Proposed Conservation Landscape for Giant Pandas in the Minshan Mountains, China

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Abstract: The giant panda (Ailuropoda melanoleuca), is one of the world’s most endangered species. Habitat loss and fragmentation have reduced its numbers, shrunk its distribution, and separated the population into isolated subpopulations. Such isolated, small populations are in danger of extinction due to random demographic factors and inbreeding. We used least-cost modeling as a systematic approach to incorporate satellite imagery and data on ecological and behavioral parameters of the giant panda collected during more than 10 years of field research to design a conservation landscape for giant pandas in the Minshan Mountains. We identified 8 core habitats and 4 potential linkages that would link core habitats CH3, CH4, and CH5 with core habitats CH6, CH7, and CH8. Establishing and integrating the identified habitats with existing reserves would create an efficient reserve network for giant panda conservation. The core habitats had an average density of 4.9 pandas/100 km² and contained approximately 76.6% of the giant panda population. About 45% of the core habitat (3245.4 km²) existed outside the current nature reserves network. Total estimated core habitat decreased between 30.4 and 44.5% with the addition of residential areas and road networks factored into the model. A conservation area for giant panda in the Minshan Mountains should aim to ensure habitat retention and connectivity, improve dispersal potential of corridors, and maintain the evolutionary potential of giant pandas in the face of future environmental changes.

Keywords: conservation planning, core habitats, giant panda, least-cost model, potential protected habitats

Propuesta de Paisaje para la Conservación de Pandas Gigantes en las Montañas Minshan, China

Resumen: El panda gigante (Ailuropoda melanoleuca) es una de las especies en mayor peligro. La pérdida y fragmentación del hábitat han reducido sus números, contruido su distribución y separado las poblaciones en sub poblaciones aisladas. Esas poblaciones aisladas y pequeñas están en peligro de extinción debido a factores demográficos aleatorios y endogamia. Utilizamos modelos de costo mínimo como un método sistemático para incorporar imágenes de satélite y datos sobre parámetros ecológicos y conductuales del panda gigante recolectados durante más de 10 años de investigación de campo para diseñar un paisaje para la conservación de pandas gigantes en las Montañas Minshan. Identificamos ocho hábitats núcleo y cuatro corredores potenciales que conectarían a los hábitats núcleo HN3, HN4 y HN5 con los hábitats núcleo HN 6, HN7 y HN8. El establecimiento y la integración de los hábitats identificados con las reservas existentes crearían una eficiente red de reservas para la conservación del panda gigante. Los hábitats núcleo tenían una densidad promedio de 4.9 pandas/100 km² y contenían aproximadamente 76.6% de la población de pandas gigantes. Alrededor de 45% del hábitat núcleo (3245.4 km²) está afuera de la red de reservas naturales actual. El hábitat núcleo
total estimado disminuyó entre 30.4 y 44.5% con la adición de áreas residenciales y redes de carreteras al modelo. Un área de conservación para el panda gigante en las Montañas Misbam debería tratar de asegurar la retención y la conectividad del hábitat, mejorar el potencial de dispersión de los corredores y mantener el potencial evolutivo de los pandas gigantes en vista de cambios ambientales en el futuro.

Palabras Clave: hábitats núcleo, hábitats potencialmente protegidos, modelos de costo mínimo, panda gigante, planificación de la conservación

Introduction

The giant panda (*Ailuropoda melanoleuca*) is one of the world’s most endangered mammals (Schaller 1993). It was once distributed throughout most of the lowland forests of eastern and southern China, northern Vietnam, and northern Myanmar (Hu 2001). During the last 2 centuries, however, climatic change, habitat loss, and fragmentation from deforestation have drastically reduced the numbers and distribution of giant pandas. The remaining animals exist in a few isolated subpopulations (Hu 2001). The entire wild population is composed of approximately 25 isolated populations, each with fewer than 20 individuals (Schaller 1993). They are distributed across 6 mountain ranges in montane forests at the edge of the Tibetan Plateau (Fig. 1) (State Forestry Administration 2006). Such isolated, small populations are in danger of extinction owing to demographic and genetic factors (Soulé & Mills 1998). Some 10–20% of these populations have disappeared since the 1970s.

Conservation of endangered wild giant pandas in fragmented landscapes has become a central issue for conservation biologists (Loucks et al. 2003). For more than a century, protected areas have been the cornerstones of biological conservation (Rouget et al. 2006). One important conservation measure taken by the Chinese government was to expand the system of protected areas (State Forestry Administration 2006). But in recent years, the role of protected areas in conservation has been debated on several fronts. As destruction of natural habitat continues, the protected areas established to conserve the threatened or rare species became insular within matrices of human-exploited landscapes (Rouget et al. 2006). Many of the protected areas are unlikely to maintain viable populations of species because they are too small and isolated from other populations over the long term (Rouget et al. 2006). Isolated large vertebrate populations in such refuges have a high probability of local extinction (Wikramanayake et al. 2004).

For these reasons, conservation biologists are promoting the concept of metapopulation management to conserve large, wide-ranging species (Margules & Pressey 2000) and are increasingly stressing the importance of linkages between protected areas through corridors for migratory species and the need for a protected network (Xu et al. 2006). For the remaining populations in fragmented landscapes, connectivity is a key factor in the persistence of metapopulations, and dispersal is a key process in assessing the survival of the resulting metapopulations (Jonathan et al. 2006).

To meet the panda’s long-term habitat needs, a landscape approach for conservation is required (Loucks et al. 2003; Xu et al. 2006). Systematic approaches for conservation planning have received major attention during the past 2 decades (Margules & Pressey 2000). We used least-cost modeling (Yu 1996; Adriaensen et al. 2003) that incorporated satellite imagery and ecological and behavioral parameters of giant pandas collected over 10 years (Hu 2001) to design a conservation landscape for giant pandas in the Minshan Mountains. Our objectives were to identify core habitats for the giant panda’s conservation that contain the most suitable habitat, identify habitats suitable for further protection that can function as corridors to ensure habitat retention and connectivity, develop recommendations for off-reserve land management, and propose the development of a giant panda conservation-reserve network that will maintain the evolutionary potential of giant pandas in the face of future environmental changes.

Methods

Study Area and Species

The study area was in the upper Yangtze ecoregion and covered 34,623 km² of North Sichuan and South Gansu in the transitional zone between the Tibetan and the Sichuan plains (Fig. 1). It was selected because the Minshan Mountains support half of the world’s giant panda population (Hu 2001). Up to now, 18 natural reserves have been established for panda’s conservation in the Minshan Mountains (State Forestry Administration 2006). Nevertheless, giant pandas in the Minshan Mountains are still in jeopardy despite efforts made by the government, international organizations, and local people (Li 1997). Great threats derived from human activities (road construction, agricultural expansion, collection of fuel wood) and natural processes (bamboo flowering, deforestation) affect panda habitat at a large scale (State Forestry Administration 2006). Urgent measures are needed to establish a reserve network in the Minshan.
Mountains to increase gene flow and genetic variation and thus ensure the panda’s long-term survival in this area.

The Least-Cost Algorithm

In heavily fragmented landscapes species are likely to survive only within networks of patches that are sufficiently connected by dispersing individuals (Chardon et al. 2003). Functional connectivity takes movement behaviors of species into account (Tischendorf & Fahrig 2000), which is determined by the resistance of the landscape matrix: different habitat types can hinder or enhance species movement (Debinski & Holt 2000).

Least-cost modeling is a versatile research framework through which insights into crucial conservation strategies for endangered species (Graham 2001) can be obtained. We developed a cost–distance surface on the basis of least-cost modeling in a geographic information system (GIS). Two layers, a source layer and a cost (or resistance) grid layer, formed the inputs for the model. The source layer indicated the habitat patches from which giant pandas were expected to migrate. The cost grid layer indicated the resistance value and the geographical position of all relevant landscape elements. The value of each cell in the grid was derived from the resistance of the habitat elements, such as type of land cover (vegetation type and land use), bamboo cover, topographic factors, and the effects of human activities on the habitats. The model had 4 steps: (1) identification of the source layer, (2) construction of the cost grid, (3) creation of the cost–distance grid by integrating the cost grid layer and the source layer, and (4) categorization of the cost distance to identify core habitats, potential habitats that could warrant protection, and potential corridors. The work was performed in a raster format in the grid module in ArcGIS software package (Environmental Systems Research Institute, New York). The cell or pixel size for the analysis was 30 × 30 m.

Identification of the Source Layer

We identified the source layer on the basis of distribution data on giant pandas from the third national survey for giant pandas (step 1). The Third National Survey distinguished giant panda individuals according to the average fragment size of bamboo stem in droppings, with an estimated accuracy of 71.2–92.9% (Yin et al. 2005). The bamboo stem fragment (BSF) method is currently widely applied in panda population surveys (State Forestry Administration 2006). The method is suitable for estimations of giant panda individuals across regional-scale areas such as the Minshan Mountains (Zhan et al. 2006).

We identified the source layer with the density function in ArcGIS. The average home range of giant pandas varies in size from 389 to 640 ha (Chen et al. 2000). We assumed the minimum space requirement of a giant panda was 400 ha and set 20 km² as a conservative size threshold for identifying the source layer, which was the minimum area needed to sustain a giant panda population with at least 5 breeding pandas over the short term.

Construction of the Cost Grid

Resistance of the habitats depended on landscape elements such as biotic factors (land cover and bamboo cover), topographical factors (elevation, slope, and aspect), and human activities (distance from residential areas and roads) (Liu et al. 1999; Xu et al. 2006). We created the land-cover layer with 6 Landsat Thematic Mapper images (2000–2001) acquired from the Remote Sensing
Satellite Ground Station, Chinese Academy of Sciences. We used 1:50,000 topographic maps to georeference the images and unsupervised classification. A 1:50,000 land-use map (1990s) was used to guide interpretation. To refine and correct the classification, we organized a workshop with local experts on land cover, remote sensing, and GIS. Validation was done with ground-truth surveys with 450 GPS points. The accuracy of the land-cover classification was 84%.

The giant panda is an obligate feeder on bamboo, and bamboo represents 99% of its diet (Hu 2001). We derived the bamboo cover from forest canopy data according to the fifth Forest Inventories (2000–2004) (1:50,000). The literature suggests that temperate montane broad-leaved forest, mixed temperate montane broad-leaved and conifer forest, and subalpine forest in the Minshan Mountains with 30–70% canopy provide an optimum environment for bamboo growth and regeneration (Li 1997). So we assumed that areas covered by forests with canopy cover of 30–70% were dominated by bamboo.

Topographical factors contributed to landscape resistance, which determined the ability of giant pandas to move across the landscape (Wei et al. 2000). A digital elevation model (DEM) with a resolution of 30 m was developed from the 1:50,000 topographic maps. Elevation, slope, and aspect were derived from the DEM. Pandas cannot tolerate low temperatures and inadequate food in high elevation (Schaller 1993; Hu 2001). Slope appeared to be an important habitat feature to giant pandas (Hu 2001). Restricting movements to gentler slopes has been widely hypothesized to be a means of energy saving for giant pandas (Wei et al. 2000).

Human activities have great impacts on the resistance of the landscape. We assumed that distances from residential areas and roads reflect the degree of human activity and that impacts of human activity decrease with increasing distance from residential areas and roads (Liu et al. 1999). We obtained residential-area and road-distribution data from the Forestry Bureaus of 7 counties in the Minshan Mountains.

We reclassified each of the habitat data layers on the basis of the resistance they presented to movement of giant pandas (step 2) (Xu et al. 2006). Relative resistance of land cover, bamboo cover, elevation, aspect, slope, and distance from residential areas and roads were analyzed with the Delphi method (Xu et al. 2004). We invited experts on giant panda conservation to rate the relative resistance of each factor, and then analyzed their opinions to gain an overall relative resistance value for each factor. We developed rankings from 50 (less resistance or high accessibility) to 1 (more resistance or less accessibility) for each of the layers and assigned the ranking value to the grid cell (Liu et al. 1999) (Table 1).

Assumptions behind cost assignments were that habitat resistance reflects suitability of the habitat, and it costs less for giant pandas to move across suitable habitats. This cost can be seen as the inverse of the degree to which the cell was functionally connected to the source. We considered habitats covered with bamboo and coniferous forest and habitats covered with bamboo and mixed coniferous and deciduous broadleaf forest at 2800–3100 m with gentle slopes suitable habitat for giant pandas. We considered grassland, urban, and residential areas or brushland less suitable and more costly sites for giant panda to move through. We based these assumptions on long-term fieldwork on life history (Schaller 1993), population dynamics (Hu 2001), social behavior (Wei et al. 2000; Hu 2001), and habitat requirements (Liu et al. 1999; Xu et al. 2006) of giant pandas in the Wolong, Wanglang, and Tangjiahe reserves and other reserves in the Minshan Mountains.

After all the layers were reclassified (Table 1), we used a weighting system to develop the cost grid (step 2). We developed the cost grid from the weighted linear

Table 1. Grid-cell values of the cost grids, including land use, bamboo, elevation, slope, aspect, and distance from residential area, main road, and small road for giant panda in the Minshan Mountains.

<table>
<thead>
<tr>
<th>Habitat characteristic</th>
<th>Grid-cell value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Land-cover type</td>
<td></td>
</tr>
<tr>
<td>coniferous forest, mixed coniferous and deciduous broadleaf forest</td>
<td>50</td>
</tr>
<tr>
<td>deciduous broadleaf forest</td>
<td>30</td>
</tr>
<tr>
<td>evergreen broadleaf forest</td>
<td>15</td>
</tr>
<tr>
<td>brush</td>
<td>5</td>
</tr>
<tr>
<td>grassland, croplands etc.</td>
<td>1</td>
</tr>
<tr>
<td>Forest cover (%)</td>
<td></td>
</tr>
<tr>
<td>30–70</td>
<td>50</td>
</tr>
<tr>
<td>&lt;30 or &gt;70</td>
<td>5</td>
</tr>
<tr>
<td>Elevation (m)</td>
<td></td>
</tr>
<tr>
<td>2800–3100</td>
<td>50</td>
</tr>
<tr>
<td>1500–2800, 3100–3500</td>
<td>25</td>
</tr>
<tr>
<td>3500–3800 or &lt;1500</td>
<td>10</td>
</tr>
<tr>
<td>&gt;3800</td>
<td>5</td>
</tr>
<tr>
<td>Slope (°)</td>
<td></td>
</tr>
<tr>
<td>0–20</td>
<td>50</td>
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<tr>
<td>20–35</td>
<td>20</td>
</tr>
<tr>
<td>35–45</td>
<td>13</td>
</tr>
<tr>
<td>&gt;45</td>
<td>7</td>
</tr>
<tr>
<td>Aspect</td>
<td></td>
</tr>
<tr>
<td>east, southeast, south</td>
<td>50</td>
</tr>
<tr>
<td>southwest, northeast</td>
<td>30</td>
</tr>
<tr>
<td>west, north</td>
<td>20</td>
</tr>
<tr>
<td>Distance from residential area (m)</td>
<td></td>
</tr>
<tr>
<td>&gt;1920</td>
<td>50</td>
</tr>
<tr>
<td>1410–1920</td>
<td>30</td>
</tr>
<tr>
<td>900–1410</td>
<td>15</td>
</tr>
<tr>
<td>0–900</td>
<td>5</td>
</tr>
<tr>
<td>Distance from main road (m)</td>
<td></td>
</tr>
<tr>
<td>&gt;720</td>
<td>50</td>
</tr>
<tr>
<td>210–720</td>
<td>30</td>
</tr>
<tr>
<td>60–210</td>
<td>15</td>
</tr>
<tr>
<td>&lt;60</td>
<td>5</td>
</tr>
<tr>
<td>Distance from small road (m)</td>
<td></td>
</tr>
<tr>
<td>&gt;30</td>
<td>50</td>
</tr>
<tr>
<td>&lt;30</td>
<td>15</td>
</tr>
</tbody>
</table>
combination of each layer on the basis of expert opinion and the literature on giant panda habitat requirements (e.g., Liu et al. 1999; Hu 2001; Loucks et al. 2003). We developed the weights of all the layers with pairwise comparisons of a decision-making process known as the analytical hierarchy process (AHP).

In developing relative weights of the 8 layers (land cover, bamboo cover, elevation, slope, aspect, and distance from residential areas, distance from main roads, and distance from small roads), we compared every possible pairing of layers and entered the ratings into a pairwise comparison matrix. Ratings were on a 9-point continuous scale from 9, extremely important, to 1/9, extremely unimportant (Saaty 1977). It was necessary to sum to 1 the weights in the procedure for evaluation by a weighted linear combination (Clevenger et al. 2002). Because the pairwise comparison matrix has multiple paths by which the relative importance of criteria can be assessed, we determined the degree of consistency with a consistency ratio (Saaty 1977). If the matrix had a consistency ratio more than 0.1, it was reevaluated on the basis of the group of variables, as recommended by Saaty (Clevenger et al. 2002).

**Sensitivity Analysis of the Core Habitat Areas**

To identify the most sensitive factors in the cost–distance surface, we conducted a sensitivity analysis by excluding components or varying weights of components. We assumed that the weight of topographic factors (elevation, slope, and aspect) was constant, but the weights of land cover and bamboo cover varied with human-factor (distance from residential areas and roads) weight. We developed 6 scenarios for the cost–distance model by varying the relative importance of land and bamboo cover with respect to the importance of distance from residential area and roads (Fig. 2).

Scenario 1 excluded the effects of human activities. Human activities in the remaining scenarios led to the depletion of the total core habitat area by between 30.4 and 44.5%. In scenarios 1 through 6, the extent of core habitat area decreased sharply, whereas in scenarios 5 and 6 it decreased more gently, changing by only 1% between the two scenarios (Fig. 2). We considered land cover and bamboo cover crucial to the resistance of the landscape. Land cover and bamboo cover had the highest weights. Human activities contribute significantly to the resistance of the landscape (Liu et al. 1999); therefore, we assigned human factors a relatively high weight. We considered topographic factors of elevation, slope, and aspect to be less important than land and bamboo cover and distance from residential areas and roads. Nevertheless, ignoring topographic factors would be simplistic and invalid because topographic factors are directly related to forest and bamboo cover and the movement of giant pandas.

**Uncertainty Analyses of the Land-Cover Classification of Core Habitat**

We used the Monte Carlo method to investigate the effect of uncertainty of land-cover classification on the cost–distance model. The land-cover classification accuracy was 84%. Nevertheless, the final land-cover classification accuracy was 91% after reclassification. We performed 20 Monte Carlo simulations to incorporate uncertainty in the cost–distance model produced by classification of the land cover. The Monte Carlo method computed cost–distance output statistics (means, variances) by repeating simulations with random generation of errors in land-cover classification (Katz 2002).

For every cell of the land-cover layer, a random number, \( r \), was generated between 0 and 1000. This value was subsequently compared with the accuracy ratio of the individual land-cover categories. For example, if \( r = 0 \) to 934, the coniferous forest or the mixed coniferous and deciduous broadleaf forest were classified as coniferous forest or mixed coniferous and deciduous broadleaf forest. If \( r = 934 \) to 941, the coniferous forest or the mixed coniferous and deciduous broadleaf forest were classified as coniferous forest or mixed coniferous and deciduous broadleaf forest. If \( r = 941 \) to 954, the coniferous forest or the mixed coniferous and deciduous broadleaf forest were considered brush. If \( r = 954 \) to 1000, the coniferous forest or the mixed coniferous and

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**Figure 2. Number of grid squares (30 × 30 m) in the core habitats in 6 giant panda conservation-planning scenarios: 1, excluding human factors from the evaluation of landscape resistance; 2, weight of distance from residential areas and roads one-fifth that of the land cover and bamboo cover; 3, weight of distance from residential areas and roads one-third of that of the land cover and bamboo cover; 4, weight of distance from residential areas and roads one-half of that of the type of land cover and bamboo cover; 5, weight of distance from residential areas and roads equal to land cover and bamboo cover; 6, weight of distance from residential areas and roads twice that of land cover and bamboo cover.**

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deciduous broadleaf forest were classified as grassland and cropland.

We repeated 20 random simulations of the reclassified land-cover types to generate 20 simulated land-cover layers. Then we combined the simulated land-cover layer with the layers of bamboo, elevation, slope, aspect, distances from residential areas, and distances from main roads and small roads to generate 20 simulated cost layers. We generated the simulated cost–distance layers by integrating the dispersal source layer with the simulated cost layers and then identifying the simulated core habitats.

The initial core habitats and the 20 simulated core habitats were in the same places because both the simulated core habitats and the initial core habitats were identified on the basis of cost–distance layers, in which the value of every cell represented the lowest possible cost from the cell to the same source layer. So the difference between the initial core habitats and the simulated core habitats was only the area difference. We conducted one-sample t tests for the area of the initial core habitats and the mean area of 20 simulated core habitats to determine whether there were significant differences between them.

One-sample t tests indicated there was no significant difference between the area of initial core habitats and the mean area of the 20 simulated core habitats at the level of 0.05 (Table 2). This suggests that although there was 9% uncertainty for the reclassified land cover, the core habitat areas and their spatial patterns were not substantially affected by the error. The Monte Carlo simulations indicated that cost–distance was not sensitive to the inaccuracy (9%) of land-cover classification, and the error in land-cover classification did not create significant uncertainty for the cost–distance surface (Table 2).

Creation of the Cost–Distance Grid

We created the cost–distance surface (step 3) to identify the core habitats, potential habitats, and linkages (step 4) by integrating the identified source layer (step 1) and cost-grid layers (step 2) in the cost–distance function of ArcGIS. The cost–distance surface indicated the accessibility of the landscapes to source populations. The least-cost value of each cell can be considered a relative measure of accessibility of the cell to source populations of pandas. The histograms of accessibility level of the landscape to source population revealed the quantitative threshold of core habitat needed according to the least-cost value (Fig. 3).

On the basis of the quantitative threshold, a relative boundary can be drawn to define the core habitat (Yu 1996; Adriaensen et al. 2003). On the basis of the core habitats and the established protected-areas layer, we identified potential habitats (core areas outside existing protected areas) and potential linkages between the core habitats. The potential linkages connected the isolated habitat blocks across the Minshan Mountains landscape, and we selected these to provide passages for the movement of panda individuals among current nature reserves and among the different core areas. Creation of the Minshan Mountains conservation landscape was achieved by combining the identified core habitats, potential habitats, and linkages.

**Results**

**Status for Conservation of Giant Panda**

Sensitivity analysis of habitat scores indicated that land cover and bamboo cover were crucial to the resistance of the landscape and were the most sensitive factors owing to the strong correlation with proximity to residential areas and roads. Uncertainty analysis revealed that a 16% land-classification error did not create significant uncertainty in the identification of core habitats within the upper and lower 95% confidence interval.

We identified 8 blocks of giant panda core habitats (CH1-CH8) with a total area of 6221.8 km². 18% of the total Minshan Mountains study area (Fig. 4). These core habitats encompassed 76.6% of the giant panda population in the Minshan Mountains. With an average density

<table>
<thead>
<tr>
<th>Core habitat</th>
<th>n</th>
<th>Mean area of simulated core habitat (km²)</th>
<th>SD</th>
<th>SE of the mean</th>
<th>t</th>
<th>df</th>
<th>Significance</th>
<th>95% CI of the difference</th>
</tr>
</thead>
<tbody>
<tr>
<td>CH1</td>
<td>20</td>
<td>407.83</td>
<td>3.48</td>
<td>0.78</td>
<td>1.19</td>
<td>19</td>
<td>0.249</td>
<td>−0.704 – 2.554</td>
</tr>
<tr>
<td>CH2</td>
<td>20</td>
<td>863.76</td>
<td>108.75</td>
<td>24.32</td>
<td>−0.87</td>
<td>19</td>
<td>0.393</td>
<td>−72.239 – 29.549</td>
</tr>
<tr>
<td>CH3</td>
<td>20</td>
<td>641.51</td>
<td>1.39</td>
<td>0.31</td>
<td>−0.31</td>
<td>19</td>
<td>0.764</td>
<td>−0.747 – 0.5567</td>
</tr>
<tr>
<td>CH4</td>
<td>20</td>
<td>1645.98</td>
<td>4.51</td>
<td>1.01</td>
<td>2.06</td>
<td>19</td>
<td>0.054</td>
<td>−0.0035 – 4.185</td>
</tr>
<tr>
<td>CH5</td>
<td>20</td>
<td>371.92</td>
<td>3.42</td>
<td>0.76</td>
<td>1.86</td>
<td>19</td>
<td>0.079</td>
<td>−0.179 – 3.019</td>
</tr>
<tr>
<td>CH6</td>
<td>20</td>
<td>698.05</td>
<td>1.48</td>
<td>0.33</td>
<td>−1.98</td>
<td>19</td>
<td>0.063</td>
<td>−1.349 – 0.039</td>
</tr>
<tr>
<td>CH7</td>
<td>20</td>
<td>1400.39</td>
<td>5.55</td>
<td>1.24</td>
<td>1.52</td>
<td>19</td>
<td>0.144</td>
<td>−0.708 – 4.488</td>
</tr>
<tr>
<td>CH8</td>
<td>20</td>
<td>177.77</td>
<td>3.69</td>
<td>0.82</td>
<td>1.42</td>
<td>19</td>
<td>0.172</td>
<td>−0.557 – 2.897</td>
</tr>
</tbody>
</table>

*The differences are significant at the level of 0.05 (2-tailed test).*
Figure 3. Accessibility (inverse of resistance) level of the landscape to source populations of giant pandas as indicated by the cost–distance surface. The least-cost value range of accessibility is divided into 500 intervals. The threshold is the quantitative threshold that specifies the boundary of core habitats at the least-cost value.

Figure 4. (a) Core habitats (CH) and potential linkages (PL) and (b) potentially protected habitats (PH) for giant panda conservation in the Minshan Mountains derived from the cost–distance model.

of 4.9 (1.7–6.8) pandas/100 km², the core habitats have an average of 51.2% (26.6–61.8%) bamboo cover and 80.3% (67–91%) forest cover. Analysis of the overlap between the identified core habitats and the nature reserves identified 8 blocks of potentially protected habitats (PHs) (Fig. 4), and 54.8% of the core habitats were protected by nature reserves.

Core Habitats and Potentially Protected Habitats

Core habitat CH1 represented 406.9 km², of which 49.4% was protected by the Baihe Nature Reserve. Core habitat CH2, covering 885.1 km², was covered by Wujiao, Caodi, and Majia towns in Jiuzhaigou County, Muyangchang and Baima towns in Pingwu County, and Yanggashan and Tielou towns in Wenxian County. Although 64.7% of CH2 had a high density of giant pandas (6.6/100 km²) and was protected by reserves, the 2-lane Jiu-loop-line (a main road) intersected the habitat between the Baishuijiang and Wanglang nature reserves and formed a barrier to panda migrations (Fig. 4). Core habitat CH3 was the key corridor for giant panda to move from Baishuijiang and Tangjiahe nature reserves to Longdishui, Xuebaoding, Baiyang, Baodinggou, Xiaozhaizi, and Piankou nature reserves. Nevertheless, only 19.7% of CH3 was protected by reserves. Core habitat CH4, lying to west of Tangjiahe Nature Reserve, was the largest area of core habitat (1643.9 km²) and held the highest density of giant pandas (7.8/100 km²) (Table 3 & Fig. 4).

Of all the core habitats, CH5 had the greatest proportion of protection by reserves (96.7%). Core habitat CH6 maintained the highest coverage of forest (91%) and bamboo (61.8%), although only 32.5% of the patch was within reserves. Core habitat CH7 was located on both sides of
the Qingpian River. Core habitat CH8 was predominantly situated on the eastern side of the main road (Jiu loopline) (Fig. 4). Covering an area of 176.6 km², 37% of CH8 was in Baodinggou and Qianfoshan nature reserves (Table 3). Analyzing the overlap between the identified core habitats and nature reserves, we identified 8 potentially protected habitats (PH1-8) (Table 3 & Fig. 4). These potential habitats were outside the established reserve network and amounted to approximately 2749.1 km². Thus, 45.2% of the identified core habitats need further protection measures implemented.

### Potential Linkages for Giant Panda Conservation

We identified 4 potential linkages (PL1-4) (Fig. 4). The potential linkage PL1 had 86.6% forest and 81.6% bamboo cover. It was in Muzuo and Mupi towns in Pingwu County and could act as a corridor between core habitats CH3 and CH4. The combination of potential protected habitat PH3 and PH4 and potential linkage PL1 could form a vital corridor between Xiaohegou, Baishuijiang, and Tangjiahe nature reserves. Uniting the reserves would create one of the largest giant panda populations in the region.

Potential linkage PL2, in Huya and Tucheng towns in Pingwu County, would connect core habitats CH3 and CH5. This linkage would connect Wanglang, Wujiao, Baishuijiang, Tangjiahe, and Xiaohegou nature reserves to Baiyang, Baodinggou, Xiaozaizai, Xuebaoding, Piankou, Longdishui and Qianfoshan nature reserves. If potential linkage PL3 was developed to connect core habitats CH5, CH6, and CH7, it could provide greater connectivity among the Xuebaoding, Baiyang, and Piankou nature reserves. Potential linkage PL4, in the Tumenhe Valley in Maoxian County, would create a pathway between core habitats CH7 and CH8 (Fig. 4).

### Discussion

The continuous forests that once extended across the Minshan Mountains have been extensively altered and fragmented by agricultural clearing and logging within and outside reserves (Hu 2001). If the current trend of habitat fragmentation continues, pandas in the Minshan Mountains will be separated into more-isolated populations. Such fragmentation would increase the risk of their extinction in the wild (Liu et al. 2001). Until now, 18 nature reserves have been established for giant panda conservation in the Minshan Mountains (Fig. 4). Nevertheless, 60.9% of the reserve network fails to conserve core habitats. It is necessary to enlarge the current reserves and to generate new reserves and corridors that will facilitate giant panda movement and colonization among the different habitat blocks.

Our results provide the most complete assessment to date of the regional-scale landscape for giant panda conservation in the Minshan Mountains. We identified core habitats representing the highest priority for protection, of which 2749.1 km² (almost one-third of the current reserve areas) need further protection. The recommended potential habitat and linkage zones, together with the current reserve network, will form a more comprehensive conservation network in the Minshan Mountains.

Increased human demand for land, material products, and development projects has fragmented the core habitat into 8 blocks. Increasing the connectivity among these blocks is likely to establish a more sustainable ecological network. On the basis of the population viability analysis for giant pandas in Tangjiahe Nature Reserve and in Qingling Mountains (Zhang et al. 2002; Loucks et al. 2003), the 5 smaller populations in core habitats CH1, CH3, CH5, CH6, and CH8 have at least a 10–25% chance of extinction within 100 years. Connecting these habitats will facilitate the exchange of individuals and genes and result in greater ability of the populations to cope with stochastic changes and prevent the occurrence of inbreeding depression (Loucks et al. 2003). For example, extending the area of Xiaozaizigou and Baodinggou nature reserves from 900.9 to 1398.5 km² would benefit giant panda survival. We recommend that potential habitats PH1, PH2, PH6, and PH7 become extensions of the Baihe, Wujiao, Piankou, and Baiyang nature reserves. Potential habitats PH3, PH4, and PH5 together with potential linkages PL1 and PL2 should be established as new reserves to connect...
habitats from the northeast to the southwest parts of the Minshan Mountains (Fig. 4). Potential habitat PH8 and potential linkage PL4 should be established as reserves.

To ensure long-term survival, it is necessary to restore degraded habitats for refuges between subpopulations of giant panda through strategic landscape planning (Hu 2001). There are 2 approaches to achieve this. One approach is to reforest with pioneer species to create a canopy cover. After the canopy closure has occurred, species unable to tolerate open planting but representing a range of life forms and successional stages can be planted or allowed to colonize the forests (Li 1997). Another approach is to reforest the areas with species representative of more mature successional stages and bypass the natural-succession sequence (Taylor & Qin 1993). This approach allows key species to be targeted but requires much effort be put into seed collection and germination of large numbers of seedlings.

The Chinese government has undertaken action to promote the conservation of potential habitat PH8 and potential linkage PL4 as the Tudiling Corridor. Conservation of these areas would enhance the effectiveness of Baodinggou, Xiaozaizi, and Qianfoshan nature reserves and allow greater exchange and reproduction among giant panda populations (Wang et al. 2006). In an attempt to reduce the road barrier effect, local governments are preparing to construct a tunnel on the Jiu-loop-line in Tudiling. To determine whether there is panda movement in the area, further measures, such as restoring forests and bamboo and establishing monitoring programs across different seasons, have been taken (Wang et al. 2006).

To design and manage a conservation landscape and to understand the ecological processes at a landscape scale, it is crucial to determine which factors influence giant panda movement patterns and how to combine all the factors to identify areas as reserves (Prendergast et al. 1999; Graham 2001; Shi et al. 2005). Until now, most research has focused on the biological factors as criteria for identifying areas rather than integrating biological and anthropogenic aspects (Liu et al. 1999; Xu et al. 2006). Our sensitivity analysis indicated that the total extent of estimated core habitats decreased between 30.4 and 44.5% after anthropogenic information was incorporated into the analyses. Our results suggest that it is necessary to incorporate anthropogenic factors into region-wide habitat research and management for the giant panda to avoid overestimation of suitable habitat.

Commercial logging is a major threat to forests and panda habitats (Liu et al. 2001). At the end of the 1990s, the Chinese government launched the Natural Forest Conservation Program (NFCP). The program included bans on logging in natural forests, which increased protection of the panda under the framework of protection for existing forests (Loucks et al. 2001). The NFCP is complemented by the Grain-to-Green policy, which aims to help and encourage rural populations to restore hillside agricultural lands, transforming them into forest or grasslands (Loucks et al. 2001). This policy should provide stricter protection of all the remaining forests and should increase forest coverage throughout the panda’s range. Commercial logging ceased in 1998, which provided a historic opportunity to move panda conservation from the level of individual reserves to the landscape level across the Minshan Mountains (Loucks et al. 2001).

Nevertheless, negative impacts have begun to emerge in the Minshan Mountains in recent years, for example extensive road construction, fuel wood collection, and tourism development. All are having major effects on forests and panda habitats (State Forestry Administration 2006). They potentially pose a great threat to the giant panda landscape. It is likely that in a few decades the reserves will face ecological degradation similar to Wolong Nature Reserve (Liu et al. 2001). The causal relationships between human activities and panda habitat suitability and conservation need to be addressed comprehensively (Liu et al. 1999). Consideration of more factors will enhance the accuracy of analyses and ultimately lead to more effective conservation of giant panda.

Giant panda habitats are a mosaic of land covers, and the effectiveness of reserves for giant panda conservation depends on different habitats complementing one another in the landscape mosaic. Refocusing conservation efforts from site-based planning to landscape planning would complement the existing reserve network. It is at the landscape level that complementary habitats would be efficiently protected and restored for giant panda conservation. The landscape approach identifies which parts of the landscape should be conserved or reforested first, what type of reforestation should be carried out in particular locations, and what proportion of the landscape should be reforested.

Furthermore, a landscape-based approach would take into account interactions of physical, chemical, biological, social, and economic aspects of the Minshan Mountains landscape, identify the relationships, predict the effect of any proposed action, and evaluate the consequences of proposed actions in the process of formulating and implementing the conservation plan. Cooperation among research institutes, local governments, and authorities is needed to answer the complex issues surrounding giant panda conservation in the Minshan Mountains. The design and implementation of reserves for giant pandas may have important implications for giant panda conservation not only in the Minshan Mountains but also in other areas of China. It may serve as a future framework for more comprehensive identification of habitats worthy of conservation and help develop efficient landscape-scale protection methods for other endangered animals worldwide.
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