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Human footprint in Tibet: Assessing the spatial layout and effectiveness of nature reserves

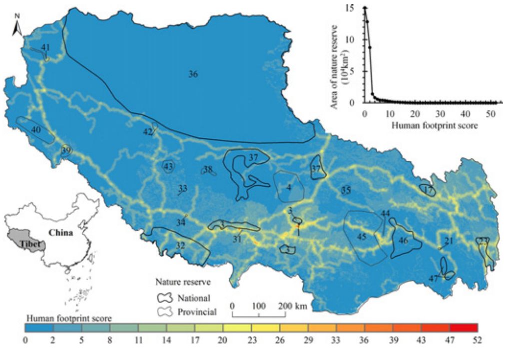
Shicheng Li [a,b,*], Jianshuang Wu [c], Jian Gong [a,d], Shaowei Li [b]

[a] Department of Land Resource Management, School of Public Administration, China University of Geosciences, 430074, Wuhan, China
[b] Institute of Geographic Sciences and Natural Resources Research, CAS, Beijing 100101, China
[c] Freie Universität Berlin, Institute of Biology, Biodiversity/Theoretical Ecology, Altensteinstraße 34, 14195 Berlin, Germany
[d] Key Labs of Law Evaluation of Ministry of Land and Resources of China, 430074 Wuhan, China

HIGHLIGHTS

- Tibet is not disturbed much by human activities now, but it is threatened by increasing human pressures.
- Grazing and road disturbance intensity contribute significantly to the increase of human footprint.
- The spatial layout of nature reserves is rational overall in terms of human footprint.
- The establishment of nature reserves in Tibet is effective in reducing human activities.
- No leakage phenomenon occurs in the surrounding regions of the Yarlung Zangbo Grand Canyon reserve.

GRAPHICAL ABSTRACT



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ABSTRACT

Humanity is causing dramatic changes to the Earth, and we may be entering a human-dominated era referred to as the Anthropocene. Mapping the human footprint and assessing the spatial layout and effectiveness of protected areas facilitate sustainable development. As the core region of the third pole, Tibet is an important area for biodiversity and the provision of ecosystem services. In this study, five categories of human pressure were summed cumulatively to map the human footprint in Tibet for 1990 and 2010, and the spatial relationship between the human footprint and national and provincial nature reserves (NRs) in Tibet was analyzed. In addition, the human footprint map was also used to evaluate the effectiveness of national and provincial NRs for reducing the impact of human activities. A comprehensive assessment was undertaken for the Yarlung Zangbo Grand Canyon (YZGC) NR. There were several key findings from this study. First, the human footprint scores (HFS) in Tibet for 1990 and 2010 were low, and increased by 32.35% during 1990–2010, which was greater than the global value of 9% for 1993–2009, indicating that Tibet is seriously threatened by human pressure. Grazing intensity and road disturbance intensity contributed significantly to the increase in the HFS. Second, the average HFS for 1990 in NRs was lower than that for the entire Tibet, but the spatial layout and extent of some reserves (e.g., the Qomolangma NR) needs to be optimized further. Third, the establishment of NRs in Tibet was effective in reducing human activities. No leakage phenomena were identified in the regions surrounding the YZGC reserve. However, the management of NRs in Tibet is still challenging in terms of reducing human activities.

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* Corresponding author at: 388 Lumo Road, Hongshan District, Wuhan 430074, Hubei, China.
E-mail addresses: lisc@cug.edu.cn, lisc.10s@igsnrr.ac.cn (S. Li), wujs07s@zedat.fu-berlin.de (J. Wu), gongjian@cug.edu.cn (J. Gong), leesw@igsnrr.ac.cn (S. Li).

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1. Introduction

Human activities have dramatically altered, and thus exposed great pressure to the ecosystems of the Earth (Vitousek et al., 1997). These alterations have been accelerated since the industrial and green revolutions (Motesharrei et al., 2016). The concept of the Anthropocene, which is a new era dominated by human activities, has been proposed (Waters et al., 2016). Many researchers have attempted to map the human footprint, which denotes the total of the ecological footprints of human population, represented by the work of the global human footprint map for the 1990s (Sanderson et al., 2002). This has been updated for 1993–2006 using the latest global satellite images and ground surveys, suggesting that human beings are stewards of nature (Venter et al., 2016). The human footprint could be a useful tool to facilitate conservation planning, and is also significant for ensuring sustainable development (Burton et al., 2014; Correa Ayram et al., 2017; Tapia-Armijos et al., 2017; Woolmer et al., 2008). The human footprint method and the maps of the global datasets have been used widely (Allan et al., 2017; Gonzalez-Abraham et al., 2015; Johnson et al., 2017).

As a category of protected area enabling sustainable development, nature reserves (NRs) are designated to protect biodiversity, especially threatened species, and ecosystem services (Xu et al., 2017). The biosphere reserves of the Man and the Biosphere Program are areas comprising terrestrial, marine, and coastal ecosystems, and have been used to establish a scientific basis for the improvement of the relationships between human beings and their environments (Bridgewater and Babin, 2017). Much attention has been given to assessing the rationality of the layout and the effectiveness of NRs (De Almeida et al., 2016; Geldmann et al., 2013). For example, the creation of Urdaibai Biosphere Reserve in Spain prevented the construction of urban megaprojects that would have dramatically affected the current natural core areas (Castillo-Eguskitza et al., 2017). China's current protected areas are insufficient to prevent the loss of areas of less-disturbed habitat (Chen et al., 2017). However, most studies concerning the assessment of layout rationality and the effectiveness of NRs have been conducted from the perspective of biosphere dimension, including the protection of biodiversity and ecosystem services (Chen et al., 2017). For example, Xu et al. (2017) reported that the layout of NRs in China needs to be strengthened in terms of the protection of important ecosystem service functions, while studies concerning the human dimension are rare.

As the core region of the third pole (Yao et al., 2012), the Tibet Autonomous Region (hereafter Tibet) is an important area for biodiversity (Newbold et al., 2015) and ecosystem services (Ouyang et al., 2016; Song and Deng, 2017). Many unique ecosystems and species are located in this region. It provides water resources for a large number of human population in the world (Xu et al., 2008). Therefore, many protected areas have been established in this region to protect the fragile environment and biodiversity. The area of NRs in Tibet accounts for more than one third of the Tibet land area (Xu et al., 2017). In addition, Tibet is also highly sensitive to human activities, which means a slight human disturbance may cause serious environment degradation. In recent decades, the environment in Tibet has changed due to human activities and climate change (Li et al., 2017a; Yu et al., 2016). However, studies involving the human footprint mapping in Tibet are inadequate (Fan et al., 2015; *Zhao et al.,* 2015b; Zhong et al., 2008), with even fewer studies assessing the layout rationality and effectiveness of NRs in Tibet from the perspective of human activity.

The Ministry of Environmental Protection of China has developed a management practice referred to as “Monitoring and Verification of Human Activities in Nature Reserves Using Remote Sensing” and launched the “Green Shield 2017” inspection over national NRs in July 2017 to monitor and reduce human activities in NRs, including the over-exploitation of mineral resources, illegal construction, and operation of hydropower facilities (Ministry of Environmental Protection of the People's Republic of China, 2017). Recently, the Chinese government punished officials over environmental violations in the Qilian Mountains national NR. These actions of the central government in China indicate that there is an urgent need to assess and reduce human activities in NRs (Ma et al., 2016, Song et al., 2017).

Therefore, the aims of this study are to: 1) map the human footprint in Tibet for 1990 and 2010, and reveal their spatial and temporal characteristics; 2) analyze the spatial relationship between the human footprint and NRs at national and provincial levels in Tibet; and 3) assess their effectiveness in reducing human activities from 1990 to 2000, especially for the Yarlung Zangbo Grand Canyon (YZGC) NR.

2. Study area

Tibet lies between 26°52′N–36°32′N and 78°24′E – 99°06′E, with an area of 1.2 million km^2. The north of Tibet is a plateau consisting of the Kunlun Mountains, González Mountains, and Nianqing Tanggula Mountains. The south of Tibet contains the Yarlung Zangbo River and its tributary valleys, while the southeast is a series of alpine canyons with an almost north-south strike. The altitude generally decreases from more than 5000 m in the northwest to less than 4000 m in the southeast (Fig. 1). The region with an altitude higher than 4000 m accounts for 85.1% of the total land area (Yao et al., 2012).

In Tibet, the incoming solar radiation is strong with an annual value of 140–200 kcal/cm^2. The annual mean temperature ranges from −2.4 to 12.1 °C, and the annual mean precipitation ranges from 66.3 to 894.5 mm (http://www.gov.cn/guoqing/2013-04/08/content_5046170.htm). Both temperature and precipitation decrease from southeast to northwest. In addition, there are many rivers and lakes in Tibet (Xu et al., 2008). The vegetation types in Tibet, from southeast to northwest, are forest, meadow, grassland, desert, and alpine vegetation. Tibet is also a global hotspot of biodiversity conservation. Most of the human activities are distributed in the eastern regions and the midstream of the Yarlung Zangbo River, but the intensity of these activities is increasing (Li et al., 2017b; Zhao et al., 2015a).

By the end of 2015, there were 47 NRs in Tibet, including nine at the national level, 14 at the provincial level, and 24 at the county level (Fig. 1). The total area of NRs is currently 41.37×10^4 km^2, which is the highest among the 31 provincial-level regions in China. The area covered by NRs accounts for 34.47% of the total area of Tibet, while the corresponding figure for China is only 15.1%. According to the protection targets, the 23 national and provincial NRs in Tibet can be classified into six types: inland wetlands, forest ecosystems, wild animals, geological relics, desert ecosystems, and wild plants.

3. Materials and methods

3.1. Human footprint mapping

Taking the regional characteristics of Tibet and data availability into consideration, we tailored the global datasets method (Sanderson et al., 2002; Venter et al., 2016) and considered five categories of human pressure (population density, land use intensity, grazing intensity, road and railways, and the electricity infrastructure) to map the human footprint for 1990 and 2010 in a spatially explicit way. These pressures were weighted according to estimates of their relative levels of influence on nature.

3.1.1. Population density

Using the global datasets method (Sanderson et al., 2002) and considering the nomadic lifestyle of Tibet (Cardillo et al., 2004; Miehe et al., 2009; Woodroffe, 2000), we assigned influence scores to the population density in each grid, where the scores for densities in the range of 0–50 inhabitants/km^2 increased linearly from 0 to 10. We assigned all population densities higher than 50 inhabitants/km^2 a score of 10, which was based on the assumption that the influence of population density reached an asymptote at 50 inhabitants/km^2. The pressure of a nomadic lifestyle on the environment is less than that of a settled

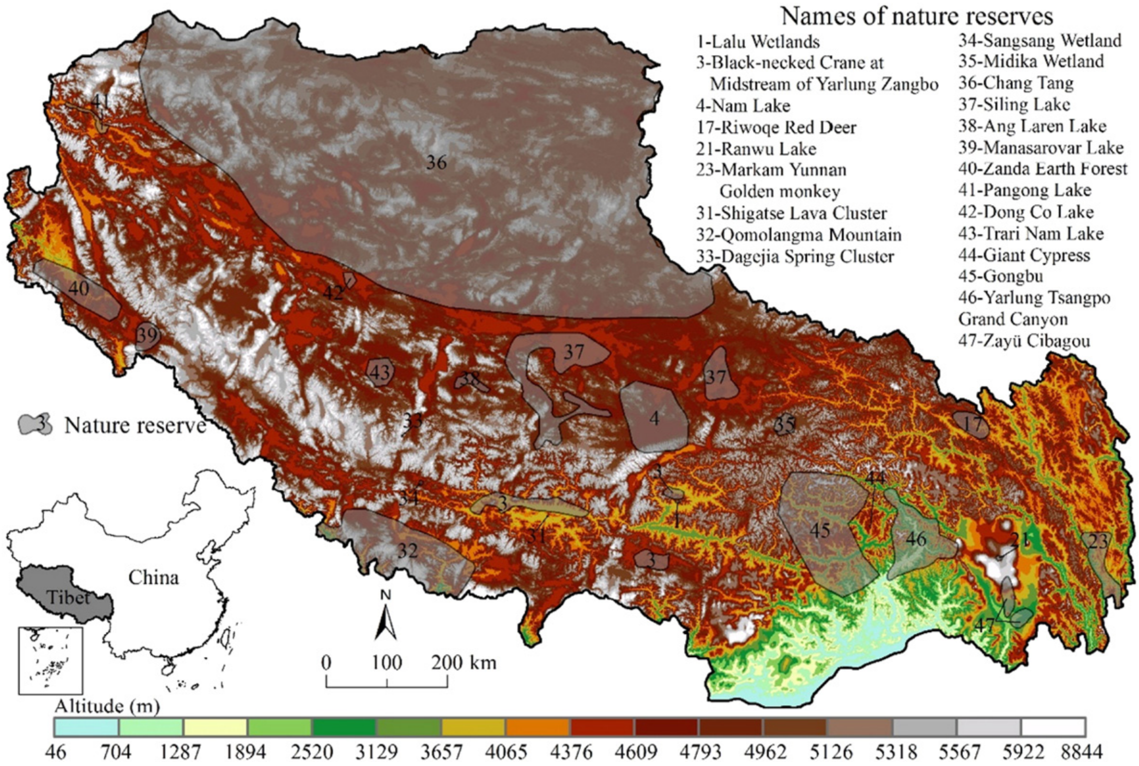

Fig. 1. Location of the study area and the distribution of national and provincial nature reserves (NRs) in Tibet. The name and code of each NR is taken from the *List of Nature Reserves in China 2015* (Department of Natural Ecological Protection of Ministry of Environmental Protection of the People's Republic of China, 2016). The altitude data were obtained from the International Scientific and Technical Data Mirror Site, Computer Network Information Center, Chinese Academy of Sciences (http://www.gscloud.cn). The spatial distribution data for NRs in Tibet were obtained from (Xu et al., 2017). The boundary data for Tibet and China were provided by the National Administration of Surveying, Mapping, and Geoinformation of China (http://en.nasg.gov.cn/).

lifestyle (Miehe et al., 2014), and therefore the asymptote was set as 50 rather than 10 inhabitants/km^2 in the global datasets (Li et al., 2017b).

The 1 km population datasets of China for 1995 and 2010 were provided by the data center for resources and environmental sciences, Chinese Academy of Sciences (http://www.resdc.cn/data.aspx?DATAID=114). The errors in the spatial population data were in the range of 4.5–13.6% (Fu et al., 2014). The population density data for 1990 were unavailable and a linear extrapolation was performed based on the total population of Tibet for 1990 (Public Order Administration of Ministry of Public Security of China, 1991) and the spatial pattern of the population for 1995 (Fu et al., 2014).

3.1.2. Land use intensity

Based on the global datasets method (Sanderson et al., 2002), the relative disturbance degree calculated in relevant studies at regional scale (Liu, 1992; Zhao et al., 2015a; Zhuang and Liu, 1997), and our own judgement regarding land-use activities in Tibet, scores were assigned to each land use type. We assigned the maximum score of 10 to built-up land, which is the land use type most influenced by humans, and lower scores to rural settlements, reservoirs/ponds, and cropland (Table 1). Tibet is one of the main pastoral areas of China, with dense grassland having the highest grazing potential, moderate grassland having the second-highest potential, and sparse grassland having the lowest potential. Therefore, human influence scores of 2, 1, and 0 were assigned to them, respectively. We assigned a value of 0 to all other land use types, which receive little influence from humans (Li et al., 2017b).

Land use data were obtained from China's land use/cover datasets, which cover the period of 1980–2010 (Liu et al., 2014). The interpretation accuracy for the six classes of land use was above 94.3%, and for 25 subclasses it was above 91.2%. In this study, the 1 km raster format datasets for 1990 and 2010, which were provided by data center for resources and environmental sciences, Chinese Academy of Sciences, were used (http://www.resdc.cn/data.aspx?DATAID=99).

3.1.3. Grazing intensity

Tibet has one of the world's largest high-mountain grassland ecosystems and is a major pastoral area of China. Therefore, grazing intensity was considered to be a human pressure in Tibet, which was consistent with previous studies of the Tibetan Plateau (Fan et al., 2015; Zhong et al., 2008).

Table 1
Land use types (Liu et al., 2014) and the human influence scores assigned to each type based on the global datasets method (Sanderson et al., 2002), relevant studies (Liu, 1992; Zhao et al., 2015a; Zhuang and Liu, 1997), and expert judgement.

Land use type	Descriptions	Score
Built-up land	Land for urban uses, including factories, quarries, mining, transportation facilities, and airport	10
Rural settlements	Land used for settlements in villages	8
Reservoirs/ponds	Man-made facilities for water storage	8
Cropland	Cultivated lands for crops, including paddy land and dry land	7
Dense grassland	Grassland with canopy coverage greater than 50%	2
Moderate grassland	Grassland with canopy coverage between 20 and 50%	1
Sparse grassland	Grassland with canopy cover between 5 and 20%	0
Woodland	Land used for growing trees, including arbor, shrub, and bamboo	0
Streams, rivers, lakes, permanent ice, snow	Land covered by natural water bodies	0
Unused land	Land not put into practical use or difficult to use, including sandy land, Gobi, salina, swampland, bare soil, bare rock, and others	0

The 1-km grazing intensity data for Tibet was unavailable, and therefore we rasterized county-scale data (Ouyang et al., 2016). There are 74 counties in Tibet. The county-scale grazing density data for Tibet for 2000 and 2010 were obtained from the results of China's first national ecosystem changes survey and assessment (http://www.ecosystem.csdb.cn/ecogj/tpcclasses_detail.jsp?id=EA1304CD2A799690CF51D02F72F7707F). Because the grazing intensity data for 1990 were unavailable, we conducted a linear extrapolation based on the data for 2000 and 2010 and the facts that the number of livestock and grazing intensity have been increasing in Tibet in recent decades (Fan et al., 2015). Before the summation of influence scores, the county-scale grazing intensity was converted into a range of 0–10 based on relevant studies at regional scale (Hu et al., 2015; Li et al., 2017b; Lu et al., 2017) and Eq. (1).

$$Norgrazd(i,t) = ROUND\left[\frac{grazd(i,t)}{MAX(grazd(i,t))}\right] \times 10 \tag{1}$$

where $Norgrazd(i,t)$ is the normalized grazing density of grid i for year t and ranges from 0 to 10. $grazd(i,t)$ is the grazing density of grid i for year t, which is the rasterized county-level data.

3.1.4. Roads and railways

The vector-based road dataset for 1990 and 2010 were obtained from the Digital Line Graphic datasets provided by National Geomatics Center of China. This road dataset includes expressways, national-, provincial-, county-, and rural-level highways, and railways (National Geomatics Center of China, 2008).

Human influence scores were assigned to roads and railways based on the global datasets method (Sanderson et al., 2002), local studies regarding the influences of roads on the environment (Chen et al., 2003; Chen et al., 2007; Li et al., 2010; Li et al., 2017b), and our own judgement regarding road construction in Tibet. The construction of the highway and railway networks in Tibet has been achieved with a high priority on ecological protection (Peng et al., 2007; Zhou et al., 2008), and therefore the maximum distance in terms of the influence of roads and railways was set to 10 km rather than the 15-km used in global datasets (Table 2). Because of the high level of ecological protection incorporated into road construction projects, only the maximum value of the human influence score for roads and railways was considered if a location was influenced by many different roads. In addition, we did not use navigable waterways as global datasets did because they currently do not serve as significant transportation corridors in Tibet.

3.1.5. Nighttime lights

The high sensitivity of the Defense Meteorological Satellite Program Operational Linescan System (DMSP-OLS) provides a means for mapping the electricity infrastructure and energy development (Elvidge et al., 2001). Nighttime lights were therefore used as a proxy of the electricity infrastructure (Sanderson et al., 2002). We converted the nighttime lights into electricity infrastructure intensity and incorporated it into the human footprint. This conversion is based on the use of the 30 arc sec (~1 km) DMSP-OLS composite images for 1992 and 2010, which are provided by NOAA's National Centers for Environmental Information (https://ngdc.noaa.gov/eog/download.html), and the intercalibration and assignment method of the global datasets (Sanderson et al., 2002; Venter et al., 2016).

Table 2
Human influence scores for roads and railways based on the global datasets method (Sanderson et al., 2002), relevant studies at regional scale (Chen et al., 2003; Chen et al., 2007; Li et al., 2010; Li et al., 2017b), and expert judgement.

Type	0–1 km	1–5 km	5–7 km	7–10 km
Expressway	10	8	7	5
National-level highway	10	8	4	2
Provincial-level highway	8	6	2	0
County-level highway	6	4	1	0
Rural-level highway	4	2	0	0
Railway	9	9	5	3

3.1.6. Summation of influence scores

The assigned influence score for each pressure ranged from 0 (least influenced) to 10 (most influenced), and summation of the assigned influence scores was conducted using Eq. (2).

$$HF(i,t) = popd(i,t) + landuse(i,t) + graz(i,t) + road(i,t) + nightlight(i,t) \tag{2}$$

where $HF(i,t)$ is the cumulative human footprint score (HFS) of grid i in year t. $popd(i,t)$, $landuse(i,t)$, $grazd(i,t)$, $road(i,t)$, and $nightlight(i,t)$ are the intensities of population disturbance, land use, grazing, road disturbance, and electricity infrastructure, respectively. Taking data availability into account, we mapped the human footprint with a spatial resolution of 1 × 1 km for 1990 and 2010. Note that the human footprint of 1990 actually represents that of the early 1990s because the datasets used for this year are not completely for the year of 1990.

Furthermore, we calculated the absolute changes of the human footprint over this period and identified the hotspots of human footprint change using Eq. (3):

$$\Delta HF(i,\Delta t) = HF(i,t_2) - HF(i,t_1) \tag{3}$$

where $\Delta HF(i,\Delta t)$ is the change in the HFS in grid i during Δt, $\Delta t = t_2 - t_1$; $HF(i,t_1)$ and $HF(i,t_2)$ are the HFSs of grid i in years t_1 and t_2.

3.2. Analysis of the spatial relationships between the human footprint and nature reserves

There are many factors that need to be considered for the establishment of NRs. These factors include not only the significance of biodiversity and ecosystem services, but also the level of economic development and human activities. A close relationship exists between human activities and biodiversity, and a high level of human activity tends to exacerbate biodiversity loss (Newbold et al., 2015).

The establishment of NRs in China lacks scientific conservation planning in the early stages (Sang et al., 2011; Zhang et al., 2017). For example, many NRs were created as an emergency measure to rescue and restore endangered species and ecosystems. To meet this need, the area of NRs in China was designated to be as large as possible, but without detailed field investigations (Zhang et al., 2017). The relationships between the spatial layout of NRs and the human footprint therefore remain unclear. In this study, we used a spatial overlap analysis between the human footprint and the distribution of national and provincial NRs in Tibet to reveal the spatial relationships between them. Human activities are limited or forbidden by law within NRs after they are created. Areas with no NRs will experience a normal level of increase in human activity. Therefore, the current human footprint can be used as an indicator to assess the management effectiveness of NRs (Section 3.3), but is not an accurate indicator to analyze the relationship between human activities and NRs. Therefore, the HFS for 1990 was used in this study to reveal quantitatively the spatial relationships between the human footprint and national and provincial NRs in Tibet. The spatial distribution of NRs in Tibet was obtained from Xu et al. (2017).

3.3. Assessment of the effectiveness of nature reserves for reducing the human footprint

We also used spatial overlay analysis to analyze the effectiveness of all national and provincial NRs in Tibet for reducing human activities. First, a comparison was made of the changes in mean HFS and the five associated categories of human pressure between the areas inside and outside all national and provincial NRs in Tibet during 1990–2010.

However, some NRs in Tibet were established later than 1990, so the comparison of changes in mean HFS for all national and provincial NRs could not completely reflect the management effectiveness of each NR, because no conservation measures were implemented from 1990 to the year when the NR was established. Therefore, we selected NRs established before 1990 and further assessed their management effectiveness.

Four NRs were established before 1990: Qomolangma (No. 32 in Fig. 1, established in 1988), Giant Cypress (No. 44 in Fig. 1, established in 1985), Yarlung Zangbo Grand Canyon (No. 46 in Fig. 1, established in 1985), and Zayü Cibagou (No. 47 in Fig. 1, established in 1985). The area of the Giant Cypress NR is only 0.08 km^2, which is too small to conduct an analysis at a resolution of 1 × 1 km. The changes in the HFS and the associated five categories of human pressures for the other three NRs were determined.

Further, we conduct a buffer analysis for the three reserves because the effectiveness of a protected area is not only due to the stabilization or reduction of human activity inside the protected area, but is also dependent on whether the human activity is moved to the surrounding area, a phenomenon known as "leakage" (Ewers and Rodrigues, 2008; Tapia-Armijos et al., 2017). However, the location of the Qomolangma NR adjoins national boundaries and the Zayü Cibagou NR contains two polygons for which it was difficult to conduct a buffer analysis. Therefore, the buffer analysis was only conducted for the YZGC NR, with an area of 9168 km^2, to assess its effectiveness for reducing human activities during 1990–2010.

To prove whether leakage was occurring in the YZGC NR, we selected a sample area that includes the reserve and its surrounding area (Fig. 2). All other NRs in the sample area were excluded to eliminate their protective effects. In this sample area, we divided the YZGC NR into three concentric zones, each with an equal area (3056 km^2), and created three concentric buffer zones outside the reserve, with the same area as the zones inside the reserve. We then randomly selected six circular zones with the same area (3056 km^2) in the sample area surrounding the reserve. These six zones were randomly selected using the random points tool in ArcGIS (Fig. 2).

The HFS both inside the reserve and in the buffer zones were compared with the average score of the human footprint in the six circular random zones, which was used as a baseline. If the difference between the HFSs inside the reserve and the baseline was greater than the difference between the HFSs in the buffer zone and the baseline, then the reserve had a positive effect in reducing human impacts. If the HFSs of the buffer zones outside the reserve were greater than the baseline, then leakage occurred (Ewers and Rodrigues, 2008).

4. Results

4.1. Spatial and temporal changes of the human footprint during 1990–2010

The HFSs ranged from 0 to 68 for 1990 and 2010, with 0 denoting the minimum human influence intensity and 68 denoting the maximum human influence intensity (Fig. 3). Generally, the HFSs in Tibet for 1990 and 2010 were low, and the percentages of grids with HFSs ranging from 0 to 2 for 1990 and 2010 were 63.53% and 54.99%, respectively. The average HFSs for 1990 and 2010 were 3.06 and 4.05 respectively. The regions with the largest HFS were the central and eastern parts of Tibet, especially the middle reaches of the Yarlung Zangbo River and the valleys containing its two tributaries (the Lhasa and the Nyang Qu Rivers).

The HFS increased by 32.35% in Tibet during 1990–2010. Grazing intensity and road disturbance contributed significantly to the increase in the HFS, with proportional contributions to the increase of 52.38 and 44.71% respectively (Table 3). In terms of the changes in the five categories of human pressures, the increased magnitude and proportional contributions of grazing intensity and road disturbance intensity were highly significant. The increase in the extent of nighttime lights made the largest proportional contribution to the total disturbance because the value in 1990 was relatively low (Table 3).

Over the two decades, the proportion of grids where the HFS increased, remained constant, and decreased accounted for 37.77%, 54.25%, and 7.98%, of the total respectively. The proportion of grids

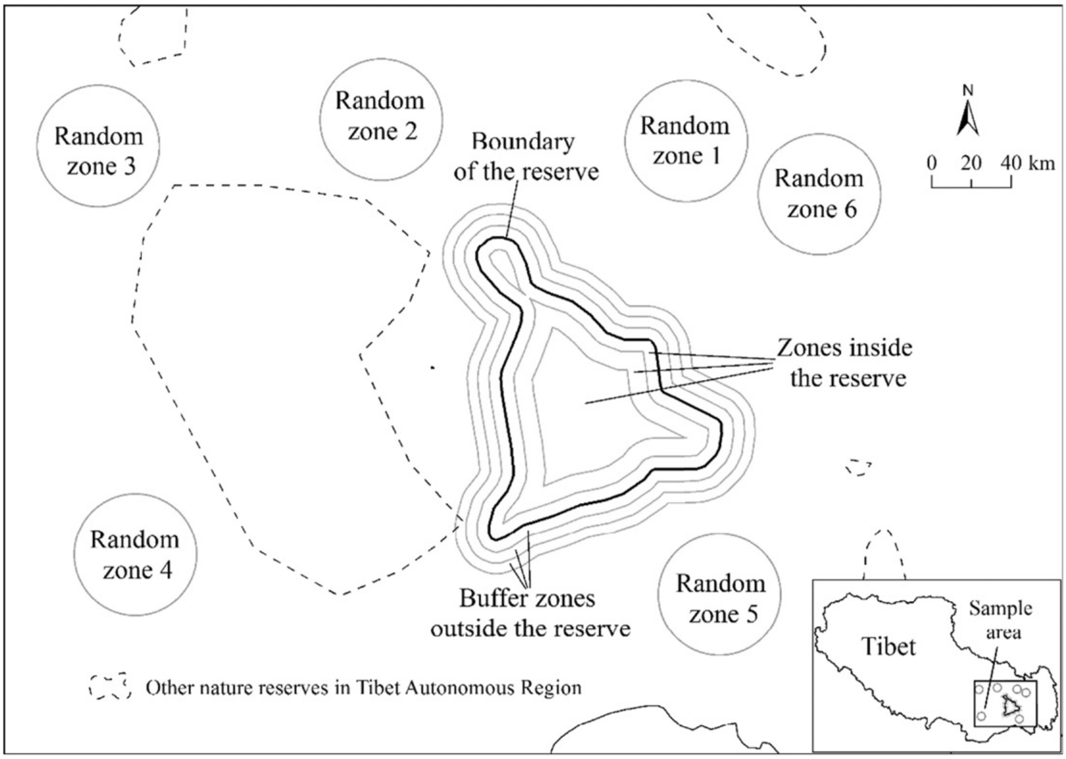

Fig. 2. The conceptual model used to evaluate the effectiveness of the Yarlung Zangbo Grand Canyon nature reserve for reducing human activities.

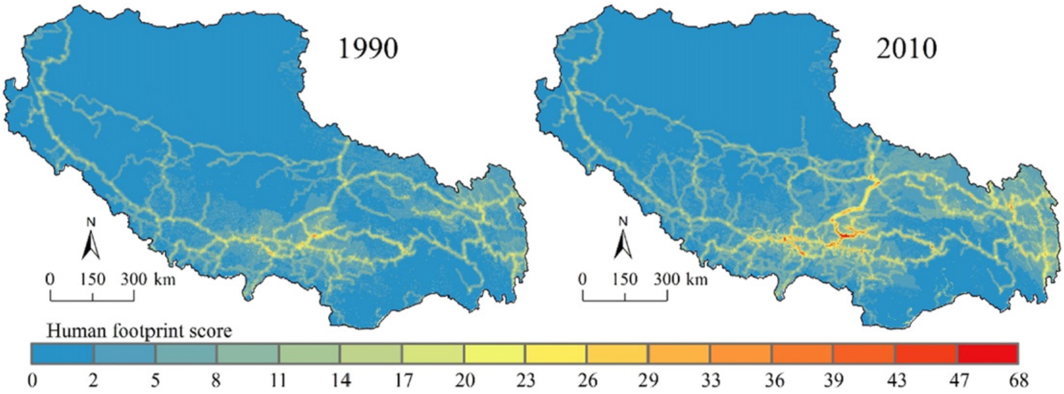

Fig. 3. Human footprint score at a spatial resolution of 1 × 1 km in Tibet for 1990 and 2010.

where the HFS increased from 0 was 5.34%, which indicates a 5.34% decline in the area of wilderness for this period.

The growth of the human footprint was uneven. The growth of the human footprint occurred mainly in the central and eastern parts of Tibet, especially the middle reaches of the Yarlung Zangbo River and the valleys of its two tributaries and the surrounding regions of major roadways and railways, including the Qinghai–Tibet highway and railway (Fig. 4). In terms of the changes in each category of human pressure, different spatial patterns of growth over the two decades could be detected. The Yarlung Zangbo River and the valleys of its two tributaries experienced population growth, the eastern and central parts of Tibet experienced growth in grazing intensity, and central Tibet also saw growth in road disturbance intensity. However, no obvious growth in land use intensity and the nighttime lights score can be detected (Fig. 4).

4.2. Spatial relationships between the human footprint and nature reserves

The national and provincial NRs are distributed evenly throughout Tibet (Fig. 5). In general, the majority of protected areas are biased to higher elevations, steeper slopes, and at longer distances to roads and cities (Joppa and Pfaff, 2009). However, many NRs are also located in central Tibet, even in the middle reaches of the Yarlung Zangbo River and the valleys of its two tributaries, which are the core areas of human activities in Tibet. The area of this core region is about 6.65×10^4 km^2, accounting for only 5.53% of the area of Tibet. However, its cropland area accounts for 45% of the total in Tibet and its population accounts for about one third of the total population of Tibet (Zhang et al., 2013).

The spatial distribution of national and provincial NRs was overlaid with the human footprint for 1990 (Fig. 5a). The average HFS for the 22 national and provincial NRs in Tibet (excluding Giant Cypress NR) was 1.60, which was lower than the average HFS of 3.06 for the entire Tibet. In addition, as the HFS increased, the associated area of NRs decreased (Fig. 5b). The area of NRs with a HFS ranging from 0 to 2 was 36.76×10^4 km^2, accounting for 87.41% of the area of all NRs in Tibet. The area covered by grids with a HFS of 3 was 1.44×10^4 km^2. The area of NRs with a HFS greater than 3 was 3.86×10^4 km^2, only accounting for 9.18% of the area of Tibet. The maximum HFS within NRs was 27, which is lower than the maximum HFS in Tibet. This indicates that when these NRs were established, the HFS within them were generally lower.

The mean HFSs within each NR were calculated (Table 4). There were only 10 of the 22 national and provincial NRs in Tibet (not including Giant Cypress NR) whose HFSs were lower than the mean value for Tibet, implying that a contradiction may exist between human activity and ecological conservation in some NRs. It can also be seen that the HFSs of NRs located in western Tibet were lower; for example, the HFSs of Chang Tang (No. 36 in Fig. 5), Zanda Earth Forest (No. 40 in Fig, 5), and Siling Lake (No. 37 in Fig. 5) NRs were 0.88, 1.64, and 1.80 respectively. The HFSs of NRs distributed in central and eastern Tibet tend to be larger, including the Lalu Wetlands, Black-necked Crane at mid-stream of the Yarlung Zangbo, and Markam Yunnan Golden Monkey NRs with scores of 16.27, 8.83, and 9.89, respectively. In addition, some major roadways pass directly through NRs, including the Qomolangma (No. 32 in Fig. 5), Gongbu (No. 45 in Fig. 5), and Markam Yunnan Golden Monkey (No. 23 in Fig. 5) NRs, indicating the irrational spatial layout and extent of these reserves in terms of the human footprint.

Table 3
Changes of five categories of human pressure scores and their proportional contribution to the increase in human footprint scores (HFS) in Tibet for 1990–2010.

Human pressures	Mean human pressure scores			Proportional contribution to the increase in the HFS (%)
	1990	2010	Increased by (%)	
Population density	0.116	0.137	18.12	2.12
Land use	0.813	0.813	0.00	0.00
Roads and railway	1.195	1.638	37.02	44.71
Grazing	0.937	1.456	55.32	52.38
Nighttime lights	0.001	0.005	415.76	0.44
All	3.060	4.050	32.35	100

4.3. Effectiveness of nature reserves in reducing the impact of human activities

The HFS inside the NRs of Tibet increased by 0.39 during 1990–2010, while the score outside the NRs increased by 1.31 (Table 5). In terms of the relative rate of change, the value inside the NRs was also lower than the value outside the NRs. A further analysis was conducted for the five categories of human pressure. Grazing intensity and road disturbance scores increased by 0.16 and 0.23 inside the NRs, with the corresponding values of 0.71 and 0.56 outside the NRs. There was a similar pattern for the population disturbance intensity and nighttime lights score. This suggests that the establishment of national and provincial NRs in Tibet has been effective in reducing the impact of human activities on the natural environment.

We then considered the changes in the human pressure and footprint scores for the three NRs established before 1990. The HFSs for Qomolangma and Zayü Cibagou NRs increased by only 0.40 and 0.02 during 1990–2010. These values were very small and resulted from increases in road disturbance and grazing intensity (Table 5). The score for YZGC was 0. For the three NRs, the population disturbance intensity declined during 1990–2010 (Table 5). The HFS mainly increased at the edges of NRs (experimental zone), and a stable or decreasing trend could be detected in the innermost regions of NRs (core zone). It can

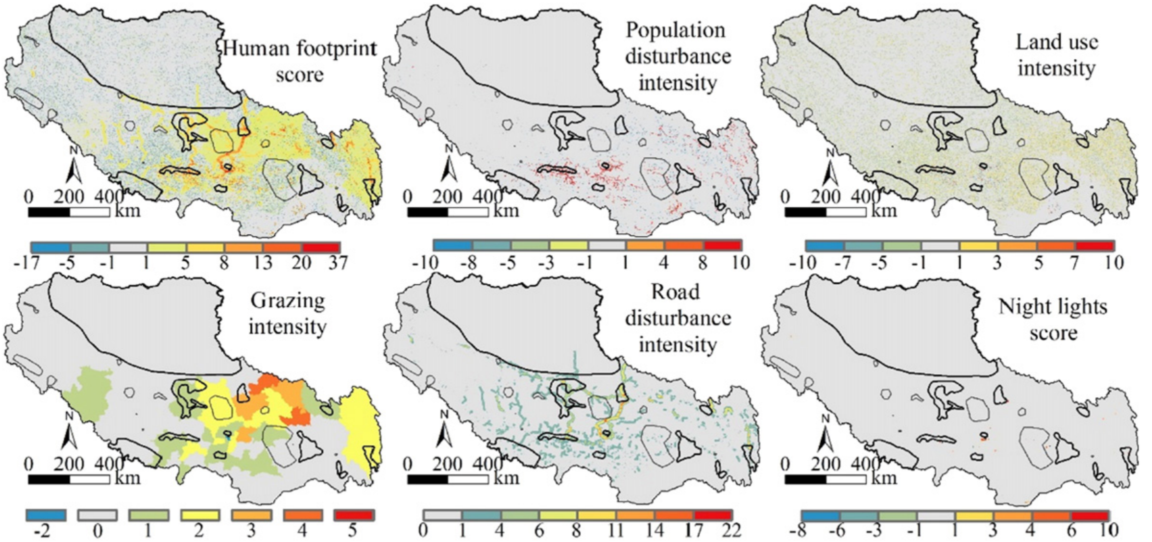

Fig. 4. Changes in the human footprint score (HFS) and the five categories of human pressure during 1990–2010 in Tibet.

also be seen that the HFSs outside the three NRs increased more significantly than inside, especially for the Qomolangma reserve (Fig. 6).

A comprehensive assessment of the YZGC NR was undertaken. Significant differences in the HFSs were found among the sample zones, buffer zones, and inside the reserve (Fig. 7). The average value inside the YZGC NR (2.27 for both 1990 and 2010) was obviously lower than the values of the buffer zones (for 1990 the value was 3.41 and for 2010 it was 3.69) and the sample zones (for 1990 the value was 4.45 and for 2010 it was 5.60). It was also found that the HFS was smaller when it is closer to the innermost region of the YZGC reserve (Fig. 7).

Additionally, significant differences in the changes of HFSs during 1990–2010 were also detected among the sample zones, buffer zones, and inside the YZGC NR (Fig. 7). The HFSs for the two innermost regions of the reserve decreased, and the value for the most marginal area of the reserve increased. For the three buffer regions, the HFSs increased by an average of 0.28. For the six sample zones, the HFSs of the four zones increased. The average value for the six sample zones increased from 4.45 in 1990 to 5.60 in 2010—i.e., an increase of 1.15, which was significantly greater than that inside the NR and the buffer zones. This indicates that the establishment of the YZGC reserve has significantly reduced human activities inside the reserve and no leakage has occurred in the area surrounding the YZGC NR.

5. Discussion

5.1. Comparison with global datasets

Because of the simplicity of the global method for mapping the human footprint (Sanderson et al., 2002; Venter et al., 2016), we adapted it and took five categories of human pressure into consideration to map

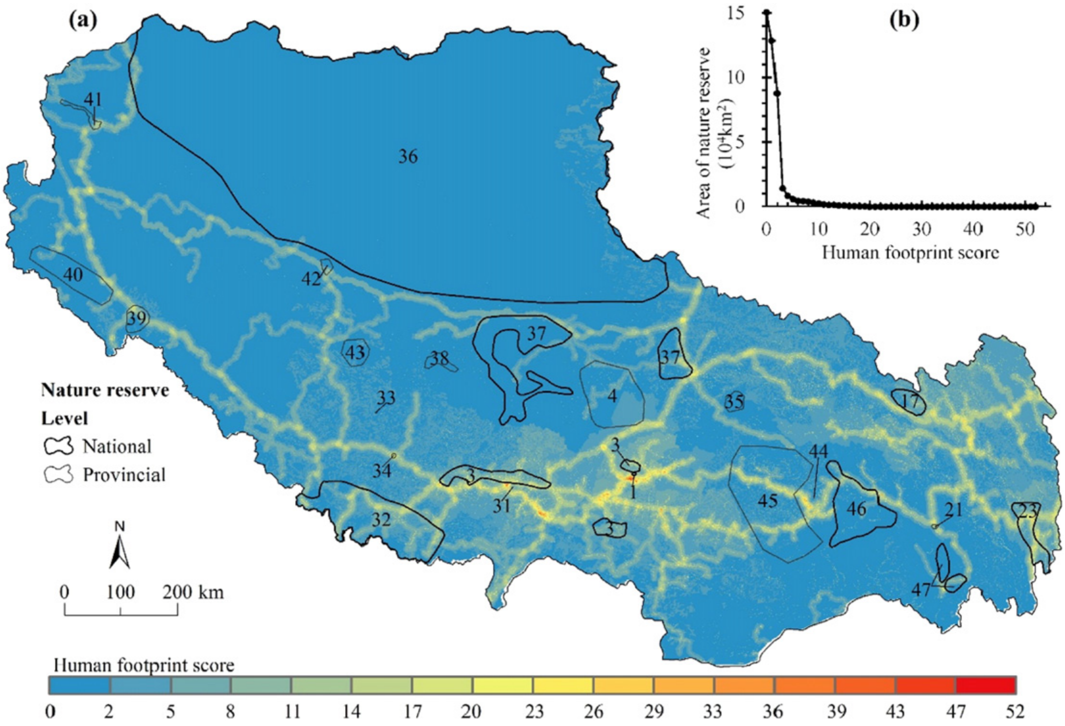

Fig. 5. Spatial pattern of national and provincial nature reserves in Tibet and the relationship with the human footprint for 1990.

Table 4
Mean human footprint score (HFS) of the 23 national and provincial nature reserves (NRs) in Tibet in 1990.

Name of NR		HFS	Name of NR		HFS	Name of NR		HFS
Code	Name		Code	Name		Code	Name	
1	Lalu Wetlands	16.27	33	Dagejia Spring Cluster	2.00	41	Pangong Lake	4.19
3	Black-necked Crane at Mid-stream of the Yarlung Zangbo	8.83	34	Sangsang Wetland	17.81	42	Dong Co Lake	3.92
4	Nam Lake	2.47	35	Midika Wetland	1.31	43	Trari Nam Lake	1.47
17	Riwoqe Red Deer	5.85	36	Chang Tang	0.88	44	Giant Cypress[a]	NA
21	Ranwu Lake	11.64	37	Siling Lake	1.80	45	Gongbu	3.99
23	Markam Yunnan Golden monkey	9.89	38	Ang Laren Lake	0.13	46	Yarlung Zangbo Grand Canyon	2.30
31	Shigatse Lava Cluster	9.00	39	Manasarovar Lake	5.79	47	Zayü Cibagou	2.83
32	Qomolangma	5.59	40	Zanda Earth Forest	1.64			

[a] NA = not applicable (the area of Giant Cypress NR is only 0.08 km^2 which was too small to conduct an analysis at a resolution of 1 × 1 km).

the human footprint in Tibet for 1990 and 2010 using more accurate data at the regional scale. This method could also be used in many other case studies by taking characteristics at the regional scale into consideration (Allan et al., 2017; Gonzalez-Abraham et al., 2015; Tapia-Armijos et al., 2017; Woolmer et al., 2008). In addition, with the advent of the era of big data, crowdsourcing and Google Earth have been used to create maps of human impacts (See et al., 2016), which is a more effective approach compared to traditional geographical information system (GIS)-based mapping methods.

Next, we compared our results with the human footprint map from the global datasets (Venter et al., 2016). Because of the differences in the human pressures considered, the absolute value was not comparable. Therefore, the values were normalized before comparison and we only considered differences in the spatial pattern and changes in the human footprint.

Both sets of results show that the regions with a large HFS and significant growth in the score were located in the central and eastern parts of Tibet and the regions with low scores were in the northeastern part (Fig. 8). However, the magnitude and scope of the growth identified in the current study were greater than those of the global datasets, possibly due to the more comprehensive and accurate data that were used in this study. Specifically, the roads, railways, and pasture land datasets used in the global datasets were static while they were dynamic in this study. The influence of the Qinghai–Tibet highway and railway on the ecological environment is shown in Fig. 8 (a3). However, this influence is not revealed in the global datasets. The major roadways in this study include expressways, national-, provincial-, county-, and rural-level highways, but they were unavailable in the global datasets.

The global human footprint increased by just 9% over the 16 years considered by Venter et al. (2016). However, the value for Tibet increased by 32.35% during 1990–2010, indicating that Tibet is a hotspot of growth in human activity and it is threatened by more human pressures. This can be of great help in terms of informing relevant policies and practices.

5.2. Optimization of the spatial layout of nature reserves

Our results show that the HFSs inside the NRs of Tibet were generally low when they were created. Therefore, there is no need to remove most human activities from NRs during the management process, although 34.47% of the area of Tibet has NR status, which is greater than any other provinces in China. And the use of land as a NR does not significantly affect the economic development of Tibet because of the excessive restrictions on human activities inside NRs. There is little conflict between ecological protection and human activity in Tibet generally, and the overall spatial layout of NRs is considered to be rational.

However, the spatial layout of national and provincial NRs in Tibet can also be optimized in terms of their human footprint. There were 12 of the 22 NRs investigated where the HFSs were larger than the average value for Tibet. Major roads pass directly through the Qomolangma, Gongbu, and Markam Yunnan Golden Monkey NRs, and further investigations are needed for these sites. To conserve biodiversity and ecosystem services in these areas, the government needs to take more effective measures, such as removing some human activities (mining, major roadways, villages, and towns). Alternatively, if the spatial extent of these NRs is irrational (e.g., including areas of low conservation value and failing to cover the main conservation targets), the government may need to adjust the boundaries of these NRs.

For example, during the establishment of Qomolangma NR, the local government designated the whole territory of Dingri, Nyalam, and Jilong counties as the NR, and even some towns were designated as core zones of the reserve. This was irrational and resulted in ineffective management, while also restricting socio-economic development in the local area. The government now plans to remove villages from altitudes higher than 4500 m from the reserve, and will also adjust the boundary of the reserve to exclude urban areas with a large population from the NR (Deng, 2017). A similar situation exists in Gongbu (No. 45 in Fig. 1) (Luo and Meng, 2014) and Black-necked Crane at Mid-stream of the Yarlung Zangbo (No. 3 in Fig. 1) NRs (Xu et al., 2009). The removal of human activities inside these reserves and the adjustment of their borders are urgently needed.

In addition, attention should also be given to regions without protected areas, where intense human activities occur, but are also very important for biodiversity and ecosystem services. For example, the southeastern part of Tibet does not currently have any protected areas, but it has been identified as an important location for the conservation of amphibian diversity (Chen et al., 2017). It is also an important area of key regulating ecosystem services (Xu et al., 2017). Therefore, studies are required to assess these conservation needs before the area is disturbed by human activities.

Table 5
Changes in the mean human footprint score (HFS) and five categories of human pressure during 1990–2010 inside and outside all the national and provincial nature reserves (NRs) in Tibet, and for the three NRs established before 1990.

Human pressures and HFS	Changes inside the NRs		Changes outside the NRs		Qomolangma	Zayü Cibagou	Yarlung Zangbo Grand Canyon
	Absolute	%	Absolute	%			
Population disturbance intensity	0.00	0.00	0.03	20.36	−0.05	−0.09	−0.08
Land use intensity	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Grazing intensity	0.16	45.97	0.71	56.72	0.12	0.00	0.00
Road disturbance intensity	0.23	49.21	0.56	35.13	0.33	0.11	0.08
Nighttime lights score	0.00	0.00	0.01	394.47	0.00	0.00	0.00
Human footprint score	0.39	24.37	1.31	34.02	0.40	0.02	0.00

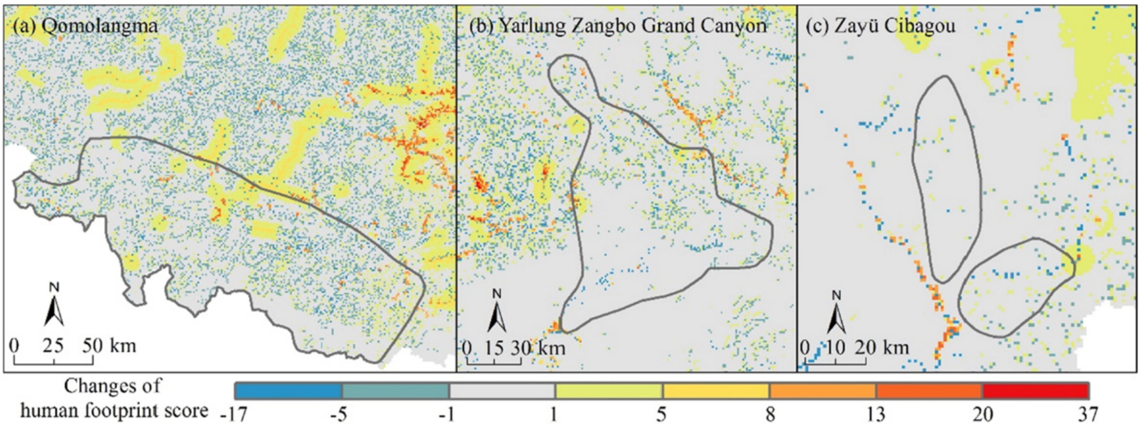

Fig. 6. Spatial distribution of the changes in human footprint scores during 1990–2010 for the three nature reserves in Tibet established before 1990.

5.3. Challenges of management of nature reserves

Our results suggest that the national and provincial NRs are effective for reducing the impact of human activities, especially the Qomolangma, Zayü Cibagou, and YZGC NRs. This has also been reported for other NRs in the world (Bruner et al., 2001; Tapia-Armijos et al., 2017). However, the management of NRs in Tibet is likely to have many challenges in the future. Road disturbance and grazing intensities inside the NRs have increased significantly during 1990–2010 (Table 5). The HFSs in the most marginal areas of the YZGC and the three buffer regions have also increased (Fig. 7). These increases indicate that the implementation of extra conservation and management strategies in the NRs of Tibet are necessary.

It has been reported that the population inside the Qomolangma NR has increased from more than 60,000 to nearly 100,000, which has generated more conflicts between environmental protection and development (Deng, 2017). In recent years, Tibet has developed very rapidly and the intensity of human activities has increased. There has been a tourism boom on the Tibetan Plateau (Tian, 2016), with the increasing number of tourists received, especially after 2010 (Fig. 9). The length of highways in Tibet has increased significantly in the 21st century (Fig. 9). The Lhasa–Xigazê Railway was also open in 2014, and the length of the railway in Tibet will reach 1300 km by 2020 (Li et al., 2016).

There are still many challenges in the management of NRs in Tibet. Sustainable development strategies must be implemented to resolve these issues, including ecotourism projects, and the construction of a transportation network, with priorities given to ecological conservation.

5.4. Limitations and future work

As a remote area, data availability in Tibet is poor and inventory records lag behind those of the mid-east regions of China. In this study, the population density, grazing density, and nighttime lights data for 1990 were unavailable in the mapping of the human footprint, so extrapolation (for population density and grazing density data) or replacement with data of neighboring years (nighttime lights data for 1992) were carried out. So the human footprint of 1990 actually represents that of the early 1990s. Moreover, the geographically explicit grazing intensity data for Tibet were unavailable, and therefore county-scale data were used. This may reduce the reliability of results at 1 km resolution considering that the average area of counties in Tibet is about 1.66×10^4 km^2. More and better data are necessary to improve the analysis in future work.

The selection of the human pressure indices and the influence of score assignment also need refinement. As with all attempts to map cumulative activities, we did not fully account for all human pressures, including tourism (Tian, 2016) and pollution (Guzzella et al., 2016), which makes this a conservative assessment of the likely threats. For example, studies have shown that traffic volume also influences the ecological environment (Theobald, 2010), but the unavailability of traffic volume data at a 1 km scale forced us to neglect this human pressure at present. Sanderson et al. (2002) also suggested that understanding how human pressures quantitatively translate into impacts, or how they should be weighted against each other, is an important area of study. Taking Qinghai-Tibet railway as an example, we know that the distance people travel from the railway varies in different places of Tibet, and therefore their influences on nature are different. In this study, we only assigned

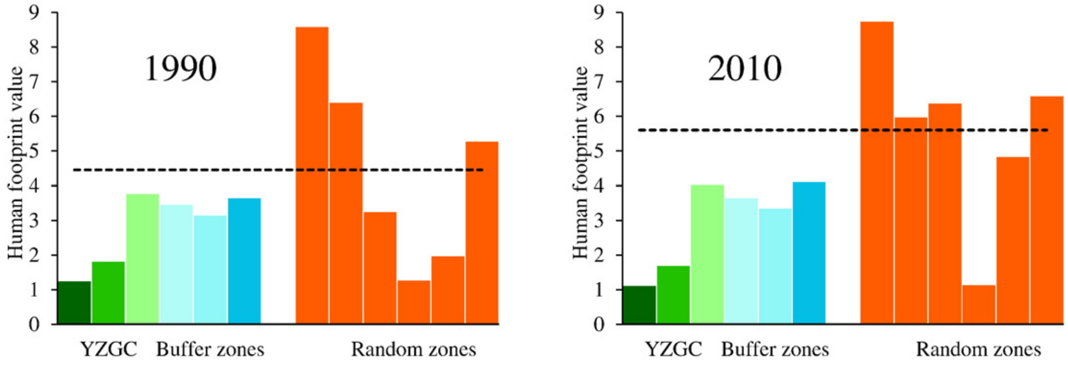

Fig. 7. Human footprint scores (HFSs) for 1990 and 2010 within and around the Yarlung Zangbo Grand Canyon (YZGC) nature reserve (NR). Green bars denote the zones inside the YZGC NR, blue bars denote the zones outside the YZGC NR and orange bars denote the six random zones around the YZGC NR. The dashed line denotes the mean HFS for the six random zones.

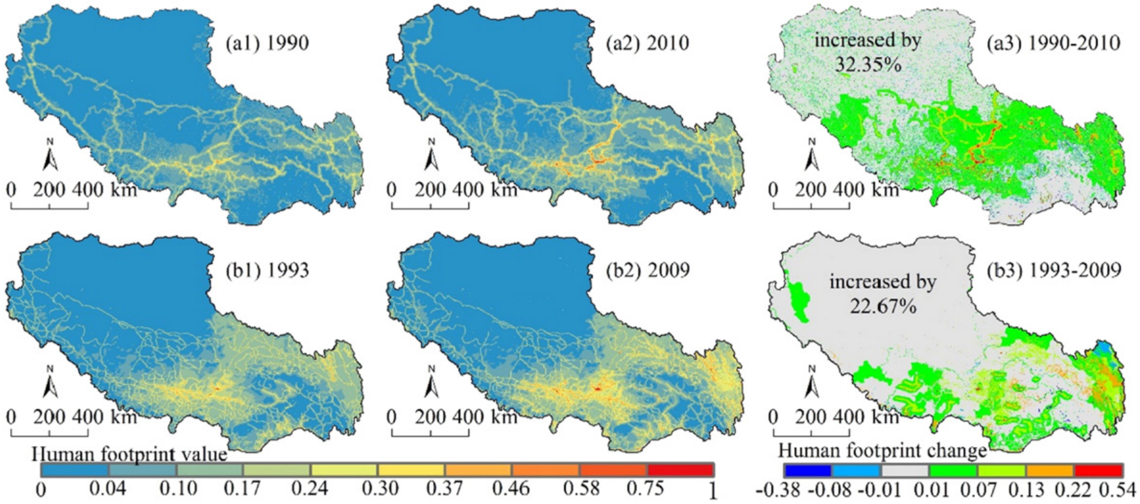

Fig. 8. Comparison of the human footprint between this study and the global datasets (Venter et al., 2016). The latter was only available for 1993 and 2009, therefore a comparison was made between 1990 (2010) values from this study and 1993 (2009) values from the global datasets. (a1) and (a2) are the normalized human footprint values from this study. (b1) and (b2) are the normalized human footprint values from global datasets. (a3) and (b3) are the absolute differences of the human footprint values from this study and those from the global datasets.

the same influence scores to the same distance based on relevant studies at regional scale (Chen et al., 2003; Chen et al., 2007; Li et al., 2010; Li et al., 2017b), and on our own expert judgement regarding road construction in Tibet (Peng et al., 2007; Zhou et al., 2008). More evidences concerning the influence assignment of human pressures in Tibet are necessary to overcome this limitation and improve the accuracy of the analysis in the future.

Additionally, with the advent of the era of big data, crowdsourcing and Google Earth have been used to create maps of the human footprint (See et al., 2016), which is an entirely different approach compared to traditional GIS-based mapping methods. We believe that such studies are promising and will gain popularity in the future.

Besides assessing the spatial layout and effectiveness of nature reserves, some additional uses of the human footprint are formulated. Combining the human footprint datasets with maps of ecosystem services and biodiversity, to determine the human footprint characteristics within these valuable regions, is an important implication of the human footprint for conservation of ecosystem services and biodiversity (Li et al., 2017b). Human pressures can be used as input of ecological models, e.g., integrated valuation of ecosystem services and tradeoffs (InVEST) (Sharp et al., 2016), to determine the losses of biodiversity and ecosystem services because of human activities. For example, Wang et al. (2016) assessed the contribution from different human activities to the observed reduction in sediment flux for the Yellow River. By linking the distribution of threatened species across China to current and historical changes in population densities, cropland, and pasture since 1700, Feng et al. (2017) found that threatened species were likely to be concentrated in regions recently under human pressure.

6. Conclusions

We mapped the human footprint of Tibet for 1990 and 2010, and analyzed its temporal and spatial characteristics. Subsequently, its spatial relationship with NRs was analyzed quantitatively and used to assess the effectiveness of NRs for reducing the impact of human activities on the natural environment. A comprehensive assessment for the YZGC nature reserve was undertaken. The major findings are summarized as follows.

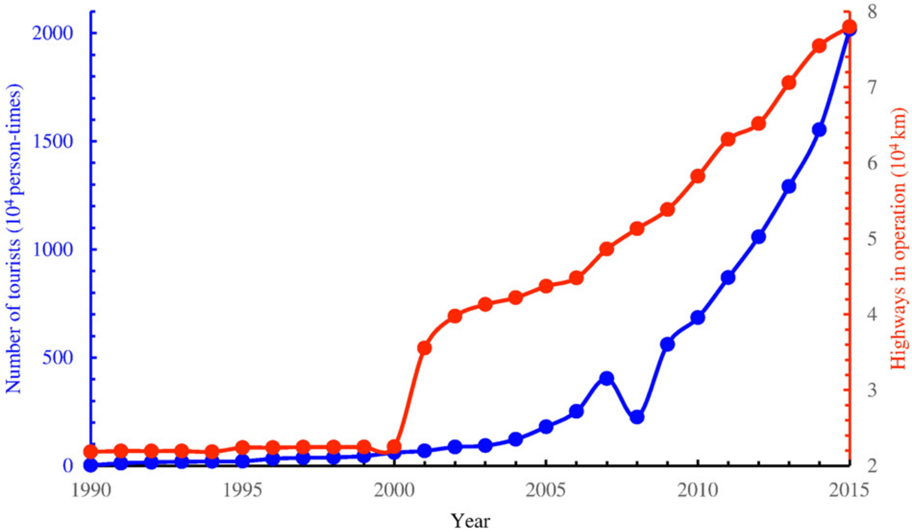

Fig. 9. The number of tourists received and the length of highways in operation in Tibet during 1990–2015. Data were obtained from the *Tibet Statistical Yearbook 2016* (National bureau of statistics of China, 2016).

First, the HFSs in Tibet for 1990 and 2010 were low, and increased by 32.35% from 1990 to 2010, with the main increases occurring in central and eastern Tibet. However, the global HFS increased by just 9% during 1993–2009, indicating that Tibet is seriously threatened by human pressure.

Second, the average HFS in 1990 for the 22 national and provincial NRs in Tibet (not including Giant Cypress NR) was 1.60, which was lower than the score of 3.06 for Tibet as a whole. However, the spatial layout and extent of some reserves (e.g., Qomolangma, Gongbu, and Black-necked Crane at Mid-stream of the Yarlung Zangbo NRs) could be optimized further by resolving the conflicts between conservation and development.

Third, the establishment of NRs in Tibet has been effective at reducing human activities, especially the Qomolangma, Zayü Cibagou, and YZGC NRs. No leakage phenomenon has occurred in the regions surrounding the YZGC reserve. However, the management of NRs in Tibet is still challenging due to the need to reduce or remove some types of human activities.

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