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Spatial and temporal patterns of fuelwood collection in Wolong Nature Reserve: Implications for panda conservation

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ABSTRACT

Approximately 3 billion people, half of the World's population, are still using fuelwood in their daily lives. Fuelwood collection has been recognized as an important factor in habitat fragmentation and degradation and biodiversity loss, especially in developing countries. Understanding spatial and temporal patterns of fuelwood collection is fundamental to understanding human–environment interactions and designing effective conservation policies. Using Wolong Nature Reserve for giant pandas (*Ailuropoda melanoleuca*) in China as an example, we surveyed 200 rural households for the locations of their fuelwood collection sites in the past three decades (1970s, 1980s, and 1990s) and other ecological, economic, social, and demographic data. We found that fuelwood collection sites were becoming higher in elevation, more remote, and closer to highly suitable panda habitat from the 1970s to the 1990s. Consequently, fuelwood collectors were traveling longer distances to physically challenging areas, in our case, to areas of high-quality panda habitat. These spatial and temporal patterns of fuelwood collection suggest that future conservation policies for giant pandas, and other species worldwide, should also consider the needs of local communities.

1. Introduction

Approximately 3 billion people, half of the World's population, are still using fuelwood in their daily lives (Population Action International, 1999). The collection of fuelwood has become important in ecological degradation worldwide, especially in developing countries, where in many rural areas fuelwood is the sole or primary energy source for cooking and heating (Chomitz and Griffiths, 2001; An et al., 2002). Fuelwood collection through cutting down trees can lead to fragmentation and degradation of wildlife habitat (Liu et al., 2001), reduction of wildlife populations (Aigner et al., 1998; Hall and Farrell, 2001), and loss of biodiversity (Rosenstock, 1998; Sagar and Singh, 2004).

Even many protected areas (e.g., nature reserves) in countries such as China are not exempt from impacts of human activities such as fuelwood collection (Liu et al., 2003b). In order to conserve its diverse natural resources for sustainable development, China had established 2531 nature reserves by the end of 2007, covering more than 15% of its territory (China.com.cn, 2007). However, many of these reserves are located in remote areas with poor economies and high human population pressures, and various types of resource extraction are inevitable. Wolong Nature Reserve, one of the largest reserves for protecting giant pandas (*Ailuropoda melanoleuca*), is a good example. Fuelwood collection is common inside the reserve and fluctuated around 7000–9400 m^3/year until recently (Liu et al., 1999b). Bearer et al. (2008) showed that panda activities in forests are reduced for several decades after timber harvesting and fuelwood collection in this reserve. An et al. (2005) found that fuelwood collection could lead up to a 1.23 km^2/year loss of habitat, depending on different scenarios of socioeconomic factors. Considering the distribution of bamboo and its periodic flowering, Linderman et al. (2005) demonstrated that over the next 30 years fuelwood collection would result in the loss of up to 30% of the habitat in the event of bamboo die-offs. If spatial arrangement and configuration of habitat had been incorporated into such an analysis, there would have been much higher impacts, as larger areas have been fragmented from a landscape ecology perspective.

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The knowledge of spatial and temporal distribution of fuelwood collection at the landscape level is central to understanding the impacts of fuelwood collection on forests (Franklin et al., 2000; Pinzon et al., 2003) and panda habitat, including understory bamboo in the case of the giant panda (Reid et al., 1991; Taylor and Qin, 1993). This understanding can aid in evaluating habitat suitability where human activities occur and providing insights to make informed conservation decisions (e.g., identifying priority areas for monitoring and altering human activities). Assessing the effectiveness of previously implemented policies related to fuelwood collection (Wolong Nature Reserve, 1998, 2000b) could also help improve several on-going conservation programs in China (Loucks et al., 2001; Zhu and Feng, 2002; Liu et al., 2008), including the Natural Forest Conservation Program (NFCP) and the Grain-to-Green Program at Wolong. However, little has been done on gaining such knowledge.

Therefore, this paper aims to: (1) characterize spatial and temporal distribution patterns of fuelwood collection in Wolong Nature Reserve; (2) analyze the spatial and temporal trends of the impacts of fuelwood collection on panda habitat; (3) discuss some policy implications for panda conservation; (4) assess the general relevance of the case study for fuelwood collection management in protected areas.

2. Data and methods

2.1. Study area

Wolong Nature Reserve was designated in 1975 to help conserve the giant panda (MacKinnon and DeWulf, 1994). It is located in Wenchuan County, Sichuan Province, southwestern China (latitude: 30°45′–31°25′N, longitude 103°52′–103°24′E) (Fig. 1). The Wolong Administration Bureau is responsible for both panda conservation and the well-being of local residents (Lü et al., 2003). It reports directly to the Department of Forestry in Sichuan Province and China's State Forestry Administration in Beijing (Wolong Nature Reserve, 2005).

Approximately 110 giant pandas, representing about 10% of the total wild population, inhabit the reserve (China's Ministry of Forestry and WWF, 1989; Zhang et al., 1997). The vegetation of the reserve includes evergreen broadleaf, deciduous, and sub-alpine coniferous forests, and alpine meadows within an elevation range of 1250–6525 m above sea level (Schaller et al., 1985). Forests covered 36.3% of the reserve in 2001 (Vina et al., 2007), less than 1% of the land is for agricultural use, and the remainder is shrubs, meadows, permanent snow, exposed rocks, roads, buildings, and water (Wolong Nature Reserve, 1998, 2005). Pandas depend on the forests for cover and shelter and use the understory bamboo (mainly *Bashania fangiana* and *Fargesia robusta*) as staple food (Schaller et al., 1985). They prefer slopes less than 30°, elevations between 1500 and 3250 m, and interior, old-growth forests (Schaller et al., 1985; Bearer et al., 2008). Panda habitat is determined by biotic features (e.g., forests), abiotic features (elevations and slopes), and human activities (e.g., roads). The widely used panda habitat classification scheme suggested by Liu et al. (1999b) includes four categories: highly suitable, moderately suitable, marginally suitable, and unsuitable. Highly and moderately suitable habitats have conifer forests and the two main bamboo species, whereas marginal habitats have evergreen broadleaf forests and other bamboo species (*Bashania fangiana* and *Fargesia robusta*). Unsuitable habitat is defined as having no forest cover and no bamboo, an elevation >3750 m, and a slope > 45° (see Liu et al., 1999b, for details on habitat classification). Due to the lack of data on bamboo distribution for the entire reserve over time, forest cover, elevation, and slope are often used for panda habitat suitability analysis (Liu et al., 2001; Vina et al., 2007, 2008). One of such efforts (Vina et al., 2007) shows that approximately 4.4% of the reserve was marginally suitable, 25.6% was moderately suitable, and 5.8% was highly suitable, and the rest was unsuitable for pandas in 2001.

Timber harvesting, poaching, and agriculture were the main threats to panda habitat and conservation. Recently, fuelwood collection by local residents has emerged as an important threat. From 1975 to 1998, the human population and the number of households in the reserve increased by 69 and 124%, respectively, while fuelwood consumption in the reserve doubled (Liu et al., 1999a,b). Traditionally, fuelwood is used for cooking food for humans and fodder for livestock, and for heating houses in winter (An et al., 2002). In 2000, there were more than 4400 local rural residents in 970 households in two townships (Wolong and Gengda, see Fig. 1 for their locations). Most human settlements were in the bottomland or on the relatively flat slopes of several valleys in the reserve. In rural China, there are three administrative units: groups, villages, and townships. Wolong Township has 9 groups in three villages, and in Gengda Township has 17 groups in three villages (Wolong Nature Reserve, 2000a). The annual amount of fuelwood consumed by each household ranged from 8 to 30 m^3, depending on household size, age structure, cropland area, and other socioeconomic conditions (An et al., 2001). Moreover, burgeoning tourism

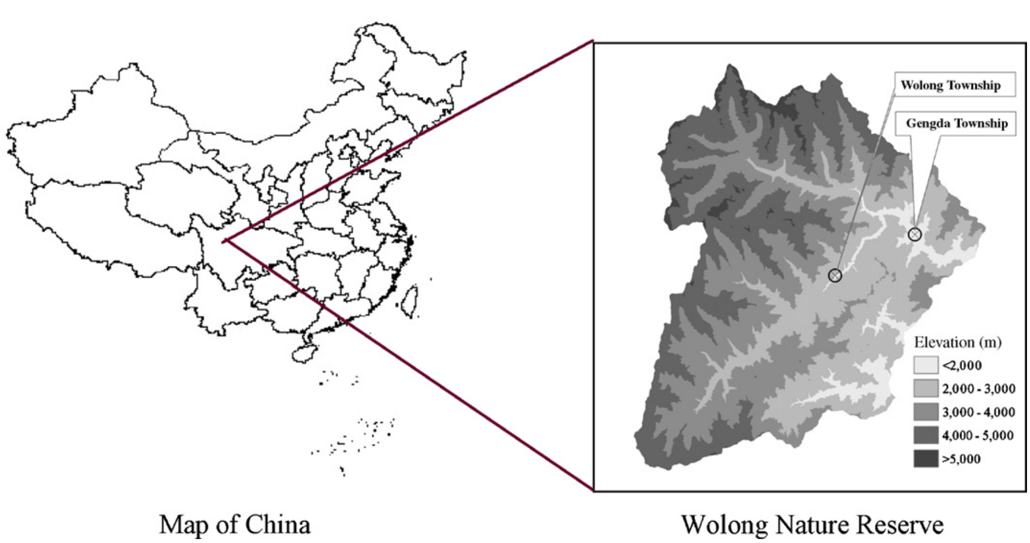

Fig. 1. The location and elevations of Wolong Nature Reserve in China. The locations of Wolong and Gengda townships are also indicated on the map.

development now may be contributing to greater fuelwood collection by local residents, who can increase their cash income by selling local products, such as bacon, which requires fuelwood to cook pig fodder and smoke-dry the pork (He et al., 2008).

The household is the basic unit of fuelwood consumption (Liu et al., 2003a), but fuelwood collection is often accomplished in winter by groups of 10–20 adult males each from several households to increase efficiency and minimize risks in the topographically challenging high mountains (Liu et al., 1999b). People usually walk or drive to the foothills close to the collection sites and climb up to those sites. They cut down trees with axes, then carry and slide logs to lower areas close to roads. Finally, logs are carried and loaded into vehicles, and transported home. Later, fuelwood logs are usually split into small pieces and piled near houses.

Local residents usually cut down large trees, partially removing forest canopy (An et al., 2001). Oak (*Cyclobalanopsis Oerst.*), maple (*Acer* L.), birch (*Betula* L.), spruce (*Picea Dietr.*), hemlock (*Tsuga Carr.*), larch (*Larix Mill.*), and pine (*Pinus* L.) are among the preferred tree species for fuelwood. Fuelwood collection changes the species composition in the overstory, thus stimulates denser understory bamboo stands with lower moisture content, and, consequently, discourages pandas from using the affected areas (Reid et al., 1991). Although selective cuts of a few trees for fuelwood at one time by one household may affect only a small area of habitat, collection of fuelwood by multiple households over a long time (e.g., decades) can eventually lead to the loss of a large amount of habitat (Bearer et al., 2008). Fuelwood collection started in the forests close to human settlements along the main road through the reserve but has expanded to other areas and caused a significant reduction in the quality and quantity of panda habitat (Liu et al., 1999a).

2.2. Data collection

We used historical information on fuelwood collection over the past three decades (1970s, 1980s, and 1990s) as well as other ecological, economic, social, and demographic data to examine spatial and temporal patterns of fuelwood collection. One type of data is at the household level, such as household location (An et al., 2005), population (Wolong Nature Reserve, 2000a), fuelwood collection sites of the last three decades, attitudes toward fuelwood policies, and household economy of 2001. Another type of data is at the reserve level, which consists of digital elevation model (DEM), interpolated from digitized 100 m contours with a vertical accuracy of <50 m root-mean-square error (RMSE)) (An et al., 2005), habitat suitability index (HSI) maps, including four categories of habitat – highly suitable, moderately suitable, marginally suitable, and unsuitable – of 1974 and 1997 (Liu et al., 2001), and road network and construction records.

2.2.1. Household survey

Intensive face-to-face household interviews were conducted in the summer of 2002. Two hundred households (about one-fifth of the total) were sampled based on a random sampling method stratified by villages and groups using the population census data of 2000. Of the 200 households interviewed, 12 established in the 1980s did not collect fuelwood in the 1970s, 8 did not collect in the 1990s, and 1 had not collected since the 1980s. Because of this, the degrees of freedom for tests of different time combinations may be different (e.g., 385 for the comparison of the 1970s versus the 1980s, and 388 for the comparison of the 1980s versus the 1990s). We recorded the most frequently visited fuelwood site for a household in each of the past three decades on a Wolong topographic map with a scale of 1:50,000. The site locations for all the surveyed households were then digitized and geometrically corrected to form a geographic information system (GIS) layer in ArcGIS.

Table 1
Eight activities not allowed in fuelwood collection.

Number	Description
1	Do not cut newly planted seedlings for fuelwood
2	Do not cut young trees for fuelwood
3	Do not cut trees in the previously harvested areas for fuelwood
4	Do not cut trees in the erosion-prone areas for fuelwood
5	Do not cut trees of rare and precious species for fuelwood
6	Do not cut riparian trees for fuelwood
7	Do not cut trees in research zones for fuelwood
8	Do not light a fire in forests

Source: Translated from government documents (in Chinese) (Wolong Nature Reserve, 1998).

We also simultaneously investigated the attitudes of the household heads, who usually know more about fuelwood collection activities than other household members, toward two fuelwood-related regulations to examine whether these policies affected the spatial and temporal distribution of fuelwood collection. The first regulation designated the allowable amount, time, and location of fuelwood collection. The second regulation forbad local residents to do eight specific activities during collection (see Table 1). The regulations were released in 1984 (Wolong Nature Reserve, 2000b), about halfway through our study period. We also asked household heads whether they: (1) knew about the regulations, (2) if yes, how long they had known about them, and (3) what effects the two regulations had on their fuelwood collection behaviors (e.g., amount collected, time spent, and species of tree collected).

Besides the attitudes toward these two regulations, we also surveyed the household economic status of 2001 to see if relatively richer households were different from the poorer ones in fuelwood collection activities of the 1990s (economic data of households in the 1970s and 1980s were not available). We indirectly gathered data on economic status during interviews by determining the sum of annual household expenditures for all items, such as food, education, energy consumption, farming, and medical services. When collecting this retrospective information, we incorporated a widely used method in social sciences, the life history calendar, to improve the respondents' recall accuracy (Caspi et al., 1996; Axinn et al., 1999). We often asked the interviewees some indirect questions on life events more readily remembered, such as births, marriages, deaths, household separations, to help them recall less salient facts related to our research interests, for example, the location of fuelwood collection and the year they knew a regulation was released.

We recorded global positioning system (GPS) measurements and current status of fuelwood sites in the forest stands (number of stumps left, stump diameters, and tree species) to verify whether sites recorded from interviews were actually used before. We visited and surveyed fuelwood sites of 15 randomly selected households we had interviewed, each having an area of 30 m × 30 m to match the habitat map. With the knowledge of local guides (often participants in fuelwood collection), we located those sites around a heavily collected spot. Old stumps (from the 1970s) were identified by new seedlings developed from them and seedlings also helped us to recognize tree species. We found that on average there were 56.5 stumps left with a mean diameter of 16.2 cm in each site. The average number of tree species in these sites was 9.7. In total, we identified 63 species of trees collected, of which seven were conifers and 56 were broadleaves. These species were also observed in fuelwood piles during our household interviews. Therefore, we are confident that the sites were used for fuelwood collection.

2.2.2. Road network

Records of transportation system development in the reserve were kept in the Department of Transportation in Wolong (Wolong Nature Reserve, 2005). Road quality, construction/improvement time, and construction goals were well documented and road networks in different decades were mapped. Household surveys and all other non-spatial attribute data were managed in a Microsoft Access 2000 database. Spatial information (e.g., fuelwood sites, road networks, and the DEM) was warehoused in an ArcGIS 8.2 database for further analyses.

2.3. Data analysis

2.3.1. Fuelwood collection sites

To characterize the topography of fuelwood collection sites, average elevation, aspect, and slope in 30 m × 30 m area (0.09 ha) around the sites were derived from the DEM. We chose this size as a conservative estimation of annual collection area for a household consuming a minimum amount of fuelwood (8 m^3) (An et al., 2001) and collecting a relatively large percent (around 60%, field observations, 2002) of trees in a mixed evergreen and coniferous forest stand (most frequently visited, with an average stock of approximately 120 m^3/ha) (Bearer, 2005). This selection also matches the resolution (30 m × 30 m) of available data (DEM and HSI map).

We used the point density function from Spatial Analyst Tools in ArcGIS 8.2 to generate density maps of fuelwood collection sites. The densities were arbitrarily categorized into three groups: 0–5, 5–10, and 10+ points per km^2. Then we identified newly emerging heavily used areas, usually centered by points with densities of 10+ points per km^2 as fuelwood collection hotspots by comparing the maps in different decades.

2.3.2. Distances between fuelwood collection sites and household locations

Because the household is a basic unit of many human activities in the reserve (Liu et al., 2003a), their characteristics (e.g., location, economic status, labor) could be important in fuelwood site selection. To understand the temporal and spatial relationships between fuelwood sites and household locations, three distances were measured using ArcGIS. ED is defined as the Euclidean distance between a household and its fuelwood collection site. TD stands for the length of the shortest road traveled by a household to the corresponding fuelwood site in road networks. ND indicates the Euclidean distance from a fuelwood collection site to the location of the nearest household, which may not be the focal household. ED and TD were designed to describe the relationships between individual households and their fuelwood collection sites at the household level. ND reflects collective interactions between households and fuelwood collection locations at the reserve landscape level.

We used information on household expenditures of 2001 as a proxy of economic status of the 1990s. We categorized households into three groups by annual expenditures of 2001: low (≤5000 RMB, 8.25 RMB = US$ 1 in 2001), medium (>5000 and ≤10,000 RMB), and high (>10,000 RMB). Annual per capita expenditures of 2001 were also classified into three categories: low (≤1400 RMB), medium (>1400 and ≤2800 RMB), and high (>2800 RMB). The number of laborers in a household in 2000, derived from the 2000 population census data, was used to group the households to test whether it affected households in terms of fuelwood collection in the 1990s (data on the laborers in the 1970s and 1980s are not available). We treated household members from 18 to 60 years old as laborers, and distinguished households with two or fewer laborers from those with three or more laborers.

2.3.3. Relationships between fuelwood collection and panda habitat

To examine the spatial and temporal trends of the impacts of fuelwood collection on panda habitat, we measured two variables. First, we calculated the distance (HD) from a fuelwood site to the nearest pixel of each type of habitat on the HSI map of 1974. Second, we derived the percentages of households collecting fuelwood in a certain type of habitat in a given decade by overlaying fuelwood sites on the HSI map. These variables should indicate temporal trends of fuelwood collection distribution in relation to panda habitat at the reserve landscape level rather than ED or TD at the household level.

We used *t*-tests and analysis of variance (ANOVA) to test for differences of elevation, slope, ED, TD, and ND of the three decades. As an exception, the Mardia–Watson–Wheeler test was applied to test for the differences of aspects of fuelwood sites in the three different decades because aspects are circular measurements (Batschelet, 1981). In addition, we calculated and reported descriptive statistics on attitudes of local residents toward fuelwood policies.

3. Results

3.1. Fuelwood collection sites

Our results on the temporal changes of three topographic characteristics (elevation, slope, and aspect) of fuelwood sites suggest that local residents had to climb to physically challenging areas with an average elevation > 2000 m and mean slope > 30° (Fig. 2). The one-way ANOVA test rejects the null hypothesis that the means of the three groups of elevations were equal ($F = 47.78$, $p < 0.0001$). The *t*-tests (1970s versus 1980s [$t = 6.57$, $p < 0.0001$] and 1980s versus 1990s [$t = 3.47$, $p = 0.0003$]) show that site elevation significantly increased over time (on average, 100–150 m per decade) (Fig. 2a). The slopes of the three decades were not significantly different ($F = 2.73$, $p = 0.066$) while they increased only from the 1970s to the 1980s at the significance level of 0.05 ($t = 2.33$, $p = 0.016$) (Fig. 2b). The Mardia–Watson–Wheeler test shows that there were no significant differences among the aspects of fuelwood sites during the three decades studied ($W = 5.92$, $p = 0.21$) (Fig. 2c).

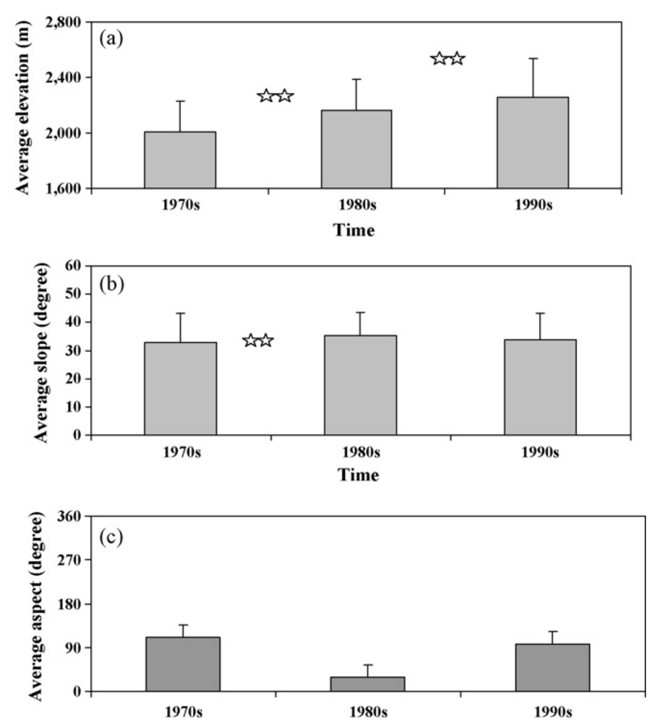

Fig. 2. Temporal dynamics of fuelwood collection sites in elevation (a), slope (b) and aspect (c) with 1 standard deviation. Two stars indicate that the value to their left was significantly smaller than the one to their right at the significance level of 0.05.

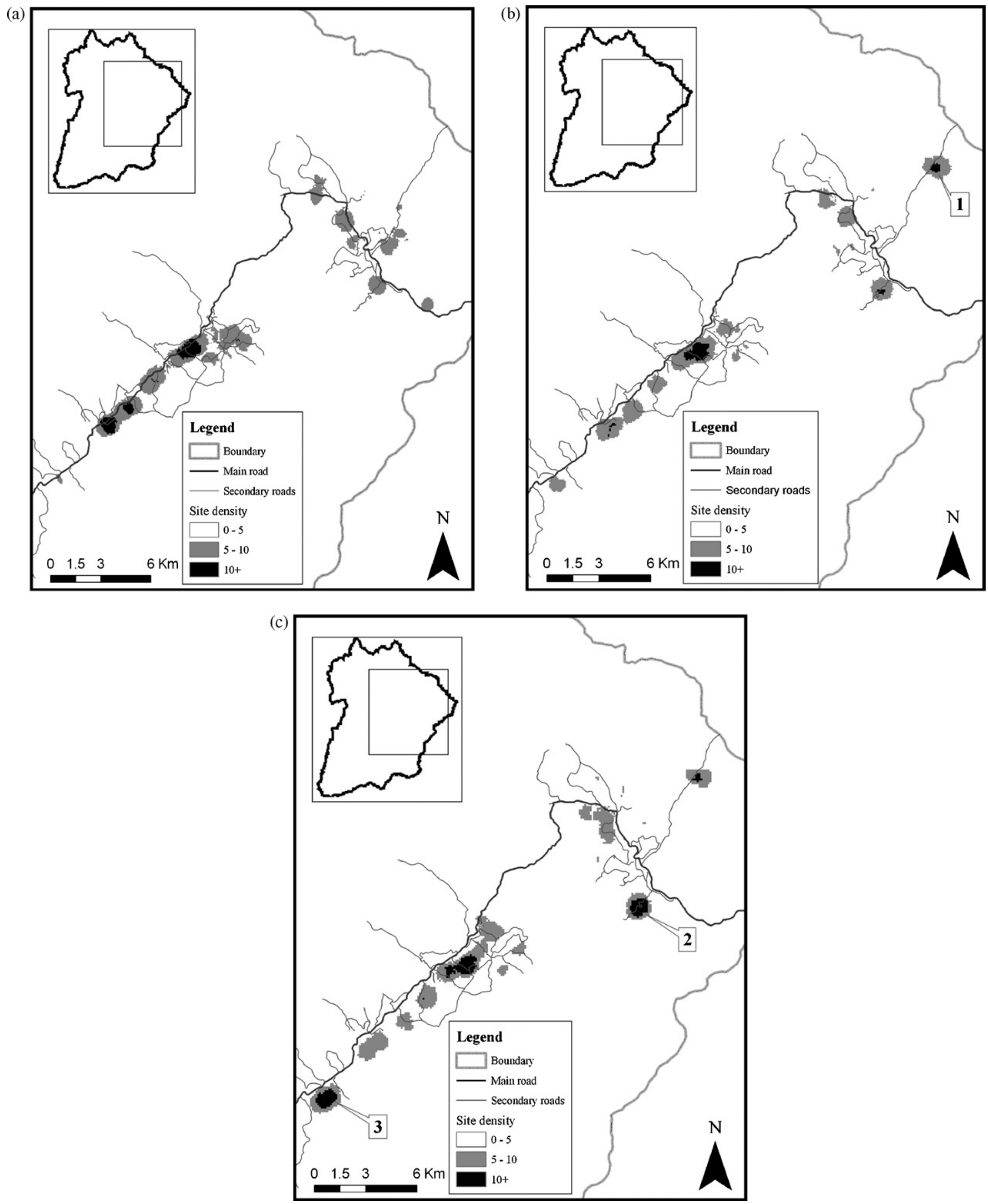

Fig. 3. Fuelwood collection site density maps of the 1970s (a), 1980s (b), and 1990s (c), and emerging fuelwood hotspots in the 1980s (b), and 1990s (c). The density unit is points per square kilometer.

Density maps of fuelwood sites used during the 1970s, 1980s, and 1990s clearly indicate clustering of fuelwood collection across the reserve landscape (Fig. 3). Several fuelwood hotspots had emerged over time in the reserve (b and c in Fig. 3). We identified Area 1 as a hotspot in the 1980s by comparing the maps in the 1970s and 1980s (Fig. 3b). Similarly, two hotspots, Area 2 and Area 3, attracted many households for fuelwood in the 1990s (Fig. 3c). Furthermore, linking road construction information with these hotspots shows that road development might have contributed to their emergence. Roads near Area 1 were constructed from a trail to improve local access to markets with support from the United Nations' World Food Programme for panda conservation in the early-1980s (Wolong Nature Reserve, 2005), but extended so far into the forests that they clearly facilitated fuelwood collection in Area 1. Roads near Area 2 were originally developed for mining in 1987 and assisted many households in fuelwood collection in the

Table 2
Three types of distances between fuelwood sites of the 1990s and locations of households grouped by the total household expenditure of 2001 (A), household per capita expenditure of 2001 (B), and number of laborers in each household in 2000 (C).

Distance Types	A (total household expenditure, in RMB[a])			B (household per capita expenditure)			C (number of laborers)	
	≤5000	5000–10,000	>10,000	≤1400	1400–2800	>2800	≤2	≥3
ED (Euclidean distances between fuelwood sites and households, m)	2096 (2961) $F = 0.33$, $p = 0.57$	1416 (1179)	1771 (1815)	1825 (2639) $F = 0.14$, $p = 0.71$	1505 (1207)	2013 (2247)	1746 (2199) $F = 0.11$, $p = 0.74$	1645 (1375)
TD (travel distances between fuelwood sites and households, m)	3721 (4648) $F = 0.42$, $p = 0.52$	2784 (1699)	3218 (2649)	3277 (4177) $F = 0.25$, $p = 0.62$	2893 (1756)	3627 (2937)	3176 (3211) $F = 0.00$, $p = 0.97$	3158 (2173)
ND (Euclidean distances between fuelwood sites and their nearest households, m)	849 (495) $F = 0.79$, $p = 0.37$	833 (530)	946 (849)	846 (523) $F = 1.10$, $p = 0.30$	829 (471)	1018 (1071)	855 (727) $F = 0.63$, $p = 0.43$	937 (539)

Note: For each type of distance measurement, in the first row, the number outside the parentheses is the mean of the distances in the group and the number inside is the standard deviation; the second row shows the results of one-way ANOVA tests of the three groups by the factor A, B, or C. The group factors A, B, and C are also shown in the first row of the table, and the group definitions for each factor are given as divided columns below the factors.

[a] 1 RMB = approx. 15 cents U.S. currency.

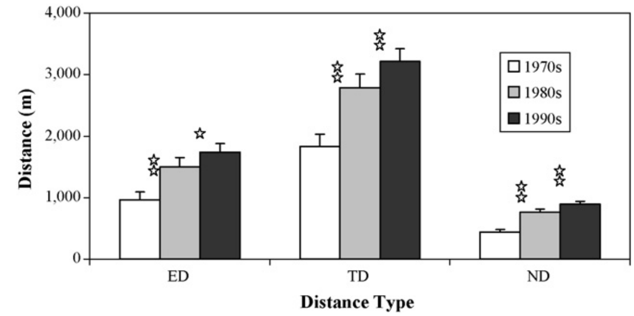

Fig. 4. Temporal dynamics of distances (ED defined as the Euclidean distance between a household and its fuelwood collection site, TD defined as the length of the shortest road traveled by a household to the corresponding fuelwood site in road networks, and ND defined as the Euclidean distance from a fuelwood collection site to the location of the nearest household) of fuelwood collection sites from household locations with 1 standard error of mean. Two stars indicate that the measurement to their left was significantly smaller than the one to their right at the significance level of 0.05, while one star indicates that at the significance level of 0.10.

1990s (Wolong Nature Reserve, 2005). The quality of the main road across the reserve, from the east side to the lower southwest corner and constructed for commercial timber logging in the 1960s before the establishment of the reserve, was greatly improved in the early-1990s (it was paved, which was rare in western China during that time). These roads fragmented the reserve, and facilitated household fuelwood collection considerably. People living far away from the road could easily travel to Area 3, which had high forest stock and was rarely used as a fuelwood site before the mid-1990s.

3.2. Distances between fuelwood collection and household locations

Besides climbing higher into the mountains, as mentioned above, local residents also traveled greater distances (TD) to fuelwood sites, because sites became increasingly farther away from households (ED) over time (Fig. 4). On average, local households had to reach out an extra 20–50 m farther (ED) or travel 50–80 m more (TD) yearly to find good fuelwood sites. Although the distance difference seems small, it often occurred in steeper and higher mountainous areas, which meant greater hardship and more time required for fuelwood collection. Statistical evidence concerning the distance between a fuelwood site and its nearest household (ND) shows that, at the reserve level, fuelwood collection was expanding gradually farther away from residential areas (Fig. 4).

From further analyses of spatial characteristics ED, TD, and ND, grouped by economic status of 2001 (annual household and per capita expenditures) and number of laborers in 2000, we found no significant differences between rich and poor households, or households with more or fewer laborers in terms of fuelwood site selection in the 1990s (Table 2). Presumably, this is because

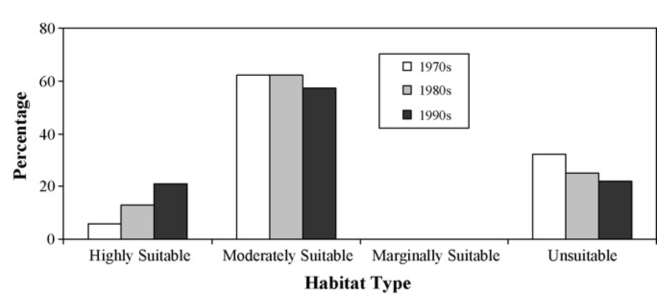

Fig. 5. Percentages of fuelwood sites of three decades (1970s, 1980s, and 1990s) falling in four types of habitat (highly suitable, moderately suitable, marginally suitable, and unsuitable) in 1974.

fuelwood collection was accomplished by groups of households rather than by individual households. Another reason might be that unavailability of fuelwood was the same for all households, whether they were poor or rich, with more or fewer laborers.

3.3. Relationships between fuelwood collection and panda habitat

The percentage of fuelwood sites in highly suitable panda habitat of 1974 increased from 6 to 21% during the three decades studied (Fig. 5). Most of fuelwood collection (varying between 68 and 78%) occurred in areas of highly suitable and moderately suitable panda habitat and much smaller percentages (ranging from 22 to 32%) in areas of unsuitable habitat (Fig. 5). Surprisingly, no fuelwood collection appeared in any areas of marginally suitable habitat. The reason might be because marginally suitable habitat is characterized by steep slopes and high elevations (Liu et al., 1999b). From the perspective of the distance between a fuelwood site and its nearest habitat type, we found that local residents collectively went closer to highly suitable habitat (144, 132, and 105 m for the 1970s, 1980s, and 1990s, respectively) and farther from unsuitable habitat (90, 127, and 145 m for the 1970s, 1980s, and 1990s, respectively) to find good sites for fuelwood over time.

To further demonstrate the spatial trends of fuelwood collection impacts on panda habitat, we calculated the distance between a household and its nearest habitat pixel of a given type. The locations of households were relatively stable. Our results show that for highly suitable habitat, the average distance between households and the 1974 habitat (153.43 ± 131.59 m) was significantly shorter than the one between households and the 1997 habitat (330.86 ± 264.58) ($t = 12.80$, $p < 0.001$). Similarly, for moderately suitable habitat, the mean distance corresponding to the 1974 habitat (113.14 ± 99.11) was significantly shorter than the one corresponding to the 1997 habitat (236.35 ± 169.36) ($t = 13.86$, $p < 0.001$). Because the data for panda habitat in the 1980s were not available, we only analyzed the habitat change of the fuelwood sites from the 1970s to the 1990s by overlaying the fuelwood sites on the habitat maps in both 1974 and 1997. This analysis shows that more than 50% of fuelwood sites with highly suitable habitat in the 1970s had become unsuitable and the rest had no change. One-quarter of sites that were moderately suitable in the 1970s had become unsuitable and the rest were unchanged. In total, the quality of 18.8% of fuelwood sites in the 1970s had been reduced by the 1990s. To summarize, the continual collection of fuelwood in the 1970s, 1980s, and 1990s had degraded habitat quality and affected the spatial distribution of panda habitat; primarily, suitable habitat had been pushed farther away from households.

3.4. Knowledge about and attitudes toward fuelwood-related policies

Dissemination of fuelwood-related policies to local residents within the reserve was effective. Among the 200 household heads interviewed, 134 (67%) said they had known about at least one regulation. Among these 134 respondents, 84 had known about the regulations for less than 10 years, while the rest had known about them longer than 10 years. However, as to the effects of the policies on fuelwood collection, only 42% of those interviewed (84 of 200) or 63% of those who knew the regulations (84 of 134) said that their fuelwood collection activities had been affected. Even among those who followed the regulations, only approximately half of them (56%) believed that less fuelwood was harvested because of the existence of regulations, while for others regulations had no impact on the amount of fuelwood collected. Regarding the effect of regulations on fuelwood collection time, 43% of household heads who followed the regulations thought that they spent less time while 31% spent more time and 26% saw no change. The major changes brought about by the policies were that the local residents went to more remote sites (77% of households who followed the regulations) and collected more small trees (93% of households who followed regulations). Thus, regulatory policies and the unavailability of the resource in places nearby might have contributed to the spatial trend of fuelwood collection activities moving farther away from households over time in the reserve.

4. Discussion and implications

Our results reveal that local residents in Wolong Nature Reserve had to select gradually more distant sites at increasingly higher elevations to collect fuelwood during the last three decades of the 20th century, and most of tree fellings occurred in areas of highly suitable and moderately suitable panda habitat rather than areas of marginally suitable and unsuitable habitat. Fuelwood collection occurred frequently in areas close to households, while some new hotspots had emerged due to local road expansion. Many households were aware of the fuelwood collection regulations and understood their importance to panda conservation, but many of them did not comply strictly with them. As good forests receded from households at the reserve level, local residents experienced a gradually increasing hardship in their fuelwood collection, which exacerbated an already-existing conflict between people and pandas. The implications of our results for policy are discussed below.

4.1. Road construction

Our study suggests that road systems facilitated fuelwood collection in suitable panda habitat. Therefore, road extension should be carefully planned, especially in conservation-oriented areas, such as Wolong Nature Reserve. Investment should be focused on improving the roads that may facilitate the access of local residents to markets to sell their agricultural products (e.g., cash vegetables like cabbage). Roads should not be expanded into areas without residents or into areas from which residents have been encouraged to move. Also, roads originally designed for mining or other non-agricultural activities in the past should have been closed to prevent illegal use for resource extraction.

4.2. Energy-related policies

Over time, local residents have experienced increasing difficulties in collecting fuelwood, involving tedious trips to steep and remote mountains. Energy is a crucial issue for both human welfare and panda conservation. This is becoming even more important and serious, as fuelwood collection is no longer officially allowed. In 2001, the Natural Forest Conservation Program was initiated in the reserve. Each rural household was assigned one or more forest parcels to monitor for illegal harvesting and given a yearly subsidy (available until 2010) equal to one-quarter or more of household annual income. This direct income gained from NFCP along with serious law enforcement has prompted most households to reduce fuelwood consumption since 2001 by switching to electricity (Wolong Nature Reserve, 2005). The average electricity consumption per household increased from 800 kWh in 2000 to 2800 kWh in 2003 while fuelwood consumption per capita declined from 1.4 to 0.3 m^3 during the same period (Wolong Nature Reserve, 2005). A new, so-called ecohydropower plant began operation in October of 2002, but the price of electricity, a widely proposed substitute (An et al., 2002; Wolong Nature Reserve, 2005), is still high relative to household income (about 90% of the local rural residents interviewed complained about it). The effect of lowering the price of electricity on panda habitat can be significant. For example, a simulation study indicated that a reduction in electricity price by

0.05 RMB could save approximately 15 km^2 of panda habitat over a period of 30 years (An et al., 2006).

With substantial income losses when the NFCP ends, the households will likely resile and cut down trees for fuelwood again. Economically affordable, socially acceptable, ecologically sound, and sustainable long-term alternatives are needed. An on-going Grain-to-Green Program applies a national policy that focuses on restoring ecological functions as well as encouraging economic development in steep cropland; the program requires at least 80% of trees planted for ecological restoration, and at most, 20% of trees for economic purposes (Zhu and Feng, 2002; Ye et al., 2003). However, it may not effectively address the local residents' main need: fuelwood in Wolong Nature Reserve. As suggested by some other scholars for other regions (Madeschin, 1999; Zhang et al., 2000; Kohlin and Parks, 2001; Richardson et al., 2002), we also recommend that most of steep cropland returned to vegetation should be designated specifically for growing fuelwood forests, providing both energy resources and ecological functions in the reserve. By continuing to use fuelwood, local residents (of three minority ethnic groups: Tibetan, Qiang, and Hui) may preserve their traditional lifestyles and cultures (Ngugi, 1988; Mahiri and Howorth, 2001).

4.3. Panda habitat conservation

Considering the reality that fuelwood collection is unavoidable, the impacts on panda habitat could be mitigated if more fuelwood collection were to occur in areas with panda habitat of relatively lower quality, where little fuelwood was collected in the past. It is evident that fuelwood policies did not change the local residents' fuelwood collection behaviors. There were three major reasons for the apparent failure of these regulations. First, law enforcement was weak: fuelwood collection occurred in topographically difficult and relatively large areas, but the Wolong Administration Bureau had limited staff for resource monitoring and protection (Wolong Nature Reserve, 2005). Second, the tragedy of the commons (Hardin, 1968) is applicable in Wolong: collecting fuelwood from forests is free, except for the time it takes (Liu et al., 2007), and, based on the current Chinese land system, local residents have only usufruct rights; therefore, there is little incentive for them to grow trees for fuelwood, use energy-efficient stoves, or reduce fuelwood needs.

Third, some of the local residents' basic needs (e.g., energy) were not well addressed (Sharma, 1990): many potential alternatives (e.g., biogas and wind/sun power) were unavailable, were expensive (e.g., coal, because of transportation), or had other negative environmental effects (e.g., greenhouse gases from burning charcoal and coal). Although the eight hydropower plants in the reserve had a total capacity of 33,960 kW in 2003 (Wolong Nature Reserve, 2005) and local residents were willing to switch to electricity (An et al., 2002), the people could not afford to buy it and most of the electricity was sold to cities. At the average price of 0.13 RMB/kWh in 1999, a price decrease of 0.05 RMB would have doubled the number of households switching to electricity (An et al., 2002).

We suggest that resources or efforts should be shifted to monitor fuelwood collection in the areas of highly suitable and moderately suitable habitat. Currently, the farther an NFCP parcel is from the household assigned to monitor it, the more subsidies the household receives. To improve the efficacy of the NFCP's investment, household should receive higher subsidies if their parcels are in better shape, i.e., the habitat quality is better.

Meanwhile, we suggest that households be officially allowed to collect dead tree branches and shrubs for fuelwood from nearby NFCP parcels, with a maximum limit. This compromise should be allowed only for a short period, because in the long run it may also have negative impacts on ecosystem health and services (Bengtsson et al., 1997; Aigner et al., 1998; Rosenstock, 1998; Kumar and Shahabuddin, 2005). This proposal is most likely feasible because of the successful implementation of NFCP: forest parcels were well monitored and few were illegally harvested. This will also give enough time for the reforested trees in the Grain-To-Green Program to grow for fuelwood.

Understanding spatial and temporal patterns of fuelwood collection will not only help researchers scale up their evaluations of the impacts of fuelwood collection on panda habitats from the household level to the reserve landscape level, but also provide fundamental knowledge for reserve managers to make informed and effective decisions, and evaluate and adjust policies. For example, different conservation priorities could be set for areas with different types of habitat quality affected by fuelwood collection. Furthermore, the results obtained from and the methods used in this study may be useful for similar efforts in analyzing temporal and spatial patterns of fuelwood collection or other human activities in other parts of the world.

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