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ORIGINAL ARTICLE

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Impact of the 2008 Wenchuan earthquake on biodiversity and giant panda habitat in Wolong Nature Reserve, China

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Abstract Natural disasters such as earthquakes have profound effects on the earth's biodiversity. However, studies on immediate earthquake impacts are rarely conducted at fine scales due to logistical constraints. We conducted the first post-earthquake field survey in Wolong Nature Reserve, Wenchuan, China, less than 1 year after it was hit by a magnitude 8.0 earthquake in 2008. Since Wolong harbors approximately 10% of the endangered wild giant panda (*Ailuropoda melanoleuca*) population, the impact of the earthquake on the giant panda and its habitat is of particular concern. We established 15 transects in three focus areas within the Reserve where we classified occurrences of earthquake damage according to vegetation and geophysical characteristics. In the 11.2 km^2 area sampled, we recorded 156 occurrences of earthquake damage consisting of landslides and mudflows, which comprised a total area of 0.88 km^2. Of all earthquake damage occurrences sampled, only 36% of occurences (73% of surface area) corresponded to damaged areas previously detected through broad-scale remote sensing. The remaining damaged areas mainly consisted of occurrences too small to be detected without field observation. Although there were significant losses to tree and shrub species diversity and richness in earthquake-damaged areas, remnant vegetation was found in the majority (80%) of damaged areas, suggesting the potential for forest recovery. Most earthquake-damaged areas were too steep to be classified as suitable giant panda habitat (79%). In addition, a sizable number of signs of giant panda (67) and other wildlife (148) were observed near the earthquake-damaged areas, and there appeared to be avoidance of earthquake damage only at short-range distances. This study has implications for understanding the impact of natural disasters on biodiversity and highlights the importance of fine scale on-the-ground assessments of disaster impacts on wildlife and their habitats.

Keywords Biodiversity · Earthquake · Giant panda · Natural disasters · Wildlife habitat

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Introduction

Natural disasters have far-reaching impacts on biodiversity worldwide. Some disaster events may severely threaten plant and animal species due to their destruction of resources (Gould et al. 1999; Lai et al. 2007). However, in certain ecosystems, periodic disaster events are seen as necessary for introducing variability in complex systems (Tilman 1996; Vittoz et al. 2001). In forest ecosystems in particular, natural disasters are known to have profound impacts on forest structure and function by causing changes in forest diversity, loss of vegetative biomass, and declines in soil fertility (Guariguata 1990; Allen et al. 1999). Recent advances in remote sensing technology have allowed for significant gains in the study of such effects of natural disasters (Tralli et al. 2005), but these gains may have come at the expense of field studies being conducted on immediate disaster impacts at a finer scale.

On May 12, 2008, a magnitude 8.0 earthquake struck with its epicenter in Wenchuan County, Sichuan Province, China. The earthquake had a profound effect on human livelihoods, as it was responsible for over 80,000 deaths, in addition to causing an estimated 845.1 billion RMB (126 billion USD) in property damage (China Central Television 2008). The natural environment was also significantly affected. It is estimated that 1,221 km^2 of forest, grassland, and wetland ecosystems was destroyed as a result of the earthquake and subsequent landslides (Ouyang et al. 2008).

Of particular concern in the months following the earthquake was the status of the giant panda (*Ailuropoda melanoleuca*), an endangered species and national treasure in China. The area affected by the earthquake encompasses approximately 11,084 km^2 of giant panda habitat and contains 19 nature reserves for giant pandas (Ouyang et al. 2008). Several studies have been conducted to assess the impact of the earthquake on giant panda habitat (Dong et al. 2008; Ouyang et al. 2008; Wang et al. 2008; Xu et al. 2008; Cheng et al. 2009; Xu et al. 2009a, b). These studies have primarily used remote sensing to analyze broad-scale impacts of the earthquake on land cover. They reveal that approximately 656 km^2 (5.9%) of giant panda habitat was lost (converted from forest to bare land) due to the earthquake (Ouyang et al. 2008).

While such studies are highly valuable in understanding broad-scale effects, there is also a need to assess the impact of the earthquake on panda habitat at a finer scale, particularly with respect to forest biodiversity and giant panda use of earthquake-damaged areas. However, such studies have not been conducted to date because continual earthquake aftershocks have made field sampling logistically difficult. We hoped to fill this gap in this study by conducting the first post-earthquake field survey of giant panda habitat. We conducted line transect surveys in select areas of giant panda habitat in Wolong Nature Reserve, where we collected data on various geophysical and vegetation characteristics, in addition to recording the presence of wildlife signs. We describe the type and area of earthquake damage observed and whether the damage was detected previously using the broader-scale approach of remote sensing. We assessed the extent of damage to vegetation by comparing the trees and shrubs that were still alive in earthquake-damaged sites to what had been there before the earthquake, based on what had been killed. In addition, we investigate the effect of the earthquake on giant pandas by assessing the proportion of damaged sites that would have been suitable for use by pandas before the earthquake, using habitat suitability criteria from the literature. We also examined the distribution of panda sign as a function of distance from damaged sites.

Methods

Study area

Our study area was located in Wolong Nature Reserve (102°52′–103°24′E, 30°45′–31°25′N; Liu et al. 2001), Sichuan, China (Fig. 1). Wolong encompasses a 2,000 km^2 area that supports approximately 10% of the total wild giant panda population (Liu et al. 2001; State Forestry Administration 2006). Aside from giant pandas, there are over 2,200 other animal species and 4,000 plant species present within the reserve (Tan et al. 1995).

Wolong lies on the Longmen Mountain fault and has been subject to frequent tectonic activity. In fact, since 1933, there have been eight earthquakes above magnitude 7.0 within 200 km of the 2008 earthquake epicenter (China Earthquake Networks Center 2008). Although the percentage of habitat loss was lower in Wolong than some other reserves (Ouyang et al. 2008), we believe that Wolong is an important place to study the impact of the earthquake on giant pandas and their habitat, considering the large percentage of wild giant pandas inhabiting the reserve and the historical importance of this reserve as a flagship for conservation of the species. In addition, Wolong is a place where there have been long-term studies on biodiversity and habitat conducted over the last several decades (Hu et al. 1985; Schaller et al. 1985; Liu et al. 1999, 2007; State Forestry Administration 2006; Tuanmu et al. 2010), thereby providing a comprehensive pre-earthquake perspective that is rarely afforded in post-disaster assessments.

We chose three focus areas for sampling within Wolong: Qicenglou, Huangcaoping, and Wuyipeng, which were 8, 12, and 20 km from the earthquake epicenter, respectively (see gray areas in Fig. 1). These focus areas were selected because high densities of giant pandas were observed there consistently during the several years before the earthquake (State Forestry Administration 2006). It should be noted that the focus areas were not chosen for the purpose of capturing the full range of variability of different degrees of earthquake damage in the Reserve and in fact do not comprise the most heavily impacted sites (areas that may or may not have been heavily used by pandas before the earthquake). This is because our main objective was not to characterize the spatial extent of damage but to investigate earthquake impact in specific areas that experts consider to be "core panda habitat" over a long-term time frame. The altitudinal range of the focus areas was from 1,700 to 3,100 m. From low to high elevation, the focus areas encompassed three forest types: deciduous broad-leaved forest, broad-leaved and coniferous mixed forest, and subalpine coniferous forest. Arrow (*Bashania fangiana*) and umbrella (*Fargesia robusta*) bamboo, two staple bamboo species for the panda, dominated the forest understory.

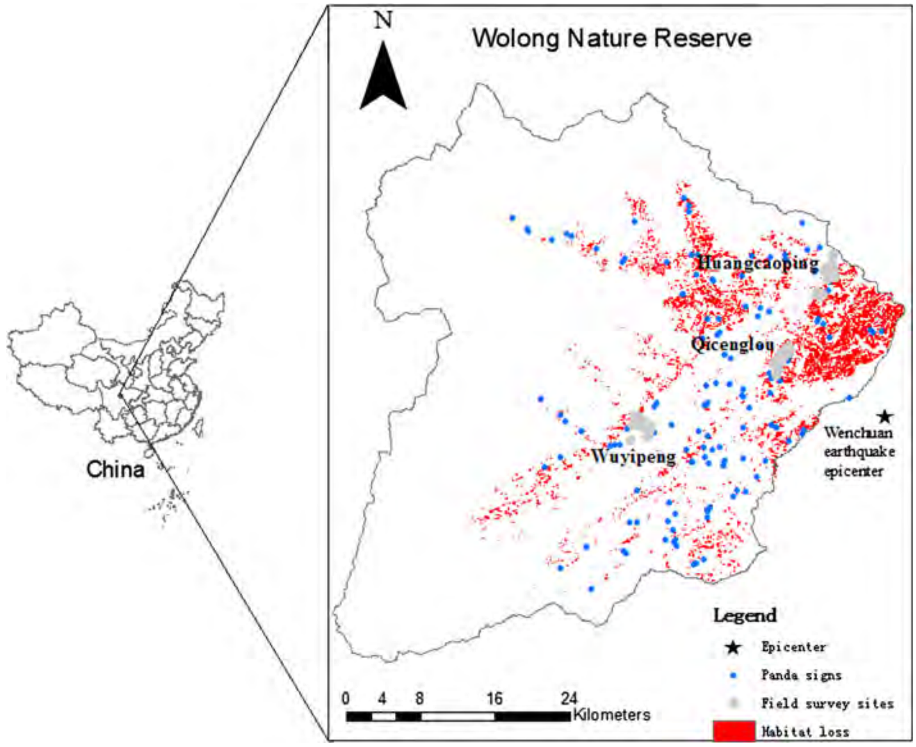

Fig. 1 Map of Wolong Nature Reserve, Sichuan, China. *Gray areas* depict the focus areas where sampling occurred: Wuyipeng, Qicenglou, and Huangcaoping. *Red portions* labeled "habitat loss" represent areas identified in Ouyang et al. (2008) as being damaged by the earthquake (converted from forest to bare land). *Blue dots* represent panda signs found in the 2001 National Giant Panda Survey in Wolong (State Forestry Administration 2006)

Field surveys

Field sampling was conducted from December 2008 to April 2009 (7–11 months after the earthquake occurred). We set up variable length (500–4,000 m) line transects in each of the focus areas: Qicenglou (four transects, total 12 km), Huangcaoping (four transects, total 10 km), and Wuyipeng (seven transects, total 18 km). The position and orientation of the line transects were chosen based on convenience sampling to correspond with well-established animal pathways that tortuously followed natural terrain and also to capture the variability in forest type across the elevations of each focus area. We walked along each transect and recorded incidences of earthquake damage within 100–200 m of each side of the path (for a total transect width of 200–400 m). We kept the sighting distance constant within each transect and focus area by excluding any areas estimated to be farther than the maximum allowable distance and making efforts to circumvent any visibility barriers in the path, but the width differed across the three focus areas due to differences in visibility. We recorded wildlife signs detected along each transect within 10 m of each side of the path. We were interested in wildlife signs as an index of use relative to distance to the earthquake-damaged sites, as opposed to a comprehensive measure of wildlife use of whole focus areas.

The position of each damaged area and wildlife sign was geo-referenced with a Pathfinder Pro XRS GPS unit (Trimble Navigation, Sunnyvale, CA, USA). We conducted sampling with local guides familiar with these specific pathways from frequent sampling of these areas for other research over the last 5 years. Thus, these individuals were able to differentiate any instances of damage that were independent of the earthquake, which we excluded from this analysis. Earthquake damage included visibly obvious landslides or mudflows caused by the earthquake. These were areas of at least 15 m^2 where the observer could see signs of fallen rocks, trees, or large aggregations of mud that had slid down a mountain slope that had not been present in other field excursions prior to the earthquake.

When we encountered earthquake damage, we estimated the area of habitat damaged by multiplying the two greatest perpendicular distances that crossed the affected area. These lengths were delineated by clearly visible fallen trees and rocks. We also recorded slope, aspect, and position of the damaged area with respect to the height of the mountain slope. Aspects were grouped according to four types: east-facing (45°–135°), south-facing (135°–225°), west-facing (225°–315°), and north-facing (315°–45°). The position of the damaged area on the mountain slope was determined by visual estimation according to five categories (from high to low): ridge, upper slope, middle slope, lower slope, and valley.

We visually estimated the straight-line distance from the damaged area to the nearest water source (m). We visually estimated the percentage of the total surface area (to the nearest 10%) taken up by earthquake damage that was covered by bare rocks (those larger in size than a fist), scree (mixed gravel and loose dirt), bare soil, and remnant vegetation. We visually estimated percent surface area of the earthquake damage that was taken up by newly growing grass to the nearest 5%. We

Table 1 Percentage of earthquake-damaged areas sampled ($n = 156$) in Wolong Nature Reserve, Sichuan, China belonging to different giant panda habitat suitability classes

Factors	Suitable		Moderately suitable		Unsuitable	
	Class	%	Class	%	Class	%
Slope (°)	≤ 20.0	0	20.1–45.0	20.79	> 45.0	79.21
Aspect	Eastern	23.84	Western	31.98		
	Southern	11.63	Northern	32.56		
Position on mountainside	Middle slope	16.76			Lower slope	20.11
					Valley	31.28
	Upper slope	25.14			Ridge	6.7
Distance to nearest water source (m)	≤ 100.0	59.04	100.1–500.0	11.7	> 500.0	29.26

Classifications of suitable, moderately suitable, and unsuitable habitat were generated based on previous studies of giant panda behavior and ecology in Wolong Nature Reserve

also identified the genus and species of live trees and shrubs in the entire region contained by the earthquake-damaged area. We did the same for dead trees and shrubs when identification was possible on remnant plant parts. Dead vegetation was restricted to that observed to be destroyed by the earthquake.

Data analysis

We estimated the total area sampled by multiplying the width of the transect by the total length and summing across all transects. We calculated the width and length of transects and the distance between wildlife signs and earthquake-damaged areas using ArcGIS 9.3 (Environmental Systems Research Institute 1999–2009). We also overlayed our sampled earthquake-damaged areas with the predictions for earthquake-damaged areas across the reserve that were derived from remote sensing analysis (Ouyang et al. 2008). We first created buffered regions around the earthquake-damaged area points with a radius of 30 m to account for potential GPS measurement error and then performed a spatial overlay of field-sampled earthquake damage and remotely detected earthquake damage in ArcGIS. We then summarized the percentage of field-sampled earthquake-damaged areas overlapping with remotely detected earthquake-damaged areas and compared the surface area of earthquake-damaged areas detected using the two methods.

We classified the tree and shrub communities present in the earthquake-damaged areas (at the species level) using four community structure indices:

Species richness index (Gleason 1922): $D_{GL} = S/\text{In}(A)$;
Shannon-Wiener index (Shannon and Weaver 1949): $H' = -\sum_{i=1}^{s} p_i \,\text{In}\, p_i$
Simpson index (Simpson 1949): $D = 1 - \sum_{i=1}^{s} p_i^2$
Species evenness index (Pielou 1966): $J' = H'/\text{In}(S)$

where A is the area of the earthquake-damaged area sampled, S is the number of different species in the community, and p_i is the proportion of the ith species in the community. The Shannon-Wiener and Simpson indices both measure species diversity. Most earthquake-damaged areas had trees and shrubs buried under rocks that were damaged to the point of not being recognizable by our field team. Therefore, in order to minimize a potential tree and shrub detection bias, we restricted this analysis to only those earthquake-damaged areas in which we could be sure that we measured and correctly classified all trees and shrubs present in the earthquake-damaged area both before and after the earthquake ($n = 26$). We did not actually survey the area before the earthquake, but we reconstructed the vegetation that existed at each damaged site based on living and earthquake-killed trees and shrubs that we observed afterward. We tested for significant differences in the community structure (as measured by the number of different species and the four community indices) before and after the earthquake using the paired t test. All statistical analyses were performed using SPSS 16.0 (SPSS for Windows 2007) with a significance level of $p = 0.05$. The data were checked for normality prior to all analyses using the Kolmogorov-Smirnov test.

We analyzed the relationship between occurrences of earthquake damage and quality of habitat with respect to suitability for giant pandas according to four factors: slope, aspect, position on mountainside, and distance to water. For each criterion, we characterized the areas as suitable, moderately suitable, and unsuitable according to literature on giant panda behavior and ecology in Wolong Nature Reserve (Hu et al. 1985; Schaller et al. 1985; Hu 2001; Zhang and Hu 2002; Hu and Wei 2004, see Table 1). We omitted bamboo cover from this assessment, since we had no way of knowing the percent bamboo cover prior to the earthquake because most bamboo was damaged beyond recognition. We omitted elevation from this assessment because all elevations in the focus areas were within the "suitable" range for giant pandas.

We measured the distance between giant panda and other wildlife signs to the nearest earthquake-damaged area observed in the field using ArcGIS. We performed the same analysis on a broader scale by measuring distance from observed giant panda and other wildlife signs

Table 2 Summary of density and area of damage due to the Wenchuan earthquake in three focus areas of giant panda habitat in Wolong Nature Reserve, Sichuan, China

Focus area	Number of transects	Total transect length (km)	Transect width (m)[a]	Number of earthquake damage occurrences	Density of earthquake damage sites (n/km^2)	Total area of damage (km^2)	Percent sampled area damaged (%)
Qicenglou	4	12	300	65	18.06	0.32	8.9
Huangcaoping	4	10	400	47	11.75	0.5	12.5
Wuyipeng	7	18	200	44	12.22	0.06	1.7
Total	15	40	–	156	13.93	0.88	7.9

[a]Transect widths differ due to differences in visibility across the terrain

Table 3 Surface area (m^2) affected by earthquake damage created by the Wenchuan Earthquake in Wolong Nature Reserve, China, as detected via remote sensing and field surveys

Statistic	Remote sensing		Field surveys	
	Total earthquake damage (n = 9,662)	Panda habitat damage (n = 5,454)	Detected via remote sensing (n = 56)[a]	Not detected via remote sensing (n = 100)
Mean	12,827	7,737	11,632	2,447
Standard deviation	465,651	26,221	26,990	4,521
Minimum	900	900	80	15

Remote sensing results are separated into total earthquake damage and only those areas that satisfy conditions to qualify as giant panda habitat with respect to appropriate slopes, elevations, and forest cover type (according to subjective, but broadly accepted criteria outlined in Liu et al. 1999). Field survey results relate to damage detected through line transect sampling in three focus areas of Wolong and are separated into those overlapping with areas already detected via remote sensing and those occurring in areas where remote sensing did not detect earthquake damage

[a]Areas were classified as detected via remote sensing if a 30 m circular buffer built around each survey location (accounting for location measurement error) overlapped with earthquake-damaged areas detected by remote sensing

to the nearest earthquake-damaged area detected using the remote sensing analysis performed by Ouyang et al. (2008). We also generated 10 replications of 67 point locations distributed randomly throughout the transects using the random point generator in Hawth's Tools for ArcGIS 9.x (Beyer 2004). We chose a sample size of 67 because it matched the sample size of giant panda signs found in this study. We calculated distance from each random point to nearest earthquake-damaged area (derived from both field and remote sensing data) and obtained the average, minimum, and maximum values for distance to earthquake damage across the 10 replications.

Results

Occurrences, area, and types of earthquake damage

In the 11.2 km^2 area sampled, we detected a total of 156 occurrences of earthquake damage to giant panda habitat as a result of the Sichuan earthquake in our focus areas in Wolong Nature Reserve. Of our three focus areas, Qicenglou had the greatest number of occurrences of earthquake damage and density of damaged sites, but Huangcaoping had the greatest percent area of earthquake damage (Table 2). The large number of occurrences in Qicenglou is likely related to the fact that it had some of the steepest slopes of the three focus areas, while the large percent area of damage in Huangcaoping is likely related to the geophysical structure of this area that created mudflows, which took up a greater area than landslides. Wuyipeng on the whole was subjected to less damage than the other two, likely because of its greater distance from the earthquake epicenter (Fig. 1). The average area and standard error of habitat damaged in each occurrence was 5,693 ± 1,365 m^2 (range 15–180,000 m^2). However, the distribution was skewed to smaller-sized areas, such that the median area was 1,200 m^2 (the 25 and 75% quartiles were 300 and 4,538 m^2, respectively). The total area of habitat damage was 0.88 km^2, which comprised 7.9% of the total area sampled (Table 2).

Of all earthquake damage areas observed, only 36% of damage occurrences corresponded to areas previously detected through the broad-scale approach of remote sensing. Considering surface area taken up by earthquake damage, 73% of the total field-surveyed damaged area (0.88 km^2) was detected by remote sensing. The areas not detected were mainly damaged areas smaller in size than what could be seen through remote sensing (Table 3). Because the remotely sensed imagery was limited to a grain of 30 × 30 m pixels, any earthquake-damaged site smaller than 900 m^2 was missed by this approach. In addition, 40% of the missed observations were larger than the minimum resolution of 900 m^2. The

Table 4 Tree and shrub community structure in damaged areas before and after the Wenchuan earthquake in mixed deciduous broad-leaved forest in Wolong Nature Reserve, Sichuan, China (significant differences determined using paired *t* tests)

Index	Layer	Pre-earthquake[a] (mean ± SE)	Post-earthquake (mean ± SE)	*t*	*df*	*p*
Number of species (*S*)	Tree	4.23 ± 0.295	2.85 ± 0.307	5.871	25	0.000**
	Shrub	5.00 ± 0.396	3.92 ± 0.368	5.026	25	0.000**
Species richness (D_{GL})	Tree	0.778 ± 0.064	0.517 ± 0.631	5.849	25	0.000**
	Shrub	0.937 ± 0.083	0.731 ± 0.065	4.487	25	0.000**
Shannon-Wiener (*H*)	Tree	1.182 ± 0.076	0.818 ± 0.100	4.521	25	0.000**
	Shrub	1.281 ± 0.089	1.094 ± 0.079	4.473	25	0.000**
Simpson (*D*)	Tree	0.627 ± 0.029	0.467 ± 0.052	3.554	25	0.002**
	Shrub	0.641 ± 0.036	0.592 ± 0.032	3.554	25	0.002**
Species evenness (*J′*)	Tree	0.849 ± 0.026	0.711 ± 0.074	1.726	25	0.097
	Shrub	0.829 ± 0.032	0.856 ± 0.031	2.767	25	0.01*

Shannon-Wiener and Simpson indices are measures of species diversity. Trees and shrubs sampled include all those within the earthquake-damaged areas that were encountered on line transects in three focus areas

*$p < 0.05$, **$p < 0.01$

[a]Determined by assessment of living and earthquake-killed vegetation

damage across all sites occurred mainly as a result of landslides (96.2% of occurrences), with mudflows making up the remainder. Within the damaged areas, the ground cover consisted mainly of bare rocks (42.6%; mean ± SE 2,623 ± 605 m^2) and bare soil (30.8%; 1,396 ± 309 m^2), with scree (1,292 ± 536 m^2) and remnant vegetation (381 ± 90 m^2) making up comparably lesser proportions of ground cover (17.6 and 9%, respectively). Future habitat recovery is likely to occur on sites with bare soil or remnant vegetation. These comprised 39.8% of the damaged areas.

Impact of the earthquake on vegetation

In our surveyed areas, there were 133 earthquake damage occurrences (85.3%) that resulted in at least one dead tree and 143 occurrences that resulted in at least one dead shrub (91.7%). However, the majority of damaged areas still had living trees (112, 71.8%) and shrubs (117, 75%) within them. New grass was observed to be growing in 70 of the damaged areas (44.9%), although it only covered <5% of the total ground surface of each damaged area.

A total of 43 different species of trees and 50 different species of shrubs were observed across all plots (including live and dead), of which 39 tree species and 40 shrub species were represented among individuals killed in the earthquake-damaged areas that we examined. There was a significant loss of tree and shrub species richness and diversity in the damaged areas after the earthquake (Table 4). Species evenness significantly declined in the damaged areas for shrubs, but not for trees (Table 4).

We believe that the subset of 26 earthquake-damaged areas is roughly representative of the full sample of 156 earthquake-damaged areas because the subset spanned the range of elevations and vegetation types present in our survey transects. When using the full sample of 156 occurrences, we still found significantly higher species richness in pre-earthquake compared to post-earthquake conditions, despite the underestimation of pre-earthquake tree and shrub densities (paired *t* tests, trees: mean ± SE 0.6 ± 0.03 vs. 0.39 ± 0.03, $t = 8.95$, $df = 155$, $p < 0.001$; shrubs: 0.62 ± 0.03 vs. 0.43 ± 0.03, $t = 7.25$, $df = 155$, $p < 0.001$).

Impact of the earthquake on habitat use of giant pandas

The areas damaged by the earthquake met some criteria for suitable giant panda habitat, but not others. Overall, only 9.6% of earthquake-damaged areas qualified as "moderately suitable" or "suitable" according to the habitat suitability criteria we used. Earthquake-damaged areas overwhelmingly occurred on steep slopes that are normally avoided by giant pandas (Table 1). In fact, 79% of all damaged areas occurred on slopes that are considered too steep to be suitable giant panda habitat. Earthquake-damaged areas also were mainly found in areas with slope aspects considered only moderately suitable by giant pandas in this study area (western and northern). On the other hand, there were a greater number of earthquake-damaged areas in mid-slope and upper-slope positions on the mountainside, areas that pandas regularly use. In addition, most of the earthquake-damaged areas we detected were within 100 m of a water source (59%), areas which pandas also frequently use. The distance to water and position on the hillside variables were strongly related to one another, as most water sources are found at the bottom of valleys.

Despite the frequency of earthquake damage throughout our transects, we recorded 67 incidences of giant panda signs. In fact, 22% of all giant panda signs were found within 100 m of a field-detected earthquake-damaged area and 15% were found within 100 m of a remotely detected earthquake-damaged area. There were some differences in distribution of panda signs with

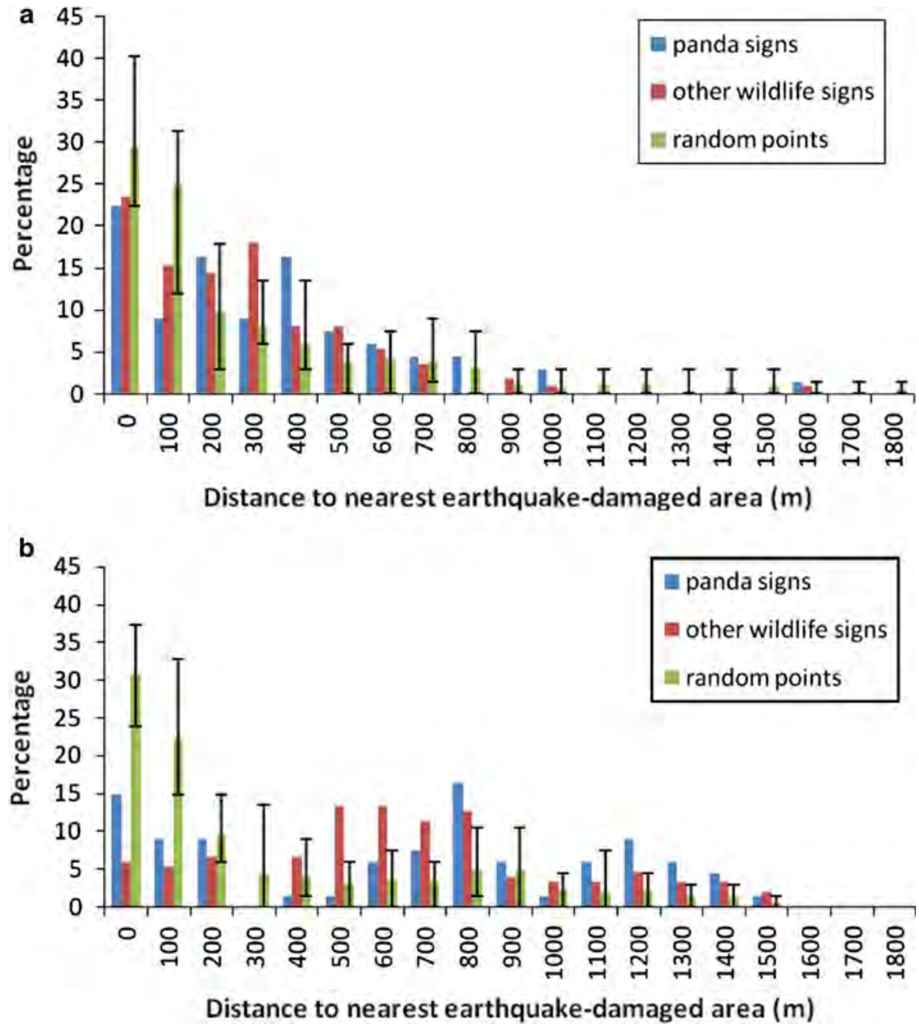

Fig. 2a, b Relationship between incidences of giant panda and other wildlife signs and distance to nearest earthquake-damaged area in select focus areas in Wolong Nature Reserve, Sichuan, China. Earthquake-damaged areas were detected via **a** field sampling along line transects and **b** supervised classification of remote sensing imagery in Ouyang et al. (2008). Panda and other wildlife signs are presented against the average percentage of points derived from 10 sets of 67 random locations within the sampling transects. *Error bars* around random point estimates indicate the maximum and minimum values obtained from the 10 random generations

respect to distance to field-sampled earthquake-damaged areas and that of random locations generated throughout the transects (Fig. 2a). At the shortest lag distance of 0–99 m, there were fewer panda signs than random points, while at the lag distance of 300–399 m, there were more panda signs than random points.

In comparison to field-sampled earthquake-damaged areas, the distances from panda signs to damaged areas detected using remote sensing were more uniform (Fig. 2b). The lack of detection of the smallest earthquake-damaged areas using this method made for greater distances detected from panda signs to earthquake damage. Excluding giant pandas, there were 148 incidences of wildlife signs around damaged areas from 16 different animal species, including red panda, takin, sambar, serow, tufted deer, Chinese goral, golden monkey, Tibetan macaque, leopard cat, wild pig, porcupine, and satyr tragopan. There were some differences in frequency of other wildlife signs and giant pandas with respect to distances to earthquake-damaged areas, the most notable being a lower percentage of signs within 100 m and a higher percentage of signs 400–500 m from earthquake damage detected via remote sensing (Fig. 2a, b). No wildlife carcasses were found in this study.

Discussion

Although previous remote sensing studies have classified broad scale impacts of the 2008 Wenchuan Earthquake (Ouyang et al. 2008; Xu et al. 2009a, b), this is the first field survey that documented fine-scale impacts of the earthquake at the level of individual plants and animals. Most of the earthquake-damaged areas that we sampled were missed by the remote sensing method, while the majority were too small in size to be detected through image classification. We also found that the field survey provided rich context to understanding on-the-ground patterns in this ecosystem's response to disturbance, particularly with respect to plant diversity and animal response to damaged habitat.

Our study demonstrates that the earthquake had an effect on the tree and shrub community in earthquake-damaged areas of Wolong Nature Reserve, China. Loss of diversity and richness could be concerning because this may contribute to declines in forest productivity (Mittelbach et al. 2001), in addition to causing declines in diversity of the animal populations that depend upon forest resources (Tews et al. 2004). However, disturbance events such as earthquakes may also create forest gaps that could contribute to new growth and higher forest diversity over the long-term and at larger spatial scales (Tilman 1996; Vittoz et al. 2001). Future research efforts should focus on investigating the impact of loss of trees and shrubs on the forest structure at such larger temporal and spatial scales.

Despite the fact that bare rocks made up the largest area of ground cover in the earthquake-damaged areas, the high percentage of damaged areas contained remnant vegetation. This suggests future vegetation recovery is likely. Previous studies in disturbed areas suggest that the presence of remnant vegetation is a driving factor for forest recovery, not only because it allows for seed dispersal, but also because it improves soil nutrient levels and raises soil humidity (Holl et al. 2000; Ferguson et al. 2003).

Regarding the impact of the earthquake on giant pandas, the single most important finding of this study was that the majority of earthquake damage occurred in areas deemed too steep to be suitable giant panda habitat. Slope is considered one of the most important factors dictating habitat suitability for giant pandas (Schaller et al. 1985; Reid and Hu 1991), and it may override other factors we investigated such as position on the mountainside and distance to water. This is because giant pandas have tight energy budgets due to their inability to digest more than approximately 17% of what they eat (Schaller et al. 1985). Therefore, energy-efficient travel along gentler slopes is a necessity for survival. Nonetheless, the fact that a number of giant panda and other wildlife signs were observed near earthquake-damaged sites suggests that the disturbances in the steep areas did not prevent wildlife from using other areas nearby. This observation highlights the fact that slope varies considerably in Wolong, even at fine spatial scales, and future research is needed in order to better understand the spatial scale at which pandas are most sensitive to slope. The finding that more earthquake damage occurred in areas closer to water is reflective of the fact that water sources more often occur in deep valleys, thus areas close to the water sources were perhaps more likely to be subject to landslide events.

This study contributes to the growing body of literature that demonstrates the capability of animals to withstand periodic disturbance (Singh et al. 2001; Ashenafi et al. 2005; Madsen and Boertmann 2008). With respect to our analysis of the relationship between panda signs and distance to earthquake-damaged area, our results suggested that there was a slight avoidance of earthquake-damaged areas at the shortest lag and preference for areas 400 m away from earthquake-damaged areas. It is important to place these results in biological context. Since giant pandas in this reserve have home ranges approximating 4–6 km^2 in size (Schaller et al. 1985), it is likely that any short-range avoidance of earthquake-damaged areas (e.g., at the 100 m scale) does not pose a significant threat to pandas, considering the possibility of a compensatory effect of more frequent inhabitance of nearby undisturbed areas (e.g., 400 m away), which appears to be what has occurred here. However, future studies should more intensively investigate the relationship between frequency and size of earthquake disturbance and panda distribution.

Considering Wolong's location directly on the Longmen Mountain fault and the history of tectonic activity in this area, it is possible that pandas have had to withstand periodic earthquakes in the past. In the context of a broader-scale discussion on response of pandas to earthquakes, it is important to recognize that we only looked at three focus areas in Wolong, which were chosen because they were core giant panda habitats. These areas were not necessarily the areas in Wolong that were most heavily impacted by the earthquake. Future studies should be conducted at the Reserve-wide scale in order to assess whether giant pandas are avoiding marginal habitat areas that may be more heavily affected by the earthquake. Further field studies should also be conducted in other nature reserves in order to assess whether the impact of the earthquake on giant pandas and their habitat may be higher in areas with greater forest loss.

Although the giant panda population may withstand periodic natural disturbances in the form of earthquakes, the population has declined significantly in recent decades due to their most severe disturbance faced since the Ice Age—the threat of humans and their associated resource extraction activities (Liu et al. 2001). The magnitude of human disturbance appears to be much greater than that of the earthquake in our study area, considering that only an estimated 6.6% of habitat in Wolong was lost as a result of the earthquake (Ouyang et al. 2008) compared to an estimated 30% of habitat loss attributed mainly to human disturbance from 1965 to 1997 (Liu et al. 2001). Human impacts have not only caused declines in overall habitat, but have degraded the suitability of habitat for pandas (Liu et al. 2001) and caused increased amounts of habitat fragmentation (Loucks et al. 2001). Recent conservation policies have been put in place to combat this trend, including the National Forest Conservation Program (NFCP), which provides a stipend for local farmers to protect remnant forests and the Grain to Green Program (GTGP), which compensates farmers for conversion of farmland to forest plantations (Liu et al. 2008). Broadscale remote sensing analysis in fact reveals that without these policies, the combined effect of human disturbance and earthquake damage could have more severely degraded forests across panda habitat (Viña et al. 2010).

This study also highlights the importance of nature reserves located in areas known for tectonic activity to integrate earthquake impacts into management planning. For instance, forested areas with flatter slopes should be given special priority as strongholds for biodiversity. Human activities in such areas should be regulated and extensively monitored, considering their importance for sustaining populations when steeper slopes are vulnerable to disturbance.

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