The population in China's earthquake-prone areas has increased by over 32 million along with rapid urbanization

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CORRIGENDUM

Corrigendum: The population in China's earthquake-prone areas has increased by over 32 million along with rapid urbanization (2016 *Environ. Res. Lett.* **11** 074028)

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The correct table 1–4 and figure 5 are presented below. The corrections of abbreviation in the tables and the bar chart in figure 5 do not affect any other results or conclusions of the paper.

Table 1. Population exposed to the most seismically hazardous areas in 2010 (population unit: million).

Area	City size	Total population	Children	Elderly	Working age population
Most seismically hazardous areas	Mg	25.33	1.26	1.12	22.95
	La	31.57	2.47	2.15	26.95
	Me	29.43	2.89	2.50	24.04
	Sm	42.88	4.46	4.06	34.36
	Total	129.21	11.09	9.83	108.29
		(100%)	*(8.58%)*	*(7.61%)*	*(83.81%)*
Mainland China	Mg	159.35	8.83	7.68	142.84
	La	366.86	32.27	26.83	307.76
	Me	445.78	43.95	36.01	365.81
	Sm	360.82	35.44	31.01	294.37
	Total	1332.81	120.49	101.53	1110.79

Note: Mg-mega CLAU (county-level administrative unit); La-large CLAU; Me-medium CLAU; Sm-small CLAU. The number in the brackets are the proportion of exposed population for each age-group to the total exposed population.

Table 2. Population change in the most seismically hazardous areas from 1990 to 2010 (population unit: million).

Area	City size	Total population	Children	Elderly	Working age population
Most seismically hazardous areas	Mg	10.91	−1.77	0.26	12.43
		(75.6%)	*(−58.4%)*	*(30.2%)*	*(118.2%)*
	La	11.75	−1.98	1.27	12.46
		(59.3%)	*(−44.5%)*	*(144.3%)*	*(86.0%)*
	Me	4.96	−4.24	1.19	8.01
		(20.3%)	*(−59.5%)*	*(90.8%)*	*(50.0%)*
	Sm	4.91	−7.20	1.69	10.41
		(12.9%)	*(−61.7%)*	*(71.3%)*	*(43.5%)*
	Total	32.53	−15.18	4.41	43.30
		(33.6%)	*(−57.8%)*	*(81.4%)*	*(65.8%)*
Mainland China	Total	200.43	−286.64	37.65	449.23
		(17.7%)	*(−70.4%)*	*(58.9%)*	*(67.9%)*

Note: Mg-mega CLAU (county-level administrative unit); La-large CLAU; Me-medium CLAU; Sm-small CLAU
The numbers in the brackets are the percentage of change, which is calculated as $(P_{2010}-P_{1990})/P_{1990}{}^{*}100\%$, whereas P_{2010} and P_{1990} refer to the population in 2010 and 1990, respectively.

Table 3. Urban population change in the most seismically hazardous areas from 1990 to 2010 (population unit: million).

Area	City size	Population in 1990	Population in 2010	Change of population	Percentage of change (%)
Most seismically hazardous areas	Mg	8.77	21.65	12.88	146.9
	La	10.44	24.45	14.01	134.2
	Me	3.83	12.02	8.19	213.8
	Sm	4.95	14.40	9.45	190.9
	Total	27.98	72.52	44.54	159.2
Mainland China	Total	238.75	670.00	431.25	180.6

Note: Mg-mega CLAU (county-level administrative unit); La-large CLAU; Me-medium CLAU; Sm-small CLAU
The percentage of change, which is calculated as $(P_{2010}-P_{1990})/P_{1990}\times 100\%$, whereas P_{2010} and P_{1990} refer to the population in 2010 and 1990, respectively.

Table 4. Rural population change in the most seismically hazardous areas from 1990 to 2010 (population unit: million).

Area	City size	Population in 1990	Population in 2010	Change of population	Percentage of change (%)
Most seismically hazardous areas	Mg	5.65	3.68	−1.97	−34.9
	La	9.39	7.12	−2.27	−24.2
	Me	20.64	17.42	−3.22	−15.6
	Sm	33.02	28.48	−4.54	−13.7
	Total	68.70	56.70	−12.00	−17.5
Mainland China	Total	893.63	662.81	−230.82	−25.8

Note: Mg-mega CLAU (county-level administrative unit); La-large CLAU; Me-medium CLAU; Sm-small CLAU
The percentage of change, which is calculated as $(P_{2010}-P_{1990})/P_{1999}\times 100\%$, whereas P_{2010} and P_{1990} refer to the population in 2010 and 1990, respectively.

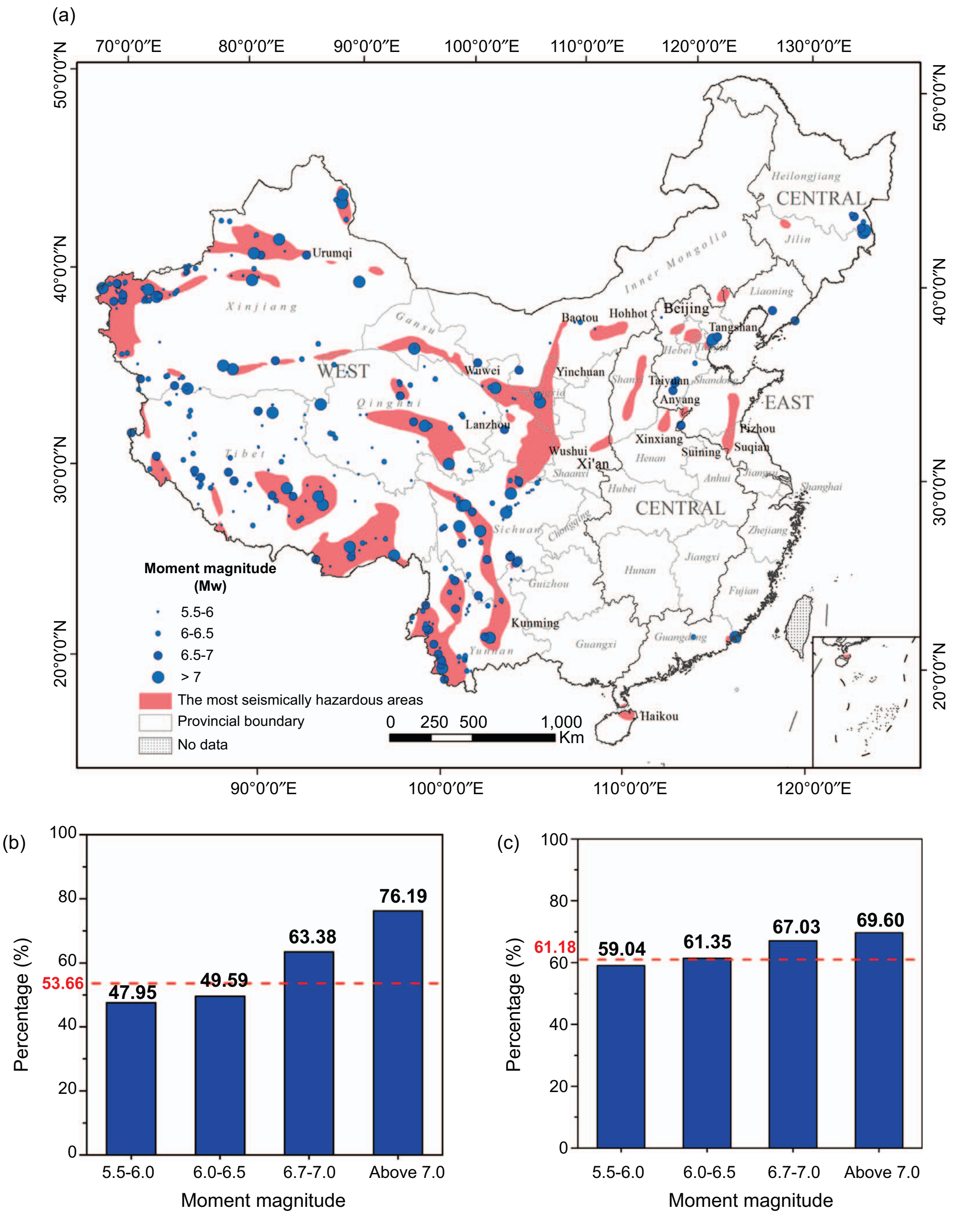

Figure 5. The earthquakes in China from 1900 to 2009 (*a*): the spatial distribution; (*b*): the proportion of earthquakes occurred in the most seismically hazardous areas by the moment magnitude; (*c*): the proportion of casualty occurred in the most seismically hazardous areas. The red dash lines in (*b*) and (*c*) represent the proportions of earthquake and casualty, respectively, with a moment magnitude equal to or greater than 5.5 occurred in the most seismically hazardous areas).

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Keywords: population exposure, seismic hazard, urbanization, urban planning, China

Abstract

Accurate assessments of the population exposed to seismic hazard are crucial in seismic risk mapping. Recent rapid urbanization in China has resulted in substantial changes in the size and structure of the population exposed to seismic hazard. Using the latest population census data and seismic maps, this work investigated spatiotemporal changes in the exposure of the population in the most seismically hazardous areas (MSHAs) in China from 1990 to 2010. In the context of rapid urbanization and massive rural-to-urban migration, nearly one-tenth of the Chinese population in 2010 lived in MSHAs. From 1990 to 2010, the MSHA population increased by 32.53 million at a significantly higher rate of change (33.6%) than the national average rate (17.7%). The elderly population in MSHAs increased by 81.4%, which is much higher than the group's national growth rate of 58.9%. Greater attention should be paid to the demographic changes in earthquake-prone areas in China.

1. Introduction

The population exposed to seismic hazard refers to the human occupancy of seismically hazardous zones, or the population present within seismically hazardous areas where potential direct damage to property and human casualties may occur (Cutter 1996, Freire and Aubrecht 2012). It is a crucial step for evaluating seismic risk (Panza *et al* 2010). That is because, relative to other natural hazards (e.g., hurricanes), the accurate prediction of the location and timing of earthquakes is more difficult (Geller 1997, Guo 2010). In addition, the risks of an earthquake event cannot be mitigated by decreasing the components of its hazards (e.g., location, geographic scope, frequency, duration, and magnitude). The remaining mitigation options are enhancing the seismic resistance of structures and reducing the population exposed to earthquake hazards (Freire and Aubrecht 2012). Rapid urbanization has led to not only significantly increased urban population (Bilham 2004, 2009) but also urban population exposed to seismic hazard worldwide over recent decades. Further, the age structure of the population in seismically vulnerable areas has been greatly altered (Chen and Shi 2007). Therefore, timely and accurate assessment of the size of the population exposed to seismic hazard becomes an essential first step for efficient and effective earthquake risk management.

As the world's largest developing country, China has suffered from severe earthquake damage throughout its history. Meanwhile, it has witnessed unprecedented urbanization during recent decades. It is among the countries with the highest number of earthquake-related deaths (Chen and Shi 2007). During the years between 856 and 2010, eight of the 38 earthquakes worldwide with more than 50 000 deaths occurred in China (Holzer and Savage 2013). China also had the highest number of earthquakes with more than 10 000 fatalities and the largest total number of earthquake fatalities between 1500 and 2004 (Bilham 2004). China's unprecedented urbanization in the past three decades has brought the proportion of the urban population from 17.9% in 1980 to 52.6% in 2012 (Bai *et al* 2014). With the migration of working-age population from rural to urban areas, rural areas are seeing a more rapidly aging population, as a direct result of the urbanization process (Peng 2011, Meng 2014). For example, in 2006, more than 80% of migrant workers in urban areas were below 40 years old according to the national agricultural census (Cai *et al* 2012). Further, the urbanization experience of developed countries suggests that this trend of rapid urbanization will most likely continue in China in the near future. In an estimate, the population of urban areas will expand by an additional 335 million people by 2030 (Peng 2011). Therefore, a deep understanding of the size and structure of the population exposed to seismic hazard and their changes in the context of rapid urbanization in China will facilitate earthquake preparedness and damage mitigation.

Most previous studies have provided snapshot estimations of the population exposed to seismic hazard at different scales (Allen *et al* 2009, Aubrecht *et al* 2011, Freire and Aubrecht 2012). However, few studies have examined the changes (e.g., space and age structure) in the population exposed to seismic hazard in the context of rapid urbanization (Donner and Rodríguez 2008). Such studies have been further hindered in China mainly because of the lack of reliable and accurate seismic hazard and population data. In terms of seismic hazard data, two widely used methods have been developed to measure the hazard (Panza *et al* 2010). The first one is the probabilistic seismic hazard analysis. For instance, the 2001 seismic ground motion parameters zonation (SGMPZ) map (national standard: GB18306-2001) (Hu *et al* 2001, Gao 2003) was based on this method and has been widely used in assessing the seismic vulnerability and capacity of buildings in China (Shibin *et al* 2010, Xu *et al* 2011). Another method is the neo-deterministic seismic hazard analysis (NDSHA, Wang 2010, Peresan and Nekrasova 2014), which has been adopted to estimate the seismic hazard in some regions, such as Italy (Zuccolo *et al* 2010), the Longmenshan fault zone, the origin of the 2008 Wenchuan earthquake (Yong and Booth 2011), and the Beijing–Tianjin–Tangshan area (Xie *et al* 2010). However, there is no national estimate of seismic hazard based on the NDSHA in China.

In addition, annual population yearbooks (APYs) have been the most important sources of population data in China (PCO (Population Census Office under the State Council and the National Bureau of Statistics of China) 2012). However, APYs have seriously underestimated urban population. APYs provide population estimates for two groups, namely, the agricultural and non-agricultural population. The latter group has commonly been used to represent urban population. The problem is that the non-agricultural population is estimated based on the household registration system, which does not account for migrant workers living in urban areas but holding agricultural registration status (Zhou and Ma 2005). For example, according to the 2010 APY, the proportion of the 2010 urban population was 34.17%. This figure is much lower than the 49.68% reported in the 2010 China population census (CPC), which counted migrant workers as part of the urban population. The difference is equivalent to 207 million people (Qiu 2012).

The new SGMPZ map released in 2015 and the 2010 CPC released in 2012 offer two significantly improved datasets useful to the study of seismic vulnerability. The new SGMPZ map (national standard: GB18306-2015) (General Administration of Quality Supervision, Inspection and Quarantine of P.R.C 2015) improved the mapping method for seismic hazards and included information of recent earthquakes, particularly the 2008 Wenchuan and 2010 Yushu earthquakes. Thus, the new SGMPZ map provides more accurate data on the distribution of peak ground acceleration (PGA, a measure of ground motion) with a 10% probability of being exceeded over a period of 50 years. Meanwhile, compared with the APY data, the 2010 CPC data are more accurate and detailed. Its estimation was based upon a 10% national survey, much higher than the sampling rate of 1% used by the census producing the APY data. The 2010 CPC provides more accurate urban population information, including data of unregistered migratory workers, which was not available in the APY. The 2010 CPC also offers additional demographic variables unavailable in the APY, such as population estimation by age group.

Taking the advantages of these two newly available datasets, the main objective of this study was to analyze the characteristics of the population exposed to seismic hazard between 1990 and 2010 in China in the context of rapid urbanization. The population change in the most seismically hazardous areas (MSHAs) was analyzed using the geographic information system at the national, regional (western, central, and eastern China), and county levels (i.e., county-level administrative units [CLAUs] with four sizes: mega, large, medium, and small units).

2. Methods

2.1. Data source

This study used three types of data. First, the population data (CPC) from 1990 to 2010 were collected from the National Population Census of the Population Census Office (PCO (Population Census Office under the State Council and the National Bureau of Statistics of China) 1992, 2012). The 2010 CPC data were more accurate and detailed than those found in APY. Both CPC and APY data contain such variables as total population, gender, and agricultural/non-agricultural population, but the CPC data provide several additional demographic variables, including urban/rural population and population by three age groups: children (aged $\leqslant$14 years), working age adults (aged 15–64 years), and elderly persons (aged $\geqslant$ 65 years).

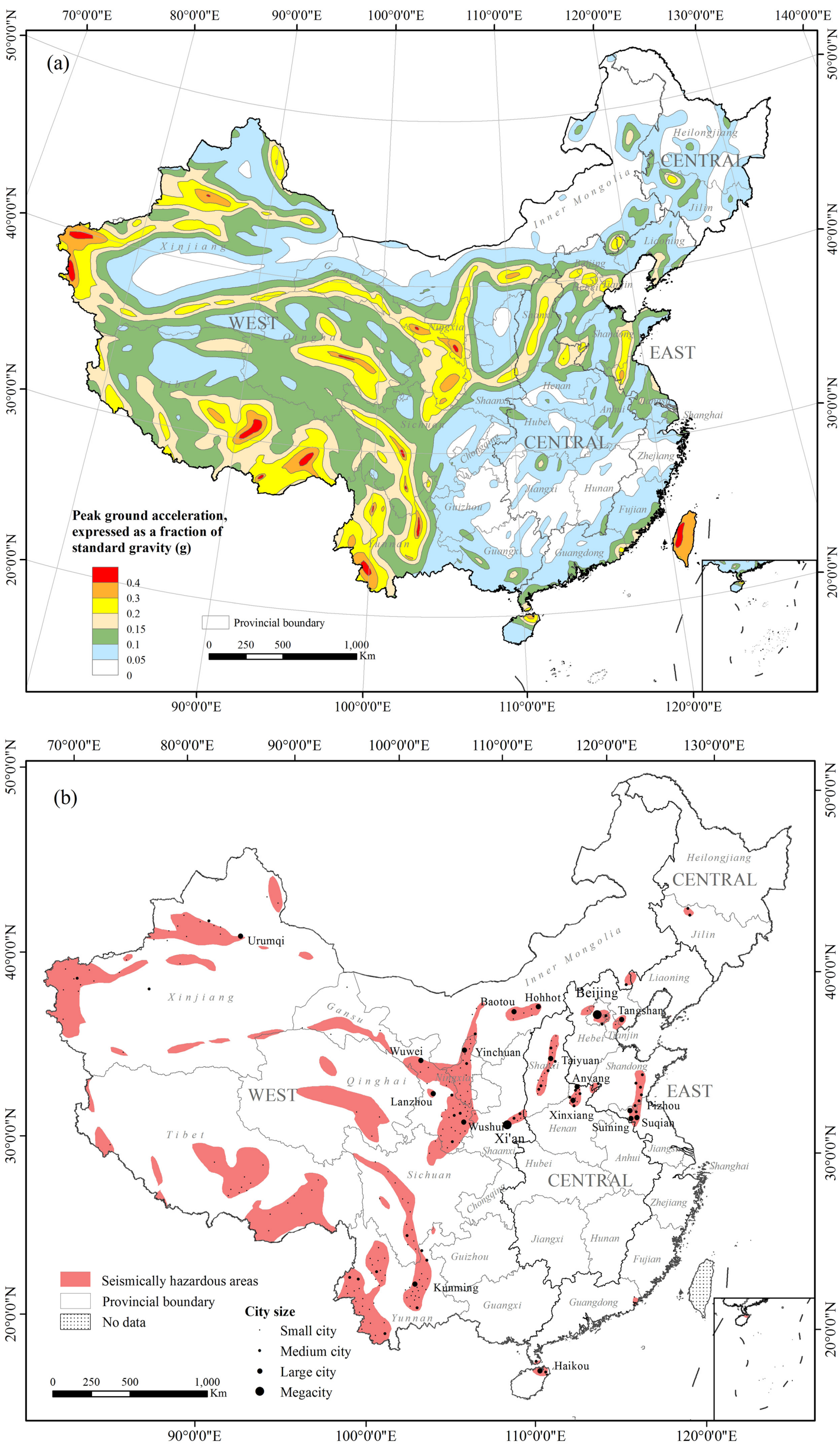


Figure 1. Seismic ground motion parameter zonation maps ((a) the peak ground acceleration with a 10% probability of exceedance in 50 years; (b) the most seismically hazardous areas with a peak ground acceleration larger than 0.2 g).

Second, the SGMPZ map (GB 18306-2015) (General Administration of Quality Supervision, Inspection and Quarantine of P.R.C 2015) was obtained from the Chinese Earthquake Administration (figure 1(a)). The map shows the distribution of the shake levels measured by the PGA; the values have a 10% chance of being exceeded during a period of 50 years in China. The SGMPZ map also provides

Table 1. Population exposed to the most seismically hazardous areas in 2010 (population unit: million).

Area	City size	Total population	Children	Elderly	Working age population
Most seismically hazardous areas	Me	25.33	1.26	1.12	22.95
	La	31.57	2.47	2.15	26.95
	Me	29.43	2.89	2.50	24.04
	Sm	42.88	4.46	4.06	34.36
	Total	129.21 (100%)	11.09 (8.58%)	9.83 (7.61%)	108.29 (83.81%)
Mainland China	Me	159.35	8.83	7.68	142.84
	La	366.86	32.27	26.83	307.76
	Me	445.78	43.95	36.01	365.81
	Sm	360.82	35.44	31.01	294.37
	Total	1332.81	120.49	101.53	1110.79

Note: Me—mega CLAU (county-level administrative unit); La—large CLAU; Me—medium CLAU; Sm—small CLAU. The number in the brackets are the proportion of exposed population for each age-group to the total exposed population.

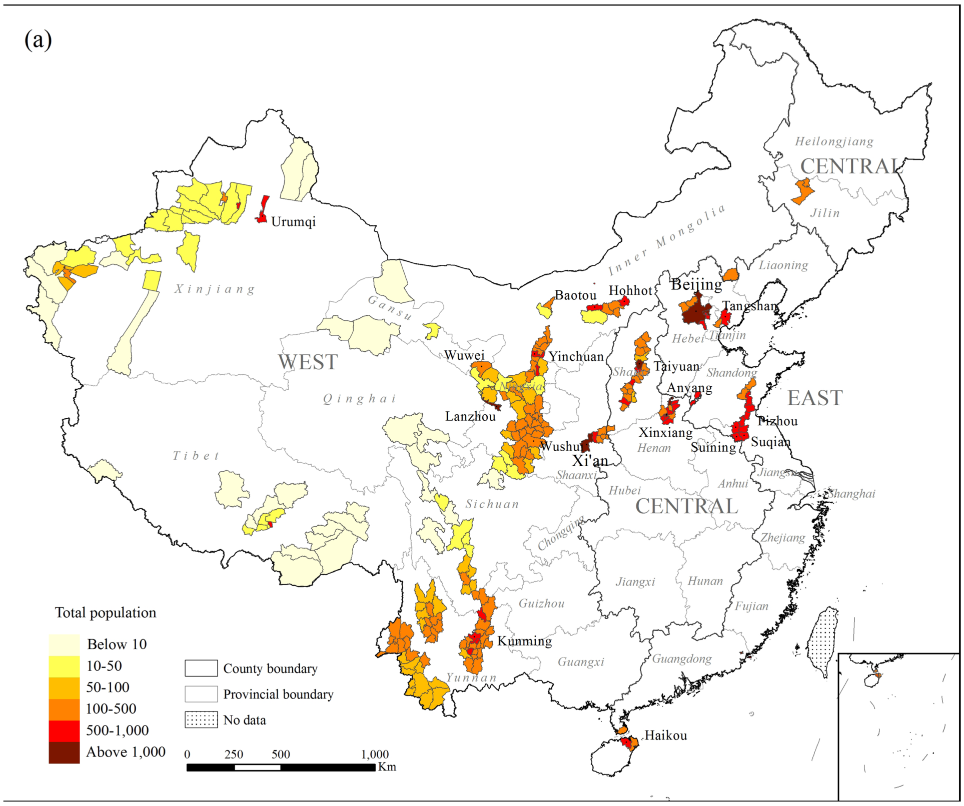


Figure 2. Population density in the most seismically hazardous areas in 2010 in China ((a): total population; (b): elderly people, age >65; (c): children, age <=14, unit: people per km^2).

building codes for buildings and other infrastructures that can withstand different levels of shaking from earthquakes.

Third, the administrative boundary data of all provinces, cities, and counties in China at a scale of 1:400 0000 were gathered from the National Geomatics Center of China. Taiwan, Hong Kong, and Macao were excluded from this study owing to the lack of census data.

2.2. Determination of MSHAs

MSHAs were determined based on the classification in the SGMPZ map (figure 1(b)). MSHAs correspond to areas with seismic impacts greater than degree VIII according to the national standard (GB-T 17742-2008) of the Chinese Seismic Intensity Scale (General Administration of Quality Supervision, Inspection and Quarantine of P.R.C, and Standardization Administration of the People' Republic of China 2008). Following the criterion used by Holzer and Savage (2013), this research defined MSHAs as those areas with a PGA value of ⩾0.2 g.

2.3. Analysis of population change in MSHAs

Population changes in MSHAs were analyzed at the national, regional, and county levels. At the regional

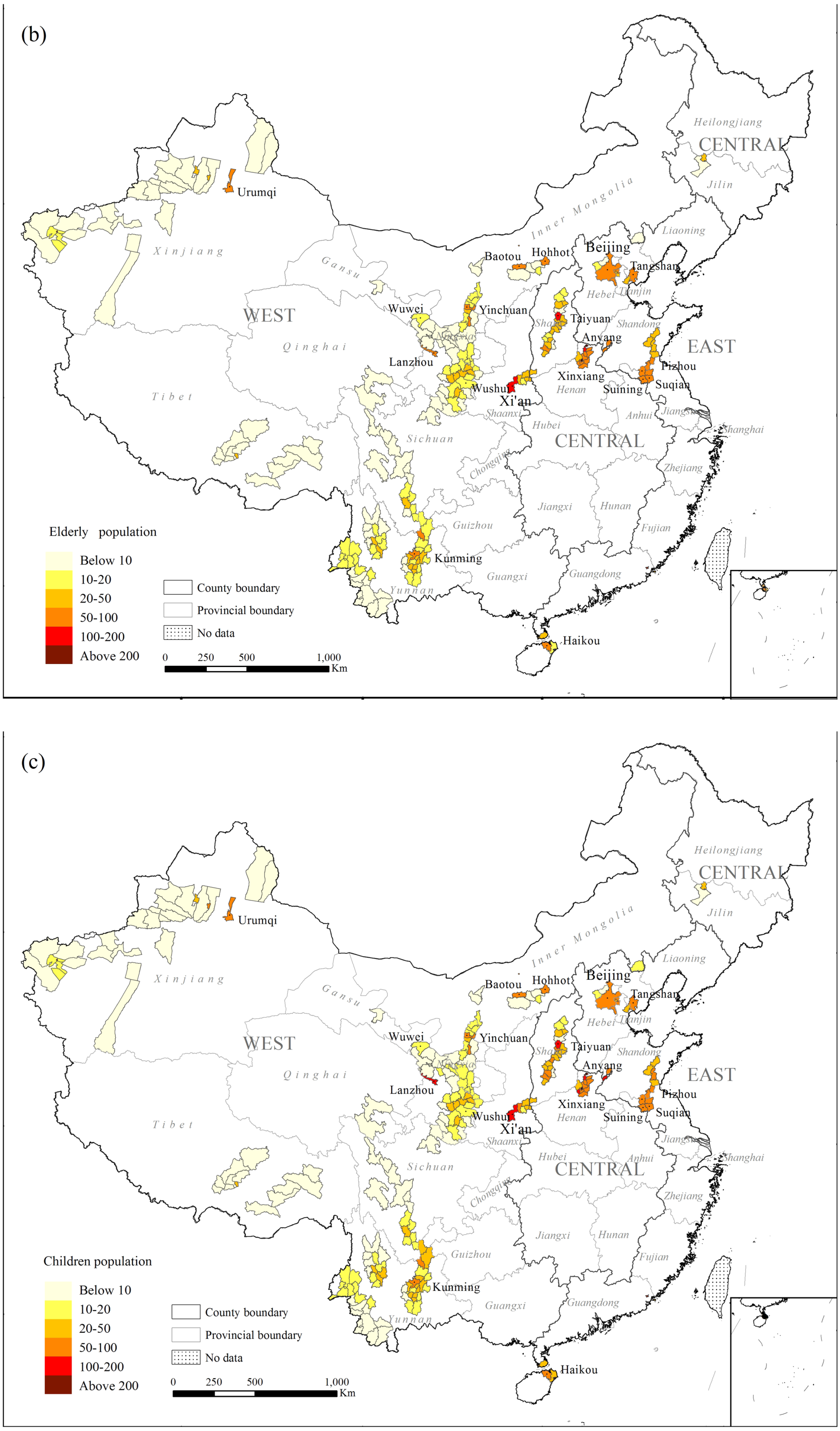


Figure 2. (Continued.)

level, the nation was divided into three economic zones (i.e., western, central, and eastern China) following the definition of the Chinese Ministry of Housing and Urban–Rural Construction. At the county level, the method proposed by Liu *et al* (2014) was applied to incorporate the boundary changes between 1990 and 2010. The administrative boundaries from 2010 to 1990 were traced to determine if the administrative boundaries of districts under the same city jurisdiction could be merged into a single

Table 2. Population change in the most seismically hazardous areas from 1990 to 2010 (population unit: million).

Area	City size	Total population	Children	Elderly	Working age population
Most seismically hazardous areas	Me	10.91 (75.6%)	−1.77 (−58.4%)	0.26 (30.2%)	12.43 (118.2%)
	La	11.75 (59.3%)	−1.98 (−44.5%)	1.27 (144.3%)	12.46 (86.0%)
	Me	4.96 (20.3%)	−4.24 (−59.5%)	1.19 (90.8%)	8.01 (50.0%)
	Sm	4.91 (12.9%)	−7.20 (−61.7%)	1.69 (71.3%))	10.41 (43.5%)
	Total	32.53 (33.6%)	−15.18 (−57.8%)	4.41 (81.4%)	43.30 (65.8%)
Mainland China	Total	200.43 (17.7%)	−286.64 (−70.4%)	37.65 (58.9%)	449.23 (67.9%)

Note: Me—mega CLAU (county-level administrative unit); La—large CLAU; Me—medium CLAU; Sm—small CLAU.
The numbers in the brackets are the percentage of change, which is calculated as $(P_{2010} - P_{1990})/P_{1990}{}^{*}100\%$, whereas P_{2010} and P_{1990} refer to the population in 2010 and 1990, respectively.

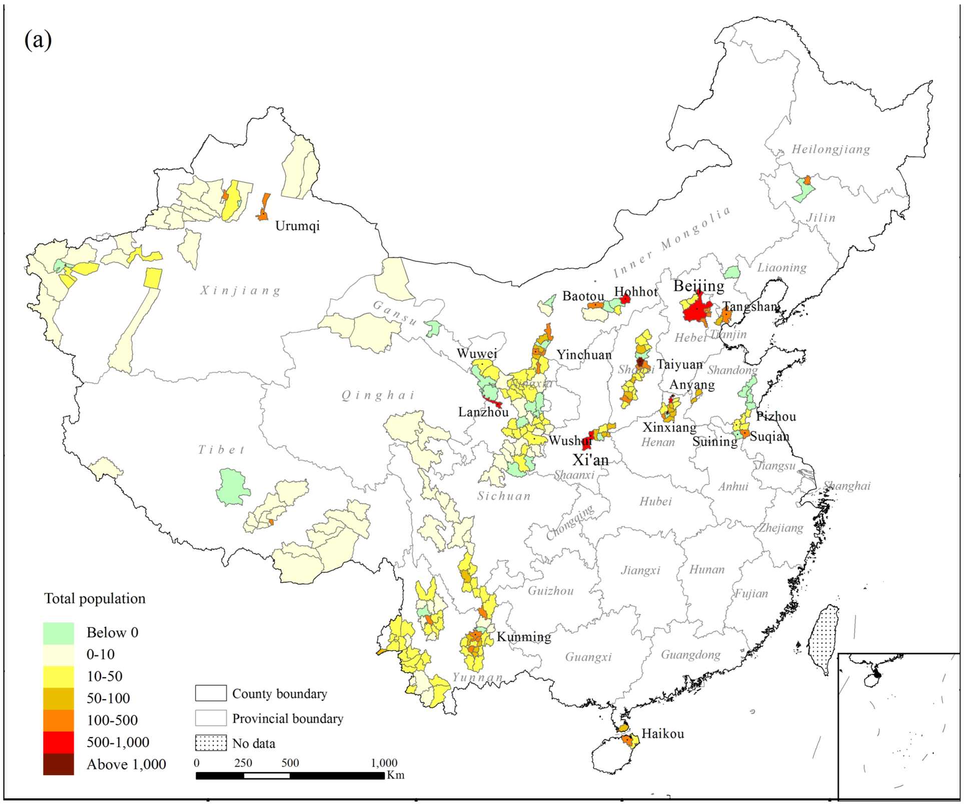


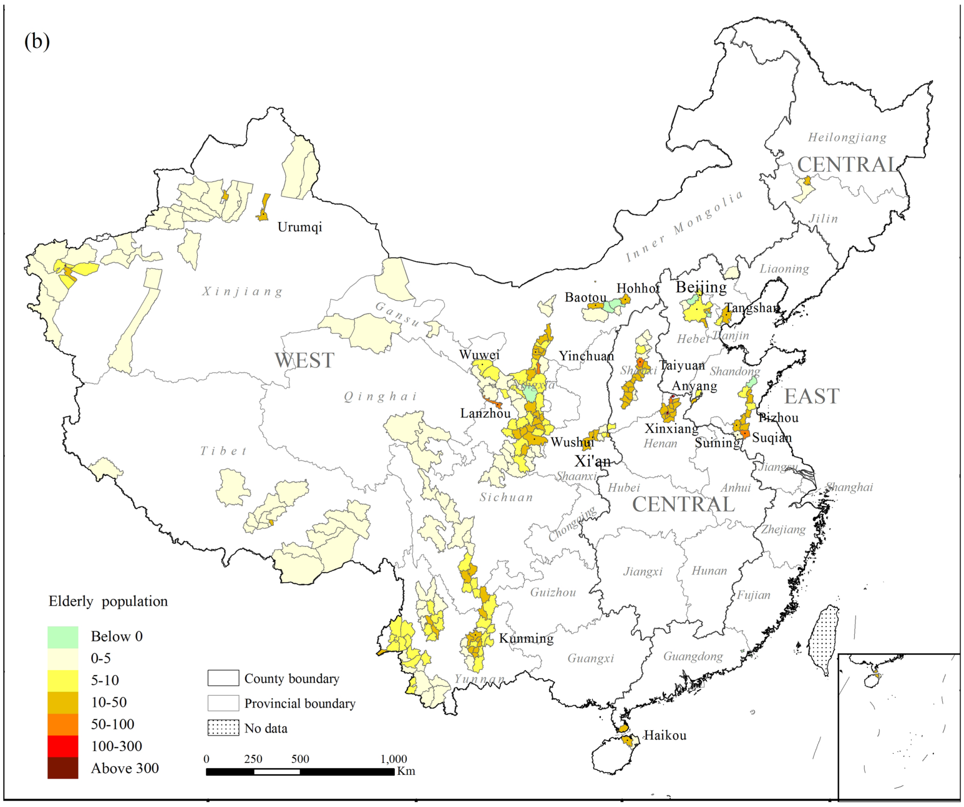
Figure 3. The change of population density from 1990 to 2010 in the most seismically hazardous areas in China (a): total population; (b): elderly people, age >65; (c): children, age <=14, unit: people per km^2).

boundary. Thus, a total of 2287 CLAUs were created for the convenience of analyses. To facilitate the comparison of the population exposed to seismic hazard among differently sized cities, these 2287 CLAUs were further classified into four categories according to the population size based on the 'New Urbanization Plan for China (2014–2020) (The Central Committee of the Communist Party of China 2014)'. The four CLAU categories were mega (total population ⩾ 5 million), large (total population ⩾ 1 million but <5 million), medium-sized (total population ⩾ 0.5 million but <1 million), and small (total population < 0.5 million). The total population in each CLAU included two general population groups: urban and rural population (figure 1(b)). The MSHA population maps of 1990 and 2000 were generated by overlaying the MSHA maps with the county-level census maps of 1990 and 2010.

3. Results

3.1. Features of MSHAs

The total area of MSHAs was 1.12×10^6 km^2 in 2010, accounting for 11.86% of China's total land area (figure 1(b)). A large portion of MSHAs (92.98%) are located in western China, and 4.21% and 2.81% in eastern and central China, respectively. In 2010, 10.48% of all CLAUs (or approximately 240 CLAUs) were located in MSHAs. Among these, two were mega, 16 large, 42 medium-sized, and 172 small CLAUs.



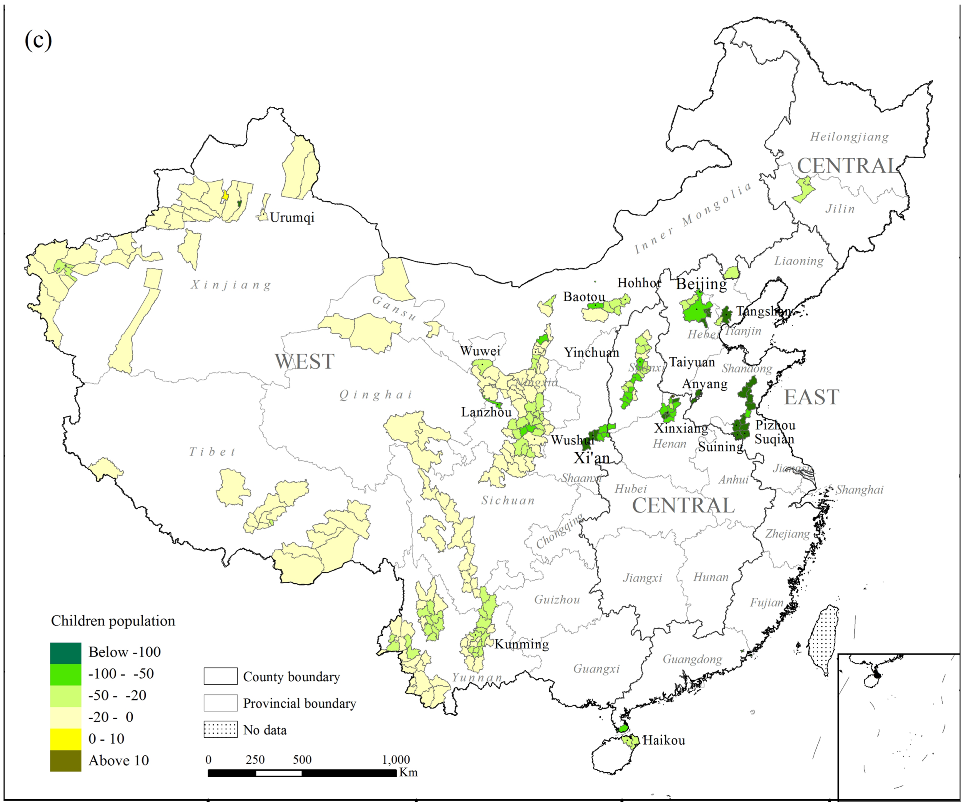


Figure 3. (Continued.)

3.2. Population characteristics in MSHAs in 2010

Approximately 129.21 million people (9.69% of China's total population), or about one in ten people, were living in MSHAs in 2010. The ten CLAUs with the largest total population had a total combined population of 47.27 million; in other words, about 36.57% of the total population living in MSHAs were in either mega or large CLAUs. Of these ten CLAUs, three (Beijing, Tangshan,

Table 3. Urban population change in the most seismically hazardous areas from 1990 to 2010 (population unit: million).

Area	City size	Population in 1990	Population in 2010	Change of population	Percentage of change (%)
Most seismically hazardous areas	Me	8.77	21.65	12.88	146.9
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	Me	3.83	12.02	8.19	213.8
	Sm	4.95	14.40	9.45	190.9
	Total	27.98	72.52	44.54	159.2
Mainland China	Total	238.75	670.00	431.25	180.6

Note: Me—mega CLAU (county-level administrative unit); La—large CLAU; Me—medium CLAU; Sm—small CLAU.
The percentage of change, which is calculated as $(P_{2010} - P_{1990})/P_{1990}{}^{*}100\%$, whereas P_{2010} and P_{1990} refer to the population in 2010 and 1990, respectively.

and Haikou) were in eastern China, one (Taiyuan) was in central China, and six (Xian, Kunming, Urumqi, Lanzhou, Baotou, and Hohhot) were in western China. Nearly 42.88 million, or about one third of the total population living in MSHAs, were in small CLAUs (table 1). In addition, the population density of MSHAs has notable spatial variation. The population density increased from 67 people per km^2 in western China to 715 and 865 people per km^2 in central and eastern China, respectively (figure 2(a)).

As for the age groups of the MSHA population in 2010, 108.29 million were working-age adults, accounting for approximately 83.81% of the total MSHA population. Meanwhile, 9.83 million elderly people (aged 65 and above) lived in MSHAs, accounting for nearly 8% of the total MSHA population. About 4.06 million elderly individuals and 4.46 million children who lived in MSHAs, representing 40% of the total MSHA population in their respective age groups, lived in small CLAUs in 2010.

The density of the elderly MSHA population in central, western, and eastern China was 27, 14, and 2 people per km^2, respectively. The population density also tended to be higher in mega and large CLAUs (figure 2(b)). The cities with the highest elderly population density include Xinxiang (401 people per km^2), Anyang (384 people per km^2), Taiyuan (144 people per km^2), Xian (101 people per km^2), and Lanzhou (90 people per km^2).

3.3. Population change in MSHAs between 1990 and 2010

The total MSHA population increased from 96.69 million people in 1990 to 129.21 million people in 2010. The rate of change (33.63%) was significantly higher than the overall national population increase in China of 17.7% during the same period (table 2). In other words, of every 100 people in China, 8.5 lived in MSHAs in 1990, and this number rose to 9.7 in 2010.

Nearly two thirds (20.64 million people) of the total increase in the MSHA population between 1990 and 2010 can be attributed to the ten largest CLAUs. Further, seven of these ten CLAUs were in western China: Xian, Urumqi, Kunming, Hohhot, Lanzhou, Baotou, and Yinchuan (figure 3(a)). The net growth of the MSHA population in seven CLAUs ranged from 0.79 to 2.20 million. In eastern and central China, the population growth in Beijing, Taiyuan, and Zhuhai were higher than that in other CLAUs (figure 3(a)).

From 1990 to 2010, the elderly population in the MSHA increased by 81.4% (or by 4.41 million), more than 20% higher than the overall national growth rate (58.9%). More than a third of the increase in the elderly MSHA population resided in small CLAUs (table 2).

Of the ten CLAUs with the highest increase in elderly population density, nine were located in central and western China (figure 3(b)). As for individual cities, the density of the elderly population in Anyang, Xinxiang, and Taiyuan in central China all increased by more than 89 people per km^2; that in Lanzhou, Yinchuan, and Hohhot in western China all increased by nearly 43 people per km^2, and that in Suqian increased by 64 people per km^2. In addition, although mega and large CLAUs had significant overall increase in total MSHA population, they had a smaller increase in density of elderly people compared with a number of small CLAUs. For example, the density of elderly people in Beijing increased by only nine people per km^2 (figure 3(b)).

4. Discussion

4.1. Significant increase in the MSHA population in conjunction with China's rapid urbanization

China's rapid urbanization plays an important role in the population increase in MSHA. First, MSHAs had higher level of urbanization compared with the national average. In 2010, 56.12% of the MSHA population resided in urban areas, compared with the national proportion of 50.27%. The population growth rate in MSHA (33.63%) is also faster than the national average rage of 17.7% over the past two decades. A significant proportion (63.57%) of the urban MSHA population lived in mega and large

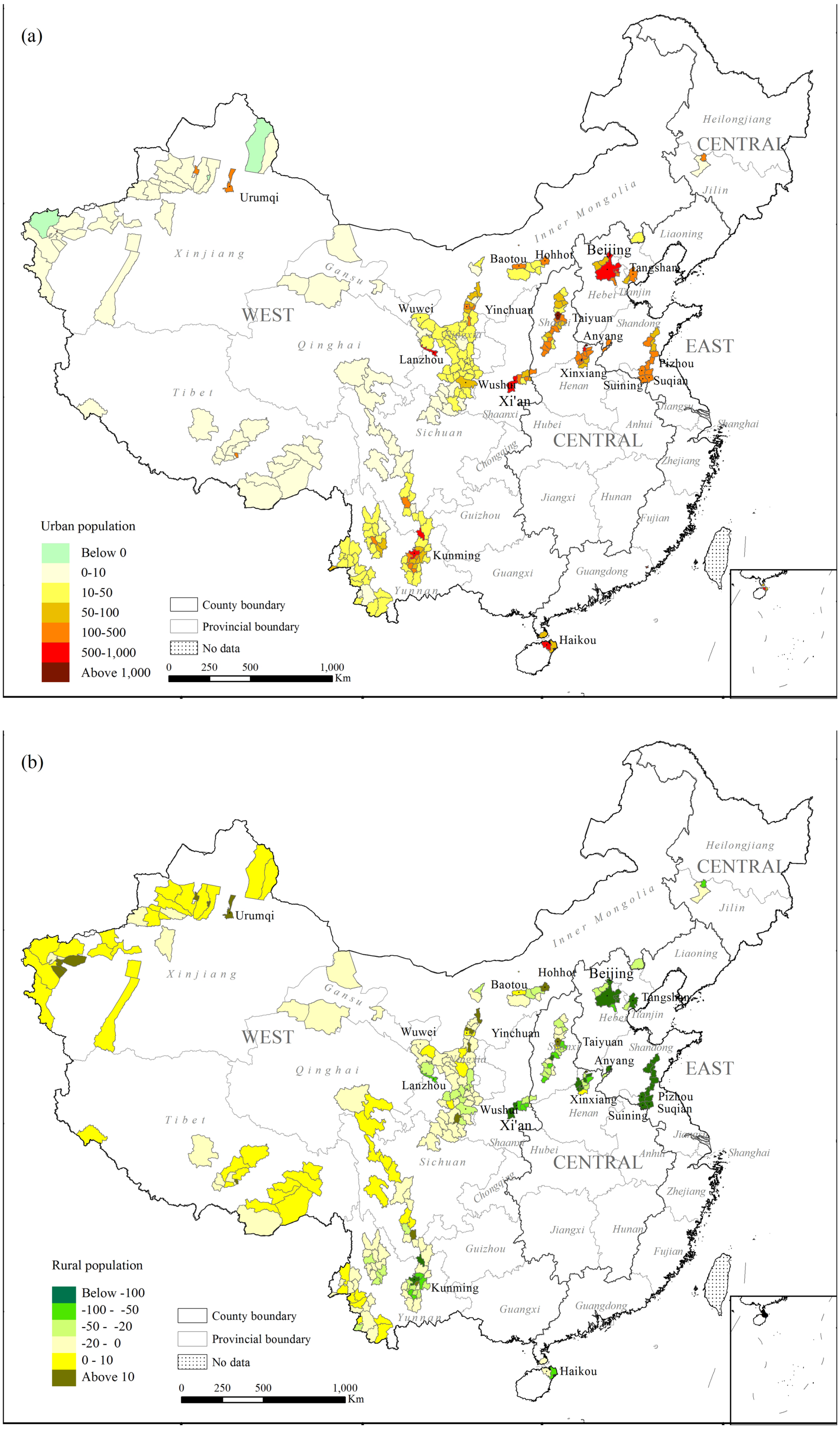

Figure 4. The change of urban and rural population density from 1990 to 2010 in the most seismically hazardous areas in China (a): urban population; (b): rural population, unit: people per km^2).

CLAUs, primarily Beijing, Xian, Taiyuan, Lanzhou, and Tangshan (table 3, figure 4(a)).

Second, the rural MSHA population decreased from 68.70 million in 1990 to 68.70 million in 2010, representing a 17.5% decline (table 4). The decrease rate was slower than the national rate of 25.8% during the same period. In addition, the rural MSHA population had slower decrease rates in the smaller CLAUs

Table 4. Rural population change in the most seismically hazardous areas from 1990 to 2010 (population unit: million).

Area	City size	Population in 1990	Population in 2010	Change of population	Percentage of change (%)
Most seismically hazardous areas	Me	5.65	3.68	−1.97	−34.9
	La	9.39	7.12	−2.27	−24.2
	Me	20.64	17.42	−3.22	−15.6
	Me	33.02	28.48	−4.54	−13.7
	La	68.70	56.70	−12.00	−17.5
Mainland China	Me	893.63	662.81	−230.82	−25.8

Note: Me—mega CLAU (county-level administrative unit); La—large CLAU; Me—medium CLAU; Sm—small CLAU.
The percentage of change, which is calculated as $(P_{2010} - P_{1990})/P_{1990} \times 100\%$, whereas P_{2010} and P_{1990} refer to the population in 2010 and 1990, respectively.

(15.6% and 13.7% in medium-sized and small CLAUs, respectively) compared with the large CLAUs (34.9% and 24.2% in mega and large CLAUs, respectively). Opposite to the trend of declining rural MSHA population, several medium-sized and small CLAUs in provinces in western China, including Xinjiang, Tibet, Sichuan, Yunan, and Gansu, witnessed growth in the rural MSHA population.

4.2. Populations living in the MSHA are subject to significant seismic risk

Populations living in the MSHA are subject to significant seismic risk in the context of China's fast urbanization. Historical data from China indicate that the Earthquakes occurring in China's MSHAs can be characterized by high frequency, high intensity, and high fatality. From 1990 to 2009, more than half of the 227 earthquakes in China with a *Ms* value greater than or equal to 5.5 occurred in MSHAs. For earthquakes with a *Ms* value equal to or greater than 7, 75% were found in MSHAs (figures 5(a), (b)) (Storchak *et al* 2015). In addition, three of the four earthquakes with a total fatality over 10 000 people occurred in MSHAs, including the 1920 Haiyuan earthquake, the 1927 Gulang earthquake, and the 1976 Tangshan earthquake. The total death toll of the three earthquakes alone amount to almost half a million residents (Liu 2013).

If the rate of urbanization between 1990 and 2000 continues, the total urban population in China will increase by approximately 330 million in the next two decades (Peng 2011). Consequently, the urban MSHA population would increase by 33 million by the year 2030, representing a nearly four-fold boost of the figure in 1990. In addition, the elderly population is expected to grow at an accelerating rate in the next two decades. Along with the rapid urbanization, the proportion of the elderly population at the national level is projected to increase from 10% in 2010 to approximately 20% in 2035 (Peng 2011). If the growth rate of the elderly MSHA population remains greater than the national average, the MSHA population will mostly likely experience a higher aging rate compared with the national average in the next 20 years. Therefore, we suggest that the Chinese government should pay greater attention to the demographic changes in earthquake-prone areas (Nelson and French 2002, Suganuma 2006, Hosseini *et al* 2009, Dan *et al* 2014).

It is also worth noting that the sheer increase in the population exposed to seismic hazard does not necessarily lead to increase in risk. It is generally recognized that the seismic risk is a convolution of the hazard, the exposure, and the vulnerability of the exposure (Chen and Shi 2007). In other words, at a given earthquake hazard, if the vulnerability is reduced due to the implementation of better building standards, the overall risk might be lower even through the population exposure has increased. For instance, the increased population exposed to seismic hazard in the urban areas might face lower seismic risk because of the more stringent building standards in cities. Therefore, the dynamics of seismic vulnerability in the MSHA should be analyzed in the future to get a full picture of seismic risk change in China.

4.3. Limitations

Nonetheless, the current study has several limitations and the results from this study should be interpreted with caution. Although the most up-to-date publicly available data were used to estimate the population exposed to earthquake hazard, uncertainties remain inevitable in the calculations. Neither the 2010 CPC nor the new SGMPZ map was completely free of errors. For example, researchers have argued that the seismic hazard estimation using the probabilistic seismic hazard analysis (e.g., SGMPZ map) might have some limitations (Castaños and Lomnitz 2002, Kossobokov and Nekrasova 2012, Wyss *et al* 2012). However, this study intends to analyze the dynamics of population exposed in the MSHA rather than to estimate the exact risk or fatalities in these areas. Therefore, using the SGMPZ map would not affect the main findings. In the future, an overlap of maps based on the probabilistic seismic hazard analysis and the neo-deterministic approach (NDSHA) could lead to a

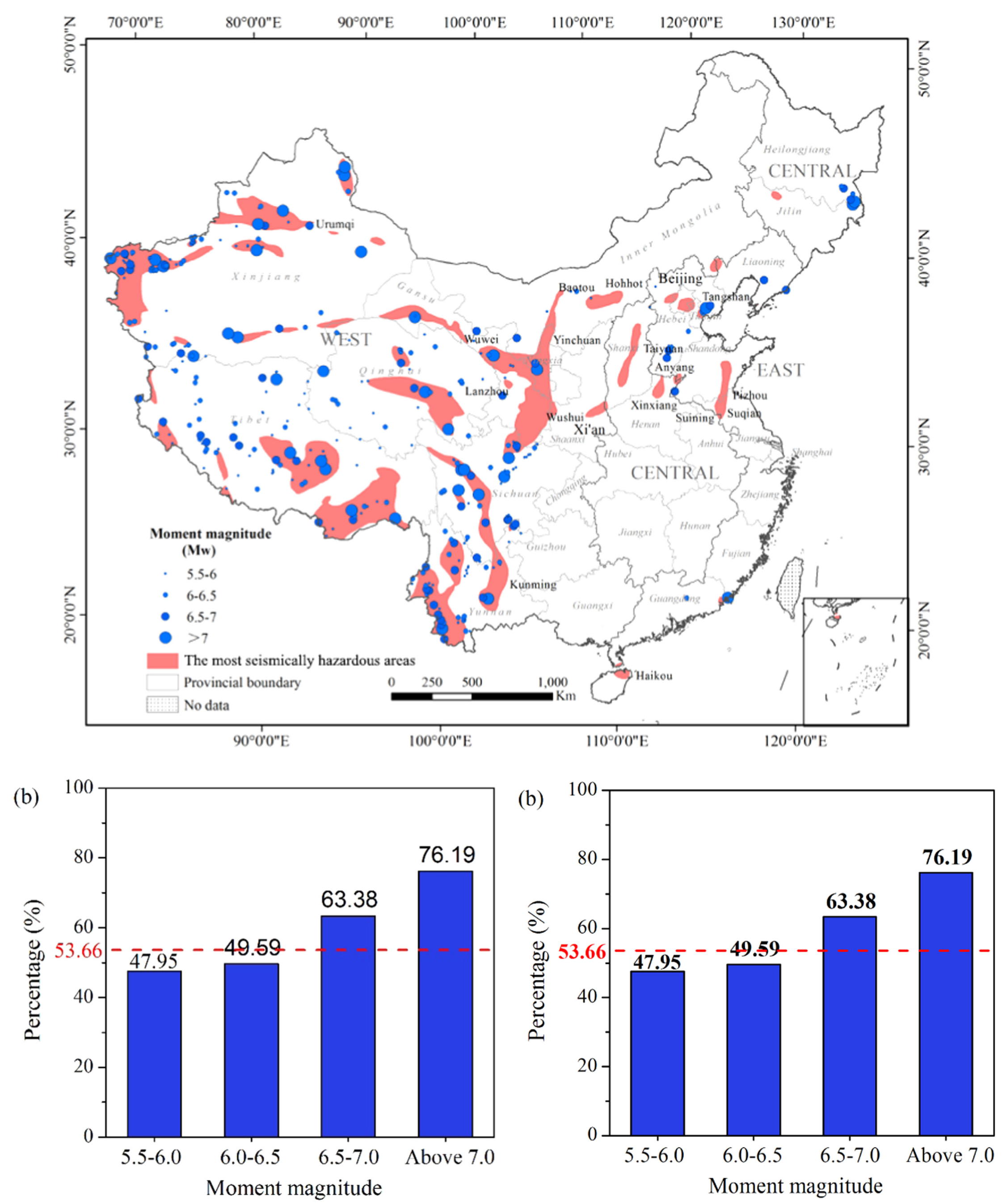

Figure 5. The earthquakes in China from 1900 to 2009 ((a): the spatial distribution; (b): the proportion of earthquakes occurred in the most seismically hazardous areas by the moment magnitude, the red dash line represents the the proportion of earthquake with a moment magnitude equal to or greater than 5.5 occurred in the most seismically hazardous areas).

more comprehensive estimation of population exposure in the seismic hazardous areas (Panza *et al* 2013). In addition, although effective, the simple overlapping analysis is a deterministic method that yields an output layer from multiple input layers (i.e., population and SGMPZ map). All input variables have been given specific values, but in reality, these variables are more likely to have intermediate and/or varying values. A possible improvement in the future is to apply a fuzzy logic-based overlay to produce probability-based output (Keramitsoglou *et al* 2013).

Meanwhile, this study examined only seismic hazard, one of many natural hazards that threaten human population. To formulate a comprehensive prevention and adaptation strategy for natural hazards, population estimation should account for simultaneous exposure to multiple natural hazards (Güneralp *et al* 2015). Moreover, an increase in the population exposed to seismic hazard does not necessarily result in an increase in earthquake fatalities and damage. The total earthquake-induced losses and damages are subject to multiple factors, such as the characteristics of the earthquake, actual population distribution in an earthquake zone, and quality of buildings and infrastructures. Nonetheless, based upon the results from the current study, it is worthwhile for the Chinese government to pay more attention to the demographic changes in MSHAs to mitigate the seismic risk.

5. Conclusions

Rapid urbanization has led to a substantial growth in the MSHA population in China between 1990 and 2010. The total MSHA population grew from 96.69 million to 129.21 million, a growth rate of 33.63%, over the two decades. The rate of increase was almost twice the national population growth rate of 17.7%. Further, the growth rate of the elderly population in MSHAs was more than 80%, the highest of the three studied age groups.

Historical records show that the MSHA population is much more vulnerable to significant seismic hazards in China. If the current trend of China's rapid urbanization holds, the population exposed in MSHA in the future will continue to increase, especially the urban population and elderly population. Thus, the Chinese government should pay greater attention to the demographic changes in MSHAs.

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