Basin, arid regions of Xingjian province, and extending to Kazakhstan and Kirgizistan. Representative species were *Coluber ravergieri* Ménétriés and *Natrix tessellata* Laurenti.

VIII, Tibet region: the Tibet region was proposed as an independent faunal endemic area because of the specific high altitude environments (Chen et al. 1996). Representative species were *Amphiesma platyceps* Blyth, and *Trachischium tenuiceps* Blyth.

IX, Ning-Meng region: denoted areas were situated in Inner Mongolia, Ningxia, south to Gansu and Shanxi. *Achalinus ater* Bourret, *Achalinus spinalis* Peters, and *Elaphe bimaculata* Schmidt were indicator species.

Areas of endemism

Parsimony analysis generated 2000 equally parsimonious trees, then a strict consensus cladogram with 2420 steps was obtained (not showed herein, but available from the authors upon request), with a consistency index (CI) of 5 and a retention index (RI) of 44. This analysis indicated four distinct area-clades that can be considered as the following major endemic areas (Fig. 4). Area 94&29 (Endemic area I), in eastern Tibet, was diagnosed by 5 supportive species: *Blythia reticulata* Blyth, *Dendrelaphis gorei* Wall, *Elaphe hodgsonii* Günther, *Oligodon multizonatum* Zhao and Jiang, *Xenochrophis piscator* Schneider. Area 121&25, 120&22 and 120&23 (Endemic area II) was located in Taiwan, and its supportive species were *Pareas macularius* Theobald, *Achalinus formosanus* Boulenger, *Amphiesma miyajimae* Maki, and *Pareas hamptoni* Boulenger. Area 100&24 (Endemic area III), located in Yunnan, was supported by 2 supportive species: *Calamaria septentrionalis* Boulenger and *Pareas boulengeri* Angel. Area 85&28 (Endemic area IV) was located in the north range of Himalayas and the southwestern part of Tibet, and was identified by the species A*mphiesma platyceps* Blyth and *Zaocys dhumnades* Cantor.

Optimal priority areas

The number of cells of each species predicted occurred (transformed from the predicted suitable range map using ArcView software), the values of all ICs and the original file of input data for Lindo software are available from the authors upon request. The median of the ICs was 0.065, which was the IC value of species *Elaphe schrenckii* Strauch. If the IC of species was larger than 0.065, then the species was assigned twice, if not it was assigned once. IC=0 denotes species that have no potential suitable ranges and were predicted to go extinct. More than 50 optimal sets were generated by linear programming, of which all sets consisted of 35 optimal cells that could protect 141 species. All optimal sets could serve as the candidate priority sets in nature reserve management. One representative set which considered the best connectivity of the areas was shown in Fig. 4.

Discussion

The present study provided a basal understanding of ecological and biogeographical patterns of Colubridae species, and established possible conservation priority areas for further consideration. Our study contributes to the ecological exploration of Colubridae species in East Asia, which combines multiple analytical techniques derived from analytical biogeography and systematic conservation planning (Whittaker et al. 2005, Diniz-Filho et al. 2007, Tolley et al. 2008).

Zoogeographic delimitation

Zhang (1999) proposed that China could be divided into seven general zoogeographical regions. Each featured region could be divided into several sub-regions when compared to the present work. The similarities and discrepancies among these two faunal systems were: the Northeast region and Southwest region were almost the same in both systems, while the Ning-Meng region in the present system extended to Qinghai province but in Zhang's system did not reach to that province. The West region of the present study was grouped into the Meng-Xing (Inner Mongolia - Xinjiang) region in Zhang's system. Taiwan was contained in the South region of Zhang (1999),

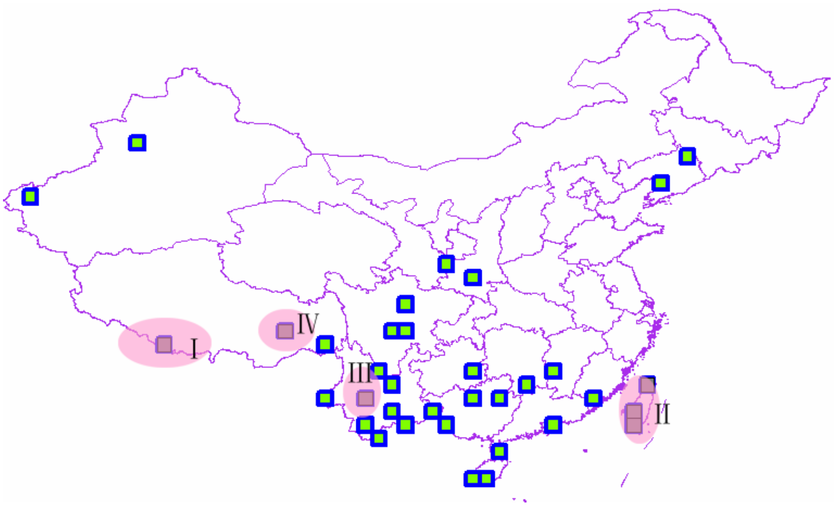

Figure 4. Four areas of endemism and the optimal priority areas for conservation of snake species in China. All of the cells shown have been selected as priority areas for conservation. Cells representing areas of endemism are also highlighted and marked with numbers.

while it was grouped into the East region of our study. The East region we identified was very similar to the Middle region of Zhang (1999) except for the position of Taiwan province. The Tibet region also formed an independent zone with Qinghai province in Zhang (1999), which was consistent with the present system.

Li (1981) recommended five principal zoogeographical regions of freshwater fishes of China. The current proposed system was not consistent with his system at the ranges of the West region. We recommended Qinghai province was included in the Ning-Meng region, in contrast to the Li's system, which regarded Qinghai province as part of the West region. The Northeastern region in the present study denoted most areas of three northeastern provinces of Liaoning, Jilin and Heilongjiang, while in the system of Li (1981), the North region only included Heilongjiang province. The Tibet plateau was a subregion categorized into the West region in the system of Li (1981). However, the results of Chen et al. (1996), Chen & Bi (2007) and the present study all regarded the Tibetan plateau north of the Himalayas as an independent faunal region linking East Asia and the Indian subcontinent.

Zakaria-Ismail (2004) identified five zoogeographic regions in Southeast Asia including ichthyofauna. The mainland zoogeographic region in Zakaria-Ismail's system that contained Mekong, Chao Phraya and Mae Khlong drainages was adjacent to the South Region in the present system and these two areas must constitute a large region. This hypothesis had been supported previously by the results of Xiang et al. (2004): the mainland of Southeast Asia and South China were grouped together by cluster analysis.

In conclusion, results from the above three comparative analyses indicated that not all regions of different taxonomies could completely overlap, and some areas even contradicted each other. The present study did not point out the pitfalls of previous zonations, it emphasized the discrepancies of zoogeographical regions of different species groups and provided new insights on the zoogeographical regions of Asia.

Analysis on faunal similarities of the seven regions indicated that the Northeastern region, North region and Ning-Meng region were overlapped partially through analyzing the distribution of TWINSPAN clusters of cells (Fig. 3). Cluster ABAAB, the indicator of the Northeastern region, could also be found in the North region. Cluster AABBA, representing the Ning-Meng region, was distributed in the other two regions. Most cellss belonging to cluster ABBAA fell into the Middle region, but a few also appeared in the East region.

Areas of endemism

The identification of endemic areas in the present study used the most applied method-parsimony analysis of endemicity, which is a heuristic method used to search all parsimonious trees. One consensus tree could be used to delimit areas of endemism. There are other approaches available that could also be used. For example, the phenetic clustering method, the optimal method, and biotic element analysis. Areas of endemism were also fully covered by optimal priority sets for conservation strategies as shown in Fig. 4. Among the four endemic areas for Colubridae species, endemic area II and III in Yunnan and Taiwan Island respectively are the two prevalent endemic areas not only revealed by various other animal groups (Zhang 1999), but also by different plant taxonomies (Wu 1991). They were also species diversification hotspots as revealed previously (e.g., Zhang 1999; Xie et al. 2004). Endemic areas I and IV, distributed in the Tibetan plateau, represented the areal characteristic of high elevation, contained many endemic species. In summary, excluding endemic area II, the other three areas of reptilian endemism located in the Tibetan plateau and Yun-Gui plateau identified herein demonstrated the complex issue of historical relationships in the high elevation and mountainous areas along the Himalayas.

In comparison with other previous studies on areas of endemism in Asia, Xu (2005) analyzed the areas of insect endemism of China based on the raw data of Catantopidae grasshopper species. Xu recognized 11 areas of endemism. Compared to Xu's results, the endemic area we identified in the eastern part of Tibet was consistent with his endemic area 7; other areas were not as congruent. Chen & Bi (2007) recognized most southwestern and south areas as endemic areas based upon the distribution of the amphibians of China. Our study was not consistent with their results. The ranges of four endemic areas in the present study were small and located in different zoogeographical regions, which did not show continuity and connectivity together compared to those of Chen & Bi (2007) and Xu (2005). This may be because of the different standard of delimitation for areas of endemism.

Conservation status of the Colubridae family and priority areas

On assessment of the conservation status of Colubridae snake species in China, 41.8% (59 out of a total of 141 species) have been documented as being vulnerable or near threatened (IUCN 2008 Red list; http://www.iucn.org). One species, *Elaphe moellendorffi* Boettger, is regarded as being endangered. These species in general have very narrow habitat ranges, and thus should be more of a conservation concern compared to widely distributed species.

Suitable distributional range was one essential attribute in priority areas selection because it directly reflected the survival status, and could be measured quantitatively and easily. However, there are other attributes for consideration in priority areas selection such as persistence ability (Nicholson et al. 2006), population genetic structure (Diniz-Filho & Telles 2006), and phylogenetic diversity (Faith 1992; Faith et al. 2004) that could contribute to global conservation strategies. Unfortunately, these attributes only measure indirect factors that may influence species survival, so they could not straightforwardly satisfy the survival needs of species. In the present work, the attribute of potential suitable habitat range has practical value, because it directly reflected species survival status.

Some authors (Peterson et al. 2000; Chen & Peterson 2002) have used species distribution modeling to assist priority areas selection through another approach known as GARP (genetic algorithm for rule-set prediction). They used the resulting potential distribution ranges as the basal map to select priority areas. An apparent deficiency was that the predicted areas were unable to represent the real occurrence of species, and therefore too many areas selected as priority areas did not actually contain the species in question. In contrast, our study only used species potential distribution range as an index of species habitat abilities. The priority areas selected are fundamentally based on species' true distribution records, and thereby guarantee the validity of candidate and final selected areas.

With respect to the procedure of carrying out priority areas analysis, the well-built distributional records were the prerequisite for selecting priority areas at finer resolutions, and then the attributes which the analysis aimed to achieve were also considered. Sequentially choosing proper methods was also important. The optimal method used here produced priority area sets that have positive values in conservation practice.

Other priority areas selection methods (Abellán et al. 2005) have their own features, but could not reach global optimization. Scoring methods were out of date for generating redundant areas, though they could be implemented easily. Annual simulations or heuristic methods were demonstrated to be suboptimal. The disadvantage of linear programming in priority areas selection was the generation of large amounts of optimal sets that made the analysis rather complex. The formula constraint IV had to be added manually which increased the calculation time.

Implications for further studies

The present study aimed to provide a framework of ecological and biogeographical characteristics involved in estimating Colubridae snake species distributions. The integrative manner for the comparatively ecological analysis used here has been successfully applied to other areas and taxonomies (e.g., Heikkinen et al. 1998; Korvenpää et al. 2003; Chen 2008).

Our study did not solely focus on either the species aspect or the areas aspect. Rather, it tried to employ integrative approaches to study biogeographical associations between species and areas, so as to document the current facts on the distribution of Colubridae species and provide potentially useful priority areas in conservation planning. Further studies should focus on the identification of common chorotypes (species sharing similar geographic distribution ranges) shared among the four major terrestrial vertebrate taxa (Amphibia, Reptilia, Mammalia and Aves), which may shed light on understanding the common species distribution patterns in Asia and the Northern Hemisphere. It is also important to carry out re-assessments of zoogeographical regions and comparisons of areas of endemism for other species groups, and to facilitate general understanding on the biogeographical boundaries and the evolvement of areas of endemism in Oriental and Palaearctic regions.

Conclusions

Nine major zoogeographical regions were proposed by TWINSPAN and four areas of endemism were identified by parsimony analysis of endemicity. Priority areas for snake species have been quantitatively identified using the linear programming method, considering the trait of species' suitable habitat ranges as the major conservation target. Zoogeographical regions identified herein have congruent and inconsistent aspects with former works. The hypothesis that the Tibetan plateau should be viewed as an independent region in the biogeographical regions system of Asia was supported through the present study. We also suggest that ecological niche modeling could be used as an extremely quantitative index of suitable habitat areas for species and to help select priority areas for conservation.

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