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Using species distribution modeling to improve conservation and land use planning of Yunnan, China

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A B S T R A C T

Part of the Himalayan biodiversity hotspot, Yunnan province in China is a highly diverse terrestrial region, particularly in the wide range of natural forest types. These forests are under considerable conversion pressure as land use intensifies with expanding human population and economic development. Conservation strategies based on the geographic patterns of botanical species richness, including the identification of meaningful floristic regions and priority areas for conservation, could improve the effectiveness of forest policy and management. These strategies should also include current threats of loss due to forest conversion to address the more urgent challenges for sustainable development. Here, we produce distribution models at $\sim$10 km^2 resolution for 2319 plant species, using geo-referenced herbarium collections, corrected for spatial bias using a null model, and detailed environmental variables. Based on 1996 species with significant non-random habitat preferences, we identify four important aspects of plant species distribution in Yunnan: (1) species diversity hotspots; (2) seven major floristic regions, using a cluster analysis of species presence/absence; (3) priority areas for conservation based on the concept of the 'irreplaceability' value of planning units and (4) the percentage remaining natural forest among the species rich and conservation priority areas, to assess the level of endangerment. Our maps provide clear priorities for the development of a sustainable and feasible biodiversity conservation strategy for Yunnan.

1. Introduction

Yunnan province, SW China (Fig. 1), is one of the botanically most diverse terrestrial regions on Earth and part of the Himalaya biodiversity hotspot (Myers et al., 2000). This region is located at a transitional zone, characterized by strong environmental gradients, between tropical, sub-tropical, temperate and alpine vegetation types, with the flora of tropical Indochina, mixing with the subtropical East Asian flora, and between major floristic regions, with the Sino-Japanese floristic region in the east and the Sino-Himalayan floristic region in the west (Li and Li, 1997; Zhu et al., 2006). The region also possesses a rich diversity of forest types, including tropical rain forest, seasonal rain forest, broadleaved evergreen forest, broadleaved deciduous forest, needle leaved forest, alpine and sub-alpine meadow, bush and mixed forest (Wu, 1987). Some parts of Yunnan have been identified as refugia during the Pleistocene (López-Pujol et al., 2011). The region has a disproportionate amount of China's overall floristic diversity (51.6%), with over 18,000 plant species (Yang et al., 2004), which includes high levels of endemism.

Yunnan's biodiversity is under considerable pressure due to the intensification of land use and an expanding human population (Li et al., 2011; Willson, 2006; Yang et al., 2004; Zhou and Grumbine, 2011). Forests have become increasingly fragmented through agriculture, logging, the planting of economic plants, mining activities and changing environment (Li et al., 2006; Xu et al., 2005). With the combined impact of anthropogenic and climate change, describing and understanding species compositional patterns and identifying areas of high species richness and priority areas for conservation has become critical for the development of sound conservation policies and their integration into a sustainable land development strategy for Yunnan.

Species distribution modeling is a widely used method to determine species diversity and compositional patterns at large spatial scales (Araújo et al., 2011; Guisan and Zimmermann, 2000;

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Pearson et al., 2006) and it produces spatially explicit and comprehensive maps that are particularly useful for identifying areas where conservation efforts are most needed or effective. The distribution models are based on data collected during botanical surveys and primarily exist as simple geo-referenced presence–absence records in herbarium collection databases, with little reliable abundance measurements. Fortunately, this particular limitation is a common feature of plant species distribution data and several modeling applications were explicitly designed to exploit presence only data (Elith et al., 2011; Pearce and Boyce, 2006; Pearson et al., 2006; Tsoar et al., 2007). These approaches can now be used effectively for a wide number of applications, greatly enhancing the power and usefulness of the large existing databases of herbarium collections.

Generally, nature reserves and protected areas are selected primarily because of their inaccessibility or unsuitable nature for other purposes, such as intensive agriculture or urban development and not to meet specific conservation objectives. This approach for designing conservation strategies exposes many species found in productive or potentially productive landscapes to conversion of habitat (Margules and Pressey, 2000). Given our current ability to model species distributions based on large databases and robust algorithms, more scientific and rigorous conservation strategies can be designed, utilizing objective predictions of species composition and diversity across the entire landscape, even in areas with little history of specimen collection. Here, we apply the theory of systematic conservation planning (Margules and Pressey, 2000) and decision making tools (Possingham et al., 2000) to identify priority areas for conservation (Carvalho et al., 2011, 2010; Wilson et al., 2005), based upon plant species distribution models. We address the following major objectives: (1) model the distribution of the woody plant flora of Yunnan to map diversity and floristic patterns across the entire province; (2) combine the current forest cover and land use maps with our species distribution models to estimate how much of Yunnan's flora has already disappeared and which of the remaining high diversity areas are most vulnerable, especially in relation to the current protected forest network in Yunnan; and (3) use these results to design a spatially explicit conservation network that would protect as many of Yunnan's woody plant species as possible in the most spatially efficient way.

2. Methods

2.1. Species data

The basic herbarium collection data for all woody species, except Fagaceae, for Yunnan province was provided by the Kunming Institute of Botany, Chinese Academy of Sciences, totaling 85,289 records. Most of these collections have been examined for the flora of China, and although some identification errors are likely, overall the identifications can be considered accurate. Although many of these records did not have latitude and longitude data, we were able to geo-reference 60,552 collections within Yunnan, using the location descriptions in the label information. These resolution of the label locations are roughly equivalent to the Chinese village level. Subsequently, species presences were scored in 5 arc min grid cells (ca. 10×10 km), avoiding duplicate species records in each grid cell. We used the 5 arc min spatial resolution because this corresponded to the environmental data resolution (WorldClim and FAO soil properties) but also because a higher resolution was not possible due to the spatial error in the geo-referenced specimen data. Species that were present in fewer than five grid cells were removed from the analysis because the statistical power of the species distribution would be too weak. Of the 60,552 geo-referenced specimens, 42,114 records, belonging to 118 plant families representing 2319 species, remained for species distribution modeling.

2.2. Environmental predictors

We initially selected 35 environmental predictors to model the species distributions. These included 19 bioclimatic predictors (1950–2000) plus elevation of the WORLDCLIM dataset (<www.worldclim.org>) and 15 soil variables selected from the FAO database for poverty and insecurity mapping (FAO, 2002) for Yunnan at 5 arc min resolution, resulting in 4936 grid cells covering the entire Yunnan province. A serious problem in species distribution modeling is formed by multi-colinearity of variables which can result in model over-fitting (Graham, 2003; Pearson et al., 2006). To avoid this problem we removed highly correlated environmental predictors. For both bio-climate and soil predictors, we used spearman's rank correlation to select the least correlated variables (spearman's <0.75). Of variables that showed correlations higher than 0.75 only the ecologically most meaningful factors were kept (Tables S1 and S2). For the bio-climate predictors the following variables were included in the analyses: (1) BIO1: Annual Mean Temperature; (2) BIO2: Mean Diurnal Temperature Range; (3) BIO4: Temperature Seasonality; (4) BIO7: Temperature Annual Range; (5) BIO12: Annual Precipitation; (6) BIO14; Precipitation of Driest Month; (7) BIO15: Precipitation Seasonality. Of the soil predictors the following variables were included in the analysis: (1) CE-T: CEC clay topsoil (CEC = cation exchange capacity); (2) CN-T: C:N ratio class topsoil; (3) CP-T: organic carbon pool topsoil; (4) DEPTH: effective soil depth; (5) DRAIN: soil drainage class; (6) NN-T: nitrogen% topsoil; (7) PH-T: pH top soil; (8) SOIL-PROD: soil production index; (9) textural class subsoil. In total 16 of the 35 predictors were kept as environmental layers for the species distribution models.

2.3. Species distribution model building and collection bias correction

To model species distributions we used the modeling application Maxent (ver. 3.3.1; <www.cs.princeton.edu/~schapire/maxent/>) (Phillips et al., 2006). Maxent was specifically developed to model species distributions with presence-only data. Of available species distribution modeling algorithms, Maxent has been shown to perform best, especially when few presence records are available, while it is also the least affected by location errors in occurrences (Graham et al., 2007). Maxent was run with the following modeling rules: (1) for species with 5–10 collection records linear features were applied, (2) for species with 10–14 records quadratic features were applied, while (3) for species with >15 records hinge features were applied (Raes and ter Steege, 2007). These rules were included in Maxent to counteract the tendency of species distribution models (SDMs) to over-fit, especially when few presence records are available. For each of the 2319 species a SDM was developed based on its unique presence records and the 16 environmental predictors.

As a measure of the accuracy of the SDMs, we used the threshold independent and prevalence insensitive area under the curve (AUC) of the receiver operating characteristic (ROC) plot produced by Maxent. All measures of SDM accuracy require absences, when these are lacking, as is the case here, they are replaced by pseudo-absences or sites randomly selected at localities where no species presence was recorded (Phillips et al., 2006). However, when SDM accuracy measures are based on presence-only data and pseudo-absences, the standard measures of accuracy (e.g. the often used measure AUC > 0.7) do not apply (Raes et al., 2009; Raes and ter Steege, 2007). Therefore, we applied the bias corrected null-model developed by Raes and ter Steege (2007) to test the AUC value of an SDM developed with all presence records against the AUC values expected by chance. However, this assumes that collection localities represent a random subset of the study areas environmental space. In many cases this is not a valid assumption due to collecting biases (Kleidon and Mooney, 2000; Reddy and Davalos, 2003; Tsoar et al., 2007).

To check for collection location bias in our dataset, we tested whether our 1406 localities represented a random subsample of the environmental predictor space. First, we divided each of the 16 environmental predictors into 10 equal-interval bins based on the ranges observed for our 4936 grid cells covering Yunnan (Loiselle et al., 2008). We then tested whether the observed frequency distributions represented by the 1406 collection localities differed from those observed for whole Yunnan using a Chi-square test. This showed that for 10 of the 16 environmental predictors, our collection locations represented non-random subsamples of Yunnan's environmental predictor space. To correct for this bias we developed a bias corrected null model by testing each species model AUC value against 1000 AUC values that were generated randomly by subsampling from all the available collection localities only. When the observed AUC value fell in the top 95% of randomly generated AUC values, it was considered to have a significant non-random distribution and was used in our further analyses. Of the 2319 modeled species of Yunnan, 1996 species showed a significantly non-random distribution in relation to the environmental variables.

2.4. Botanical richness and delineation of floristic regions

In order to determine the patterns of botanical richness of Yunnan, a threshold is needed that defines at what level of Maxent prediction values a species is considered present or absent in a grid cell. For SDMs represented by $\geqslant 10$ records we used the fixed "10 percentile presence" threshold for this purpose. This is a general rule that reflects the fact that it is reasonable to assume that 10% of the collections were wrongly identified or geo-referenced (Raes et al., 2009). For species represented by 5–9 records we used either the "sensitivity specificity equality" or the "sum maximization" threshold, whereby the sensitivity specificity equality threshold means that the absolute value of the difference between sensitivity and specificity is minimized and the sum maximization means that the sum of sensitivity and specificity is maximized (Liu et al., 2005, 2011), due to which of the two corresponding omission rate was closet to 10%. Once the threshold is set, a series of presence/absence layers of all the species becomes available. Using these layers we created a presence/absence matrix in which the rows represent the 4936 grid cells covering Yunnan and the columns represent the presence of the 1996 modeled species. Species richness was then defined as the summed number of species in each grid cell.

Based on the presence/absence matrix a hierarchical cluster analysis (Kreft and Jetz, 2010; Procheş, 2005) was applied to group the study areas in floristic regions, using sØrensen's index as distance measure in combination with the "flexible beta linkage method" ($\beta = -0.25$) as clustering algorithm. The reason we chose this method was because this method is space conserving (reflects the multidimensional distribution of points as close as possible), thereby avoiding distortion, and has the least propensity to "chain" (Perrin et al., 2006). Before we performed the cluster analysis, the statistically best point to prune the cluster dendrogram was determined in order to find the optimum number of final cluster groups. The indicator species analysis (Dufrene and Legendre, 1997; McCune et al., 2002) calculates the indicator taxa at each level of bifurcation in the cluster dendrogram and determines how well they fit the clusters (based on p values). The significance of the assignment to a cluster group is determined with a Monte Carlo test using 1000 randomizations (Kleidon and Mooney, 2000; Perrin et al., 2006). For the cluster analysis, we used summed p-values for 2–30 cluster groups to detect the optimum level of grouping. We randomly drew 1000 grid cells for each analysis and repeated the procedure five times. We found that seven groups show the lowest summed p-value so we used this as the optimum level of grouping. We then performed the cluster analysis on the complete presence/absence matrix, setting the cluster group level as 7. The cluster analysis and indicator species analysis were both performed using PC-ORD 5.0.

2.5. Priority areas for conservation

The decision making software Marxan was used to solve the minimum set reserve design problem (Possingham et al., 2000). This method aims to minimize the space for conservation, while meeting user-defined conservation targets. An important criterion for a reserve system is that it should represents as much of the available biodiversity as possible. Therefore we focused on detecting the importance of each grid cell for conservation using the 'irreplaceability' score (Ardron et al., 2010). Irreplaceability works by looking at how necessary each grid cell is to achieve the target for a given conservation feature (Game and Grantham, 2008), while the 'irreplaceability' score reflects the summed number of times each planning unit was chosen in a set of runs of the algorithm. Grid cells with a high 'irreplaceability' score include high numbers of species with low species overlap compared with other grid cells, while grid cells that have a low 'irreplaceability' score overlap in species composition with many other grid cells, although they can still have high biodiversity (Huggins, 2005).

We used the 4936 grid cells as our planning units and set the "cost" of each planning unit as 10000/(species diversity). As conservation feature we used the presence/absence of the 1996 significant species in each planning unit. For each of the 1996 species we set the conservation target as including 30% of its predicted area. We used different levels for the boundary length modifier (BLM) variable which controls the importance of minimizing the reserve system boundary length relative to its size (Stewart and Possingham, 2005) for the selection of compact and efficient reserve systems. We ran the algorithm 100 times by setting the BLM at 10 levels $(0.0001, 0.001, \ldots, 1000, 10{,}000)$ as this controls the level of fragmentation allowed to occur in the reserve system. For each of the 10 levels the average boundary length and total surface area was plotted to find the optimum level of BLM. At BLM levels higher than 10 the boundary length started to decrease while the total area started to increase fast (Fig. S2), so we chose level 10 as the optimum value for BLM. Once all the parameters above were determined, we set the algorithm to run 100 times and calculated the average 'irreplaceability' score of each planning unite.

2.6. Yunnan's remaining flora

Finally, we combined our results with a recent land use map (2009) from ESA (European Space Agency)<http://ionia1.esrin.esa.int/> at a solution at 10 arc s (1/360°). We resampled this map to produce a map with a resolution of 30 arc s (1 km × 1 km). Of the 18 land use types defined for Yunnan we only retained natural forest areas, which currently cover 36.9% of Yunnan. The resampled map had 493,600 grid cells, containing either no natural forest (0) or natural forest (1). All the maps produced by the previous analyses were multiplied by this land use layer to produce maps of remaining species diversity, floristic regions, and our proposed conservation network (see Fig. 2).

Additionally, we downloaded the current protected area network in Yunnan from the World Database on Protected Areas <http://www.wdpa.org/> (Fig. 3) and resampled the map to get a resolution of 10 km × 10 km. Although this is a coarse resolution, it serves the purpose of showing the overlap/mismatch between

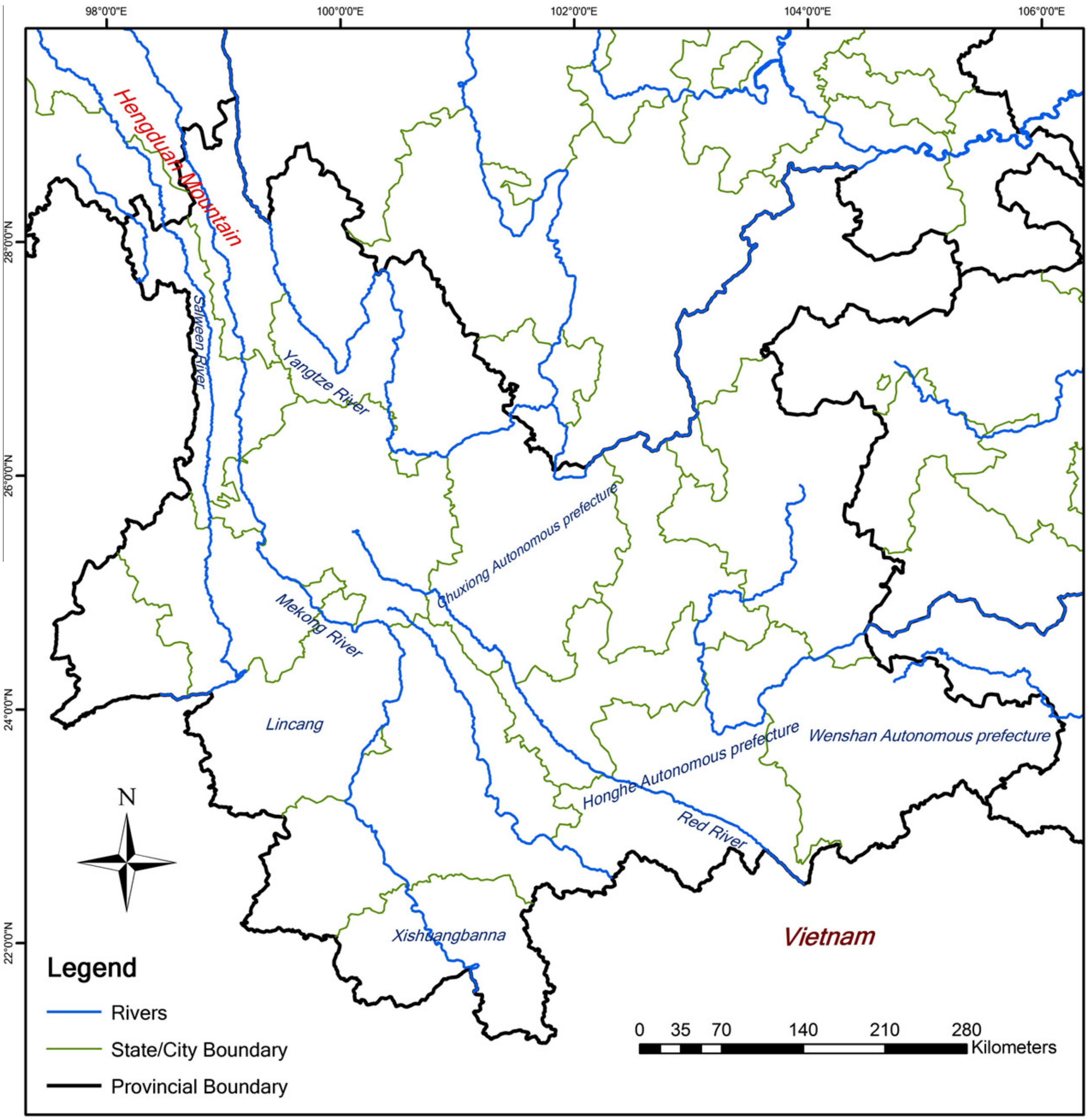

Fig. 1. Introduction of Yunnan locations.

the current protected areas and our suggested conservation priority areas. The current protected areas were evaluated by combining the map of species diversity, floristic regions and proposed priority areas for conservation to determine how well it protected Yunnan's flora.

3. Results

The plant collections used in this study covered 1406 of the 4936 grid cells in Yunnan. Of all the 2319 species we modeled, 1996 showed significant habitat preferences when tested against the collection bias corrected null model. The 1996 significant SDMs were used to map species diversity (Fig. S1A) in Yunnan. After cutting the species diversity values into five equal intervals (Fig. 2A), three species diversity hotspots were recognized in Yunnan: the northwest (The Three Parallel Rivers Region: the Yangtze, Mekong and Salween rivers), the southwest (Xishuangbanna: recognized as the tropical area of Yunnan) and the southeast (south part of Honghe and Wenshan Autonomous prefecture, on the border with Vietnam) part of Yunnan. Yunnan Province was divided into 7 floristic regions (Fig. 2C) representing different vegetation types. The 'irreplaceability' score of each grid cell (Fig. S1B) was calculated. After cutting the 'irreplaceability' score into five equal intervals (Fig. 2E), eight high conservation priority areas (i.e. areas that would protect most of Yunnan's species in the most space efficient way) in Yunnan were found. Two patches were located in the three parallel rivers region, one in the northeast part of Yunnan, one in the south part of the Gaoligong Mountains, one around and to the northeast of Ailao mountain, one in the Lincang region, one in the north of Xishuangbanna and one in the south part of Honghe and Wenshan Autonomous prefecture.

The identified conservation priority areas tended to form a connected biodiversity conservation network that covered the three

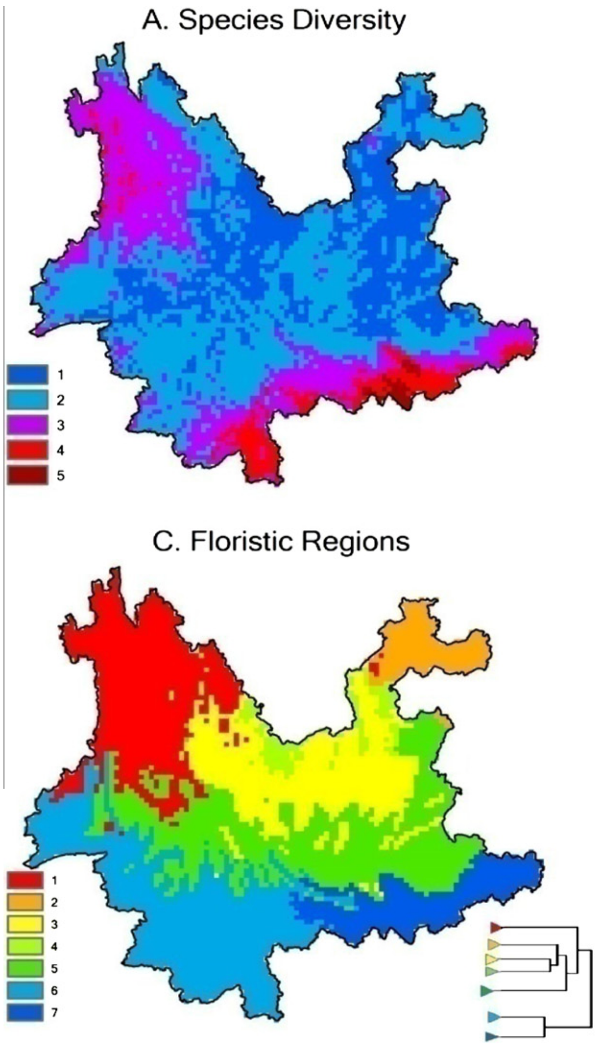

Fig. 2. (A) The five quartiles of species diversity (1 = the lowest group; 5 = the highest group); (B) the five quartiles of species diversity still covered by forest; (C) the seven floristic regions of Yunnan and their compositional relationships (dendrogram in left lower corner); (D) forest remaining in the seven floristic regions; (E) the five quartiles of 'irreplaceability' score of planning units (1 = the lowest group; 5 = the highest group); (F) the five quartiles of 'irreplaceability' score of planning units still covered by forest.

biodiversity hotpots and all the different forest types of Yunnan. Additionally, the coverage of current protected areas was also calculated by combining the three maps above (Table 1. Current Protected Areas) to evaluate the effectiveness of the current protected areas for biodiversity conservation. Our results showed that the current protected areas of Yunnan perform poorly, representing only a very limited part of Yunnan's biodiversity. Finally, we combined the current land use map with our predicted maps, removed the non-forested grid cells (Fig. 2B, D, and F), and calculated the remaining forest in each group (Table 1). We found that the

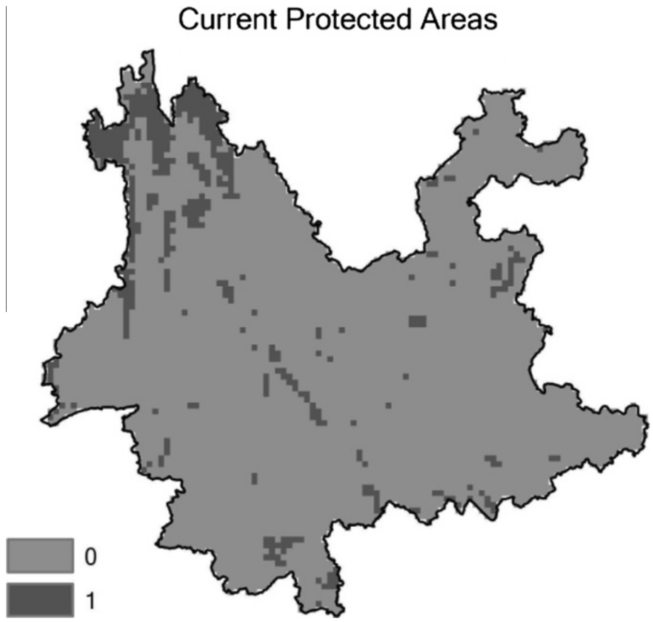

Fig. 3. Current protected areas of Yunnan (rescaled to a 10 × 10 km resolution) (1 means the areas have been protected).

remaining natural forest in Yunnan can still form a conservation network. However, for the middle plateau and south part of Yunnan (the northern edge of tropical Southeast Asia) the protection is most urgent, since most natural forest cover has already disappeared there.

4. Discussion

4.1. Botanical richness patterns and floristic regions of Yunnan

The botanical richness patterns and floristic regions that we identified were based on 1996 significant SDMs, representing 118 plant families and all woody life-forms, making this the largest dataset available for Yunnan today. Lowest species diversity (26 species) was predicted in Chuxiong Autonomous prefecture (Fig. 1), which is located to the northwest of Kunming, while the highest species diversity (1031 species) was found in Hekou country (south part of Honghe Autonomous prefecture, where the Red River enters Vietnam). Of the three recognized biodiversity hotpots of Yunnan, the Three Parallel Rivers Region is a topographically complex area known as the south part of the Hengduan Mountains. This area shows diverse ecosystems and remarkable vertical vegetation structuring, from evergreen broadleaf forests at low elevations, to mixed and conifer forest at mid elevations, to alpine screes on the mountain summits (Wu, 1987). This area was already identified as a conservation priority for plant diversity (Ma et al., 2006) and over 7000 species of plants have been recorded here (31% of Yunnan's total). It is also one of the three endemic species centers in China (Li and Li, 1997; Xu and Wilkes, 2004). Xishuangbanna has the largest tropical–subtropical forest cover in southwestern China and is locate at the northern edge of tropical Southeast Asia. The flora of Xishuangbanna includes more than 3336 plant species and 1140 genera (Zhu et al., 2005), and the vegetation can be classified into four main types: tropical rain forest, tropical seasonal moist forest, tropical montane evergreen broadleaved forest, and tropical monsoon forest (Zhu et al., 2006). The South part of Honghe and Wenshan Autonomous prefecture was recognized as the highest species diversity area. This region is also located at the northern edge of tropical southeast Asia, but this region is characterized by large limestone areas and famous for its high number of endemic species (Li et al., 2002).

Previously, Yunnan was divided into five floristic regions based on floristic surveys and expert opinion (Wu, 1987). These original five regions overlap mostly with the seven regions that our study identified: Wu's (1987) west/northwest region corresponds to our group 1, his northeast region with our group 2, his Yunnan's middle plateau region with our groups 3, 4 and 5, his south/southwest region with our group 6 and his southeast region with our group 7. Our study provided some additional detail on the middle plateau region of Yunnan province (previously considered a single floristic region) by further subdividing it into three sub-regions that represent a latitudinal gradient in species composition, suggesting a climatic driver for these patterns. In general, the species diversity in our floristic groups 1, 6 and 7 are high, while those in groups 2–5 are low. This is not surprising given that floristic groups 6 and 7 represent tropical regions, and group 1 the environmentally highly diversified northwest of Yunnan. Floristic regions 2–5 mostly represent vegetations at mid-elevation plateaus with temperate climate and occasional severe drought and frost years, thus representing a less diversified landscape with a more extreme and resource limited environment.

Table 1
Overview of diversity, irreplaceability and floristic regions in relation to total surface area, remaining forest area and surface area protected in forest reserves. Total indicated the surface area as a percentage of Yunnan's total area; Forested YN indicates the percentage of forest area compared to Yunnan's total; Forested IN indicates the percentage land covered by forest within the categories themselves; current protected areas indicate the percentage surface area included within nature reserves.

		Total (%)	Forested YN (%)	Forested IN (%)	Current protected areas (%)
Species diversity	1	26.26	7.26	27.64	12.44
	2	42.89	15.49	36.11	27.33
	3	23.93	11.15	46.62	47.78
	4	6.02	2.49	41.41	9.11
	5	0.91	0.47	51.67	3.33
'Irreplaceability' score of planning units	1	47.83	15.23	31.84	30.89
	2	14.87	6.09	40.93	18.00
	3	13.78	5.93	43.07	20.89
	4	11.93	4.97	41.66	16.22
	5	11.59	4.64	40.07	14.00
Floristic regions	1	19.55	10.95	56.01	62.67
	2	4.96	1.83	36.83	0.44
	3	17.14	4.59	26.78	5.33
	4	3.12	0.73	23.49	0.44
	5	22.53	6.44	28.57	11.33
	6	23.93	9.58	40.05	14.00
	7	8.77	2.74	31.27	5.78
Total		100	36.86		

4.2. Priority areas for conservation and current protected areas of Yunnan

The priority areas for conservation as identified by the systematic conservation planning tool Marxant, found eight high conservation priority areas in Yunnan. The three parallel rivers region, Gaoligong Mountain, Ailao Mountain and Xishuangbanna were recognized as key areas for conservation in the past, but few studies have identified the northeast part of Yunnan, the Lincang region and the south part of Honghe and Wenshan Autonomous prefecture as conservation priorities. Also, based on the irreplaceability of the PUs, we found that the boundaries of floristic regions turned out as showing especially high conservation value. This is perhaps not surprising as these boundaries represent steep floristic gradients and thus encompass many species (high complementarity) within relatively small surface areas. Since the identified conservation priority areas tend to follow the boundaries of the seven floristic regions they also form a connected biodiversity conservation network within Yunnan Province. This conservation priority network includes three predicted species diversity hotpots and all different forest types of Yunnan. It runs from south to north and east to west through strong environmental gradients, and could thus form a climate change resilient system facilitating species migration.

The current protected area network in Yunnan covers 9% of its surface area. However, it only covers about 3.3% of the surface area of the regions with the highest species diversity (floristic group 5), while covering nearly 48% of the surface area of one of the regions with the lowest diversity (floristic group 3). The map of the current conservation network in Yunnan shows very limited overlap with our map of proposed priority areas for conservation. This means that the current conservation network in Yunnan does not reflect true conservation priorities within the province and that Yunnan's conservation strategy needs to be reconsidered within the light of our new findings. Given the fast and extensive land use changes that are now taken place in the province, this strategic conservation policy change is urgent.

4.3. Current land use threats to different regions of Yunnan

By combining our results with the current land use map of Yunnan we detected how current land use has already affected different floristic regions. At present, 37% of Yunnan's surface area is still covered by natural forest but most parts of Yunnan are currently experiencing pressure from population growth and economic development. We identified the north edge of tropical Southeast Asia (Xishuangbanna, south part of Honghe and Wenshan Autonomous prefecture) and the middle of Yunnan (floristic regions group 3, group 4 and group 5) as the most threatened regions by current land use. Within our proposed conservation priority network, the two patches that are located at the northern edge of tropical southeast Asia (Xishuangbanna and the south part of Honghe and Wenshan Autonomous prefecture) are severely threatened by monocrop development (mainly rubber plantations) (Li et al., 2006; Xu et al., 2005). This is especially worrisome for the south part of Honghe and Wenshan Autonomous prefecture because it is a limestone region that regenerates very slowly after disturbance. In Xishuangbanna the government and policy makers need to balance the tradeoff between economic development and the protection of the natural forest. Another conservation priority area (northeast of Ailao Mountain), which is located in central Yunnan is also severely threatened by population growth and economic development. This area has a high population density and it is also a suitable area for urban development. Although the species diversity of this region is relatively low, this area was identified as a key area for conservation because most species occurring in this area are endemic to the middle plateau (Wu, 1987). On the other hand, the conservation priority areas in the three parallel rivers region and the south part of the Gaoligong Mountain are currently well protected. This area was known as a high species diversity area and famous for its high number of endemic species. Due to the topographically complex terrain the natural forest cover of this area has remained high and a large protected area was established in this area by the government.

A serious problem within the proposed conservation network is the connectivity between the patches. The corridor based on the 'irreplaceability' values 2–4 are still well covered by forest (40% of surface area), but habitat fragmentation inside these corridors will remain a main challenge in the future. The corridor between the patches of the Three Parallel Rivers Region, the Lincang region and Xishuangbanna show a high connectivity, but the corridor function between the Three Parallel Rivers Region, northeast of Ailao Mountain and south part of Honghe and Wenshan Autonomous are currently less well connected and the restoration of natural forest of this area is necessary to restore this connection.

5. Conclusion

The vegetation types of Yunnan are under serious and increasing pressure of population growth and economic development, making sustainable land use planning critically important for biodiversity conservation. Since it is impossible to protect all remaining forests in Yunnan due to land-use conflicts and need of economic development, the best alternative strategy is to select a network of areas that can conserve most of Yunnan's biodiversity in the most space conserving way. Our study proposes such a network based on a large species diversity data set and clear methodology. The results show that the current protected forest network in Yunnan (with the exception of the Northwest) does not effectively protect most of Yunnan's biodiversity. A better network is proposed that has as additional benefit that it can be relatively easily linked via a corridor system, which would make the network resilient to global change. Since the proposed network was explicitly designed to be space conserving, it provides an optimal conservation strategy that leaves room for economic development. However, given the fast land-use changes that are now taking place in Yunnan, it is of the utmost importance that policymakers start the process of reconsidering Yunnan's current conservation protection network. Urgency is needed because it is likely that within one or two decades, the costs of restoring lost diversity and natural forests will be too high to be politically feasible. At present it is still possible to combine Yunnan's fast economic development with a sustainable and feasible biodiversity conservation strategy.

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Appendix A. Supplementary material

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.biocon.2012.04.023.

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