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Mapping Potential Wilderness in China with Location-based Services Data

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Abstract
Wilderness mapping can provide valuable information for natural resource management. In this article, a novel, straightforward approach has been developed to identify wilderness areas in China using emerging new data. Tencent LBS (location based service) data that reflect human activities are used as a basis for mapping wilderness characteristics for the whole of China while admitting non-human-activity zones as "observed" wilderness, rather than "estimated/inferred" wilderness using spatial factors based on conventional wilderness mapping approaches using GIS. The mapping results using new data are compared and integrated with the results from the MCE approach. The wilderness map, delineating the range of wilderness across the whole of China, could be used in landscape planning to protect the remaining natural resources and evaluate existing spatial ecological protection schemes. With increasingly available new data, the proposed approach can be applied for mapping wilderness at other spatial scales and in other geographical areas.

Keywords Wilderness mapping · Non-people zone · Location based service (LBS) · National level · Nature protection · Nature reserves

Highlights
- Map potential wilderness characteristics for the whole of China using Tencent LBS (location based service) big data that reflects individual level human mobility activity by recognizing that areas with no human mobility activity are "observed" wilderness
- Compare wilderness mapping by using new data compared with mapping by using a conventional approach with GIS
- Support landscape planning to retain nature reserves, evaluate the protection of existing ecological protection areas.

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Introduction

The concept of wilderness has been developed to enable a focus on the protection of nature. The original concept of wilderness mainly expresses human impact on the natural environment and the quality of the wild. For example, the definition of wilderness used in Section 2c of the United States' 1964 Wilderness Act refers to "a wilderness, in contrast with those areas where man and his own works dominate the landscape, is hereby recognized as an area where the earth and its community of life are untrammeled by man, where man himself is a visitor who does not remain" (Wilderness Act 1964). This concept has been influential in expanding definition and protection of wilderness worldwide (Carver and Fritz 2016). The concept of wilderness used by the International Union for Conservation of Nature (IUCN) mentions that wilderness is "large unmodified or slightly modified areas that retain their natural character without permanent or significant human habitation, which are protected and managed so as to preserve their natural condition". The definition being widely used in European countries recently is that wilderness is "an area of at least 10,000 ha of land or sea, which together with its native plant and animal communities and their associated ecosystems, is in an essentially natural state" (Jones-Walters and Čivić 2010). Wild Europe (2013) defined 3000 ha as a threshold for labelling any new core area as wilderness. It emphasizes the function of wilderness in protecting the integration of ecosystems without human modification. According to EU Guidelines for the management of wilderness, the definition for wilderness is that "A wilderness is an area governed by natural processes. It is composed of native habitats and species, and large enough for the effective ecological functioning of natural processes" (Kuiters et al. 2013).

While these concepts are accepted and developed worldwide, the importance of wilderness protection and restoration has been emphasized as well. It has been accepted as fundamental in respecting biodiversity, wildlife and ecological integrity (Mittermeier et al. 1998). The IUCN's World Commission on Protected Areas' (IUCN WCPA) Wilderness Specialist Group announced that loss of the wilderness brings the loss of cultural and linguistic diversity. Molloy (1983) argued that "wilderness protection is the respect of human emotion relating to wilderness experience including aspects such as solitude, freedom, romance and challenge". The wilderness is also imperative as a subject of scientific study where wildlife and natural processes can be freely learned (Carver and Fritz 2016). Institutions are increasingly supporting wilderness protection. For instance, from 1994, the IUCN listed the wilderness as an independent management category (Category 1b), as an important landscape in protected areas. It emphasizes the management of the wildness to maintain the highest integrity of ecosystems, wildlife, and sacred and traditional culture (Casson et al. 2016). Currently there are 48 countries recognizing wilderness protection land through law, and 22 other countries protecting wilderness land through political guidance.

Wilderness mapping has been an important component in wilderness related studies and is used as a basis for regulating wilderness land. Wilderness mapping refers to "using spatial data to map patterns in variability and distribution of wilderness character" (Carver et al. 2013). Mapping what is left ought to be a fundamental theme within environmental science and management (Carver and Fritz 2016). Over the past 30 years, there have been a handful of approaches being proposed based on GIS to map wilderness so that human influence on them can be managed and conservation policies can be made (Fritz et al. 2000). Wilderness mapping could provide valuable information for natural resource management and conservation. Mapping wilderness for defining protected areas is also positive for biodiversity mapping and protecting ecosystem services (Turner et al. 2007; Myers et al. 2000; Lesslie and Taylor 1985; Nash 1967). From the integration of an ecosystem perspective, wilderness mapping is argued to be an indispensable task to wildlife ecological corridor design and network construction (Zimmerer et al. 2004; Locke and Dearden 2005). Now, a well-recognized viewpoint is to use a more connected view to perceive wilderness' so called "Cores, Corridors and Carnivores" (CCC), based on the CCC model of Worboys et al. (2010). In addition, Kliskey (1994) suggested that wilderness mapping provides a spectrum of recreation opportunities for human beings in the wilderness, where less human intervention in a landscape can maximize user satisfaction for wilderness travel.

Mapping wildness for natural resource management involves practices at different spatial scales. At the local level, Carver et al. (2012) identified a GIS model for mapping the spatial pattern and location of wild land in the Cairngorm National Park and the Loch Lomond and The Trossachs National Park in Scotland at a finer resolution of 20 m. Măntoiu et al. (2016) mapped wilderness in South Western Carpathians at the local level, which can be seen as a first step in the wilderness identification process of Romania. At the national level, Lesslie and Taylor (1985), Aplet et al. (2000), Plutzar et al. (2016), ÓlafsdÓttir and Runnström (2011), ÓlafsdÓttir et al. (2016) and Müller et al. (2015) have mapped wilderness, thus broadening wilderness mapping at the national level and optimizing wilderness mapping technologies from practices in Austria, Iceland and Denmark. McCloskey and Spalding (1989), Lesslie (1998) and Sanderson et al. (2002) provided contributions to wilderness mapping at continental or global levels. The first global wilderness distribution map was drawn in 1989 by McCloskey and Spalding (1989). Further, Lesslie (1998) used GIS to map wilderness quality of the whole world in work done for the World Conservation Monitoring Center (WCMC). In the Globio3 project, the current and future state of global biodiversity and wilderness and human impact were mapped by evaluating the land cover change, land-use intensity, fragmentation, climate change and infrastructure development (Alkemade et al. 2009).

With the rapid development of information and communication technology, emerging new data in the recent decade has involved both big data and open data. This new data includes, but is not limited to, taxi GPS trajectories, mobile phone traces, public transportation smartcard data, social media, street view pictures, point of interests (POIs) and substantial crowdsourced data. Considering most new data represent individual level human mobility and activities, these emerging new data create a new lens for wilderness mapping while looking at the nature of wilderness, where wilderness areas can be regarded as areas with few human activities. In addition, more recent work has recognized that Participatory GIS (PGIS), crowd sourcing and big data are already being used in the wilderness mapping field. For example, Oris and Geneletti (2013) stated that georeferenced material such as geotagged photographs and GPS tracks, left behind by people moving, provide a new valuable source of information about people's movements, and used crowd sourced imagery and GIS analysis to estimate visitor flows in natural areas. Walden-Schreiner et al. (2018) used crowdsourced data from web-based platforms to generate hotspot maps in two mountain protected areas of high conservation value. Mancini et al. (2018) recognized the great opportunities offered by big data for nature area protections and used Flickr photos to define trail usage in Scotland. See et al. (2014) used Geo-Wiki to determine wilderness areas by collecting information of human impact. Brown and Weber (2012) used PGIS to measure changes in the importance and spatial distribution of landscape values. There are great opportunities for introducing new data for mapping wilderness, thus extending the conventional spatial factors derived through "estimated or inferred" wilderness mapping using GIS to include the mapping of "observed" wilderness. In addition, delineating wilderness by observing human activity and the intensity of human activity could directly inform the wilderness patterns of national nature reserves, therefore to lead the planning and protections of nature reserves.

Given this background, a novel approach for wilderness mapping using LBS (location-based service) data is proposed and applied for potential wilderness mapping across the whole of China. Specifically, this paper will:

(1) Map potential wilderness characteristics for the whole of China using Tencent LBS big data that reflects individual level human mobility activity by recognizing that areas with no human mobility activity are "observed" wilderness;
(2) Compare wilderness mapping by using new data compared with mapping by using a conventional approach with GIS; and
(3) Support landscape planning to retain nature reserves and evaluate the protection of existing ecological protection areas.

This paper is structured as follows - to illustrate the research context, the "Literature Review" section will discuss and argue the theoretical basis and commonly adopted approaches of present wilderness mapping. The "methodology" section will introduce the methodology to identify wilderness, to be used in generating a wilderness map in this paper. The results will be analyzed in "Results" section, including the overall patterns of potential wilderness and the wilderness conditions in national nature reserves. In the "Discussion" section, a comparative analysis using a multi-criteria evaluation (MCE) method and an integration with the MCE method to revise the outcomes of wilderness mapping will be made. In the final "Conclusions" section, academic contribution, potential application, research biases will be discussed.

Literature Review

Theoretical Basis

Previous research of wilderness mapping defines wilderness as "exceeding the concept of biophysical or ecological 'naturalness' by the inclusion of human concerns" (Carver et al. 2013). A few standards are widely used such as remoteness (distance from nearest settlements), apparent naturalness of the land cover (the degree of disturbance) and lack of human intrusion (Carver et al. 2013; Orsi et al. 2013; Carver and Wrightham 2003). The theoretical basis of wilderness mapping as a wilderness continuum was first described by Nash (1967) and changed the mapping of wilderness from a duality of presence/absence to a spectrum of relativity. The framework of wilderness as a continuum was first practiced in developing the Australian National Wilderness Inventory (ANWI). Figure 1 shows the wilderness continuum concept proposed by Lesslie and Taylor in 1985. It emphasizes the transition from developed land to undeveloped land, which is reflected in the intensity of human impact on nature. The wilderness quality increases as the remoteness and primitiveness increase, as a result, the wilderness quality can be divided into low quality, medium quality and high quality. Subsequent wilderness mapping projects have followed a similar approach to the ANWI, which uses GIS approaches for wilderness mapping by scholars (Aplet et al. 2000; Carver et al. 2013; Carver 1996; Carver and Wrightham 2003) based on the wilderness continuum concept.

Ecological wilderness is always defined as those areas that are free from man-made structures or infrastructure, with no trace of human activity, and wild and unspoiled nature. For example, the first comprehensive wilderness map created by ÓlafsdÓttir and Runnström (2011) delineated ecological wilderness based on the geographical digital data of three factors: remoteness from mechanized access, remoteness from settlement, and apparent naturalness in a geographical model. It is stated that wilderness does not exist without an observer to experience it and is more of an idea than an ontological phenomenon (Cronon 1998; Tuan 1990), thus perceived wilderness is also critical. The perceived wilderness is a response of the perceptions of individuals to the natural environment. The perceived wilderness is influenced by a number of factors relating to people's mobility, experiences, emotions, values, culture and social-economic background, and how people define wilderness varies depending on the location and function of the assessment (ÓlafsdÓttir, Sæþórsdóttir and Runnström, 2016; Kliskey 1998; Stankey and Schreyer 1987). The emerging new data left by people moving provide new opportunities for mapping the perceived wilderness. Combining MCE techniques

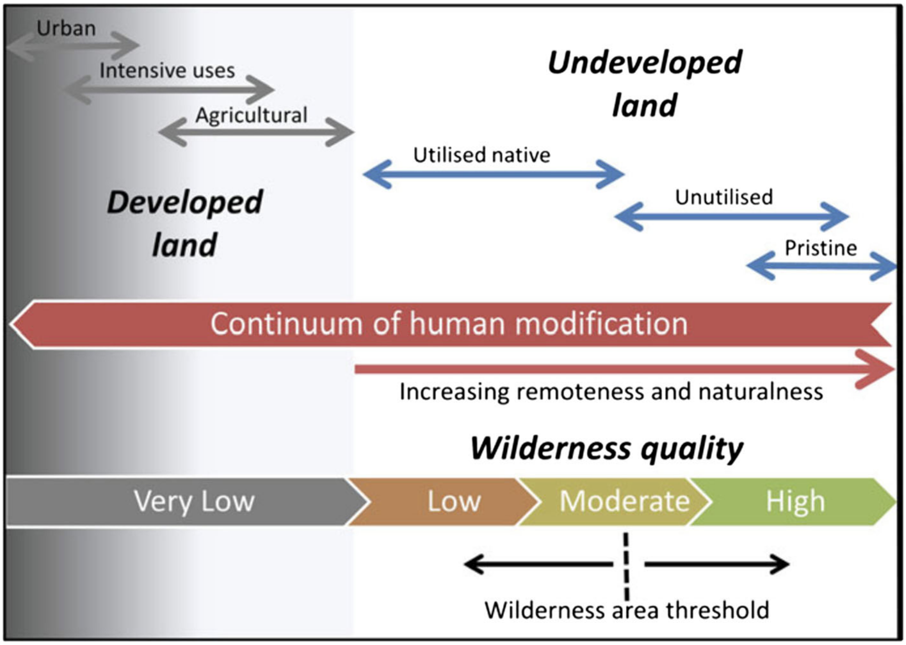

Fig. 1 The wilderness continuum concept (Lesslie 2016)

with GIS can provide users with the means to evaluate various alternatives on the basis of multiple and conflicting criteria and objectives (Carver 1991). Integrated MCE techniques within the GIS framework can support spatial decisions and site selection. Several works of wilderness mapping have employed an MCE-GIS approach to describe wilderness (Lesslie and Taylor 1985; Carver et al. 2012).

Methods for Wilderness Mapping

Combined with MCE, researchers have selected and weighted different indicators to identify the spatial pattern of wilderness (Fritz et al. 2012; Carver et al. 2012; Cao et al. 2018). For instance, indicators of MCE in developing the Australian National Wilderness Inventory (ANWI) included remoteness from settlement, remoteness from access, biophysical naturalness and apparent naturalness (Lesslie and Taylor 1985). Carver et al. (2012) proposed four indicators: naturalness, human impact, ruggedness and remoteness, to map wilderness for the Cairngorm National Park and the Loch Lomond and Trossaches National Parks. Other methods include classic ill-defined and fuzzy multi-criteria methods (Comber et al. 2010), simple Boolean inventories (McCloskey and Spalding 1989; Carver and Fritz 2016) and preference studies (Habron 1998). Taking the distance into account, Tricker and Landres (2012) and Sang (2016) identified wilderness by an assessment of the impacts of field-of-view disturbances. Hennig (2016) visualized the most remote parts of land area by deploying a gridded cartogram transformation to data to assess the accessibility of a place. These methods have worked along with the MCE approach and generate wilderness maps by deterministic overlay according to their perceived level of importance and buffer operations in GIS on the basis of site-specific information.

The wilderness continuum and MCE approaches face a range of arguments (Dawson and Hendee 2002; Lesslie and Taylor 1985; Comber et al. 2010; Carver et al. 2012; Orsi and Geneletti 2013). Dawson and Hendee (2002) and Lesslie and Taylor (1985) argued that one of the philosophical problems is, at which point of a wilderness continuum is the demarcation point between the wilderness and non-wilderness? In addition, the options of the weights and indicators to measure land cover, transportation or infrastructure are still very subjective. In support of this, Comber et al. (2010) stated that “wilderness maps reflect the viewpoint of a group of scientists and stakeholders rather than some evidence from the field”. Current wilderness mapping also states as an action to inform conservation areas, but only few of them can specifically tailor the practical management of conservation areas (Carver et al. 2012; Orsi and Geneletti 2013). Thus. it is necessary to consider human mobility when mapping wilderness and guiding wilderness conservation and spatial ecological protection schemes. See et al. (2014) collected land cover and human impact in order to determine the wilderness nation-wide. This bottom-up approach to mapping using the crowd is in contrast to more traditional GIS-based wilderness mapping methods. In their studies, data on human impact were collected through a number of different data collection campaigns using Geo-Wiki. Geo-Wiki is a visualization, crowdsourcing and validation tool developed to help improve global land cover maps (Fritz et al. 2009, 2012). This article proposes a new data approach to “observe” potential wilderness by identifying uninhabited areas to fill current gaps created by conventional methods using GIS with spatial factors (mainly naturalness and remoteness). Firstly, this people-oriented approach considers human activity and treats it as a core indicator for wilderness evaluation. Furthermore, wilderness mapping may directly inform the human activity intensity in national natural reserves to lead the management of natural protected areas. More precisely, in this study, the Tencent LBS data are used as a basis for wilderness mapping (areas having no Tencent LBS data in a specific time period are potential wilderness). The value of every LBS data point records the human activity intensity at a geographic location, thus comparing wilderness mapping with natural protected areas could inform the wilderness patterns in protected areas and could also recognize areas with certain human activity intensity (not wilderness) in protected areas.

Methodology

Study Area and Data

In China, there are 34 provincial administrative regions, 23 provinces (including Taiwan), five autonomous regions, four municipalities, and two special administrative regions (Hong Kong and Macao). Considering the data limitations, this study focuses on all provincial administrative regions in China, excluding Macao. The resolution is 1km^2 for this study. This resolution is deemed sufficient for mapping the wilderness for the whole study area. Each 1 km^2 grid cell corresponds to the spatial setting of the following Tencent LBS data.

For this study, Tencent LBS data was collected in 2016, as well as the boundary of national nature reserves. For understanding the geographical position of human activity across the whole of China, LBS from the Tencent Company, one of the most popular social network platforms and representing China's largest databases of online footprints, has been collected. In 2017, the Tencent social networking platform had over 60 million shares per day. The retrieved data are aggregated at the 1 km by 1 km grid level and human activity counts for each grid in the whole of February 2016 (29 days in total) were recorded, for all of China. Tencent Company offers location-based messaging including on the QQ App, WeChat App, Tencent Music, Tencent Browns, Tencent Map and Tencent Weibo platforms. One human activity represents one location request from any Tencent related App which records a user's geographical position through the network. All data are divided into five types according to human activity density using the Geometry Interval method (see Fig. 2a). The algorithm creates these geometrical intervals by minimizing the square sum of elements per class. Using this method can ensure that the change between intervals is fairly consistent.

The national nature reserves map from a navigation company including 397 national nature reserves in China are also used. Almost all Chinese national nature reserves are selected after comparing between Google Maps and Baidu Maps. The boundary of Chinese national nature reserves is used for the purpose of optimizing existing ecological space protection schemes and evaluating the protection of remaining national nature reserves by observing the wilderness condition in these protected areas (see Fig. 2b).

Identifying Wilderness Using LBS Data

A straightforward method is suggested to identify wilderness in China. Grids with less than one activity per day on average in February 2016 (there are 29 days in this month,

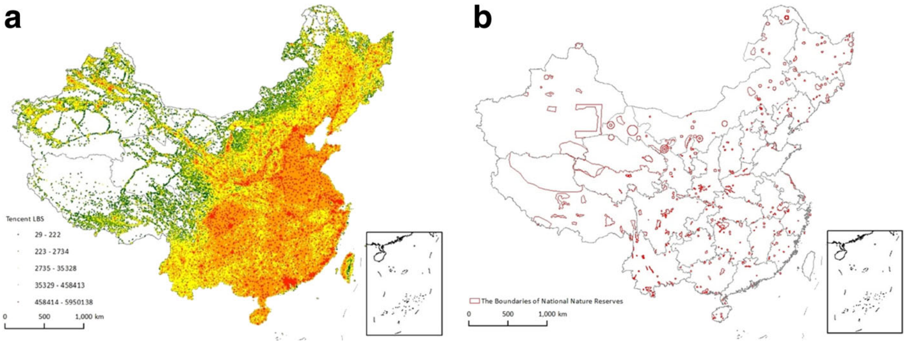

Fig. 2 **a** The location and density of LBS. **b** The boundary of national nature reserves in China. Note: This data will be applied in wilderness mapping at the national level

thus less than 29 in the whole February) are regarded as uninhabited areas, namely potential wilderness (荒野; Huāngyě) in this article. The sensitivity of the analysis used is reported on in the discussion section.

Gansu Province is used as a case for demonstrating the detailed method to identify wilderness according to LBS data. Figure 3a illustrates the distribution of LBS data traces in Gansu Province. The areas with no points mean in these areas, the Tencent data traces appear fewer than 29 times in the month (less than once per day) and there is little human activity. The areas with no points mean Tencent LBS electronic traces appear less than 29 times in this month (less than one time per day). Then Gansu is segmented into 1km^2 resolution grids. In every 1km^2 cell, if there are no points, this grid is colored green and defined as a non-people zone or an area of wilderness. Wilderness in Gansu Province is illustrated in Fig. 3b.

Evaluating National Reserves Using Identified Wilderness

Existing national reserves are then evaluated, the most important component for determining spatial natural protection policies, using the identified wilderness pattern

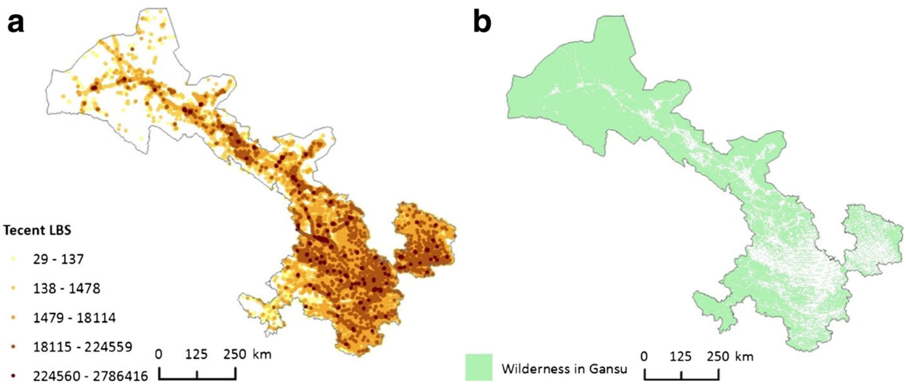

Fig. 3 **a** The distribution of LBS in Gansu. **b** The wilderness map of Gansu, as a demonstration for wilderness mapping using LBS data in a part China

based on LBS data across the whole country. The wilderness ratio is proposed as: the wilderness area in a national reserve divided by the national reserve area, to represent the degree of eco-protection from the human activity perspective. The lower the wilderness ratio is, the worse a national reserve is protected from the human activity aspect and the less the perceived wilderness is included. The evaluation results can be applied for evaluating landscape quality, supervising local management and adjusting administrative boundaries of national reserves, if necessary. The methodology will be demonstrated in the following results section.

Results

Identified Wilderness in China Using the LBS Data

China covers an area of 9.6 million square kilometers. Following the methodology, it was found that wilderness covers 6.9 million square kilometers, occupying 71.8% of the total national area according to Tencent LBS data. Chinese topography includes undulating mountain ranges and desert, such as Qinling Mountains in the center, Taihang Mountain in the northeast, Tianshan-Yinshan Mountain Ranges in the north, Kunlun Mountain in the southwest and Taklimakan Desert, Gurbantünggüt Desert and Badain Jaran Desert, which may make the wilderness area larger than in reality. The resulting Chinese wilderness map is illustrated in Fig. 4:

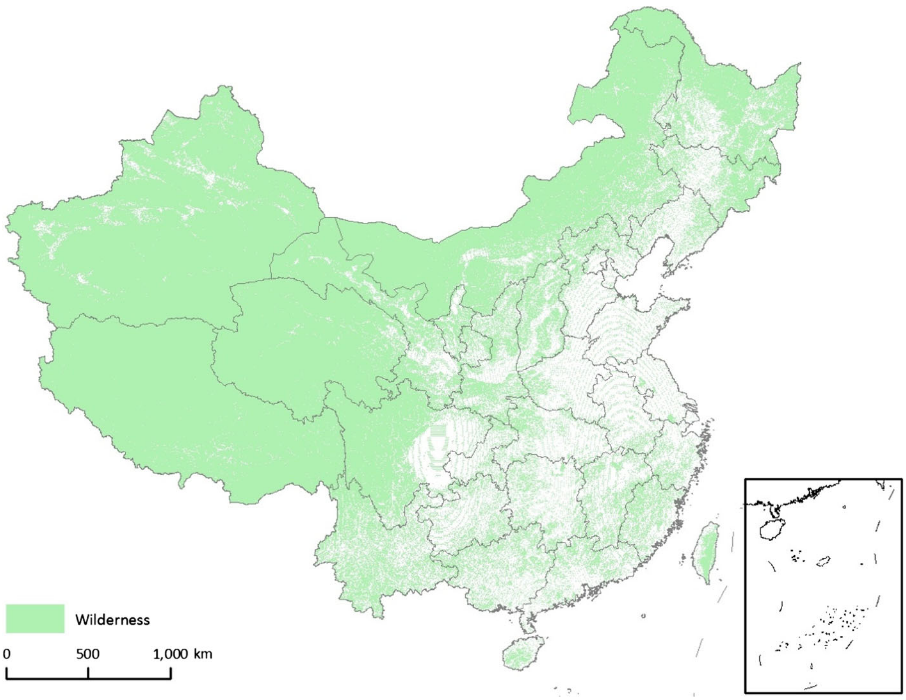

Fig. 4 Wilderness map of China based on LBS data approach

To provide a more intuitive and responsive wilderness distribution in China, the wilderness-covering ratio at the provincial level is illustrated (see Fig. 5a; see appendices for details). Five included figures (see Fig. 5b–f) demonstrate more detailed wilderness distribution in five representative cities: Qinghai, Yunnan, Hainan, Chongqing and Shandong, which indicate wilderness patterns with different wilderness ratios in provincial administrative regions.

One significant feature of Chinese wilderness is strong duality. The wilderness is at very high proportion in the west of the Heihe–Tengchong Line, which is an imaginary line that divides the area of China into two roughly equal parts. For instance, in Xinjiang, Xizang and Qinghai the wilderness-covering ratio exceeds 80% and in Gansu, western Sichuan this ratio is over 60%. The wilderness ratios to the east of the Heihe–Tengchong Line by contrast are fewer than those of areas situated to the west. More precisely, to the east of line, the wilderness-covering rate is less than 60% in

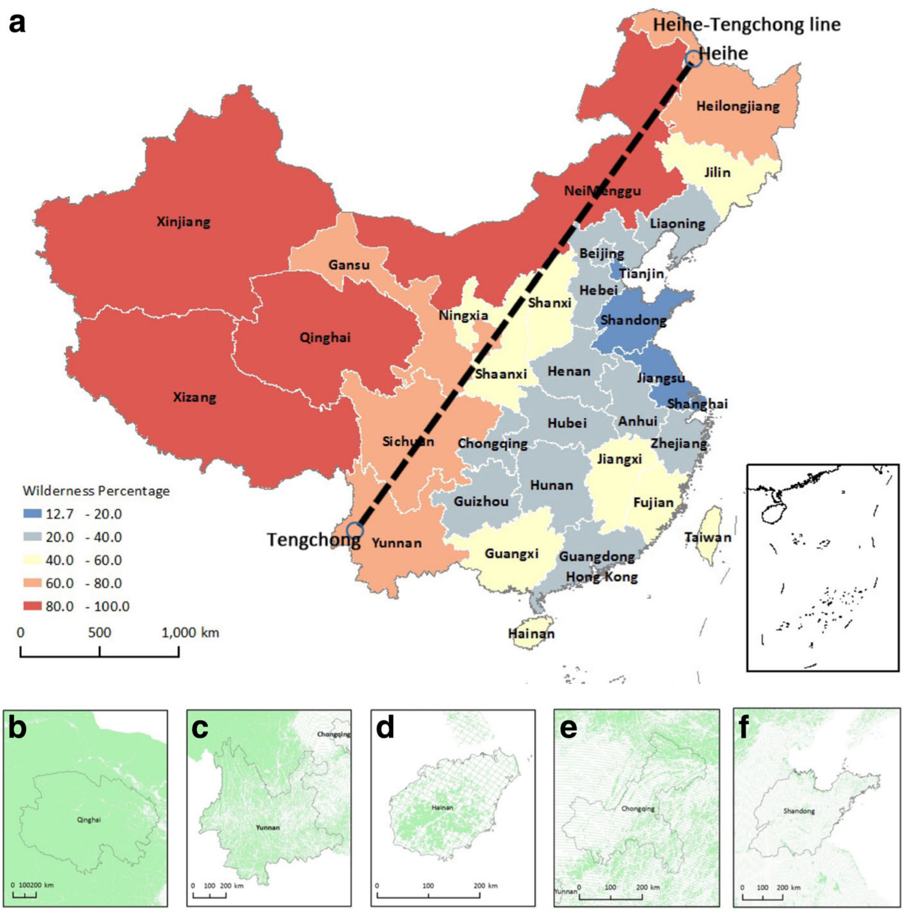

Fig. 5 **a** The wilderness ratio in provincial administrative regions. **b** the wilderness pattern in Qinghai (ratio between 80.0 and 100.0). **c** the wilderness pattern in Yunnan (ratio between 60.0.01 and 80.0). **d** The wilderness pattern in Hainan (ratio between 40.0 and 60.0). **e** The wilderness pattern in Chongqing (ratio between 20.0 and 40.0). F the wilderness pattern in Shandong (ratio between 12.7 and 20.0)

any individual provincial administrative region, and this ratio is less than 20% in eastern coastal provincial administrative regions of China.

Evaluating Existing National Nature Reserves Using Identified Wilderness

Evaluating existing national nature reserves using identified wilderness is a positive contribution to assessing eco-space protection schemes and natural resource management by observing wilderness ratios in national nature reserves. Comparing wilderness ratios in existing national nature reserves, the results in Fig. 6a and b reveal that some national nature reserves in China have a well-protected status and are associated with suitable wilderness areas, while some national reserves are not protected well and are not wilderness from the human activity aspect. However, the wilderness quality in national reserves is only evaluated from the perspective of human activity, or from the amount of perceived wilderness rather than ecological wilderness. Thus, there is a mismatch here between wilderness quality and biodiversity goals, and national nature reserves with a low wilderness ratio can have good biodiversity. Similar to the distribution of wilderness, the protection of national nature reserves embeds strong duality (see Appendix Table 3). Protection of nature reserves in western parts of China is better, while in eastern China most of the reserves fail to protect eco-space, and a few new eco-space protection schemes and natural resource management approaches are required to remediate damaged wilderness in protection areas. This detailed research result is shown in Table 1. The average wilderness rate is 87.1% among the total 178 national nature reserves situated in west China, and this percentage is 76.2% among the total 104 national nature reserves situated in eastern China. The average wilderness ratio is relatively high at nature reserves in Xinjiang, Gansu and Xizang provinces while it is low in protection areas in Hainan, Tianjin and Fujian in the eastern part of China. In eastern China, the wilderness ratio at national reserves in Shanghai is the highest, followed by those reserves situated in Jiangsu and Hebei provinces. Yunnan in western China is the worst in terms of wilderness ratio in their national nature reserves.

The following table (see Table 2) illustrates the top 10 and bottom 10 national nature reserves according to wilderness ratio from high to low. The wilderness percentage is 23.6% at Rongcheng Swan Nature Reserve, which is lowest amongst all 397 nature reserves. By contrast, this value in Qiangtang Nature Reserve is 99.3%, which is the highest in all Chinese national nature reserves. The outcome can highlight exemplar reserves for other protection areas from an eco-space management perspective and suggests the worse protection areas which require a change to their planning scheme according to wilderness stock and location. For instance, reserves may set appropriate limits in order to protect the ecological service of nature protection areas, considering their environmental carrying capacity.

Following the studies mentioned above, wilderness patterns are illustrated from a visual perspective in six typical national nature reserves to check their conservation conditions. At the Qiantang Nature Reserve in Xizang, the Sanjiangyuan Nature Reserve in Qinghai and the Mount Qomolangma Nature Reserve in Xinjiang, there is a large amount of wilderness that has been well protected (see Fig. 6c–h) - these three national reserves are all located to the west of the Heihe-Tengchong Line - while in the Datian Nature Reserve in Hainan, the Dalian Harbor Seal National Reserve in Dalian and the Shengjinhu Nature Reserve in Anhui, the area of wilderness is less (see see Fig.

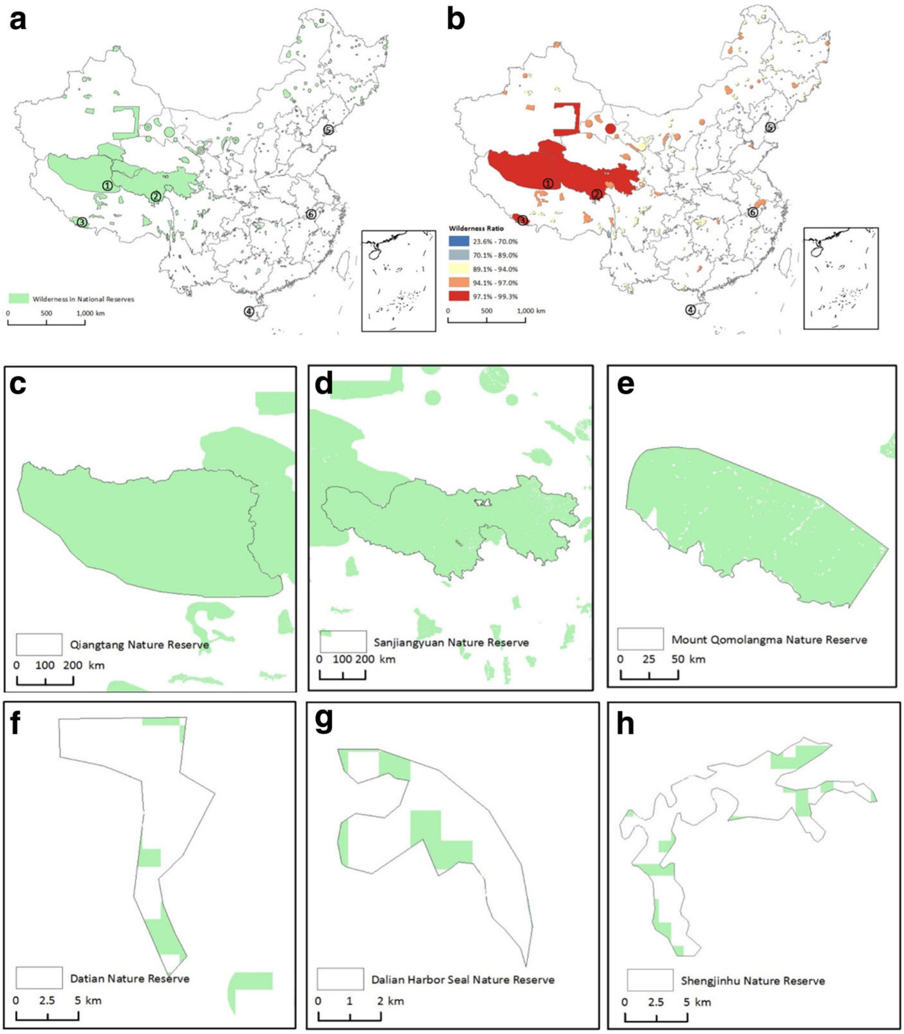

Fig. 6 **a** The location of wilderness in nature reserves according to Tencent LBS data. **b** The wilderness ratio in Chinese national nature reserves. **c** The wilderness pattern in the Qiantang nature reserve. **d** The wilderness pattern in the Sanjiangyuan nature reserve. **e** The wilderness pattern in the mount Qomolangma nature reserve. **f** The wilderness pattern in Datian Nature Reserve. **g** The wilderness pattern in the Dalian Harbor seal nature reserve. **h** The wilderness pattern in the Shengjinhu nature reserve. Note: **c**–**e** are the top three reserves according to their wilderness ratio from high to low; **h**–**f** are the bottom three reserves according to their wilderness ratio from low to high (all typical reserves are over 5km^2 in size and have regular boundaries

6c–h). By contrast, these three national reserves are situated to the east of Heihe-Tengchong Line. In addition, the size of national reserves is relatively larger in the west than those reserves in the east. The urban expansion and compact development in Chinese eastern cities are stronger than in western cities and can cause this imbalance. The size of the Datian Nature Reserve, the Dalian Harbor Seal National Reserve in Dalian and the Shengjinhu Nature Reserve are 43km^2, 18km^2 and 85km^2 respectively. In terms of habitat type, the larger national reserves in the west are more comprehensive

Table 1 The duality of wilderness ratio in national nature reserves

Provinces		Number of reserves	Ratio (%)
Western China	Xinjiang	10	95.4
	Gansu	18	92.5
	Xizang	9	91.8
	Neimenggu	31	89.2
	Chongqing	5	87
	Qinghai	7	86.9
	Ningxia	8	86.2
	Sichuan	27	85.9
	Guangxi	18	84.9
	Shannxi	18	84.8
	Guizhou	8	81
	Yunnan	19	79.8
	Total	178	87.1
Eastern China	Shanghai	2	91.1
	Jiangsu	3	87.5
	Hebei	12	83.8
	Liaoning	15	77.4
	Zhejiang	8	75.3
	Shandong	15	75.1
	Guangdong	15	75.1
	Beijing	3	74.6
	Fujian	14	70
	Tianjin	6	64.8
	Hainan	11	63.8
	Total	104	76.2

for the protection of forest systems, alpine meadows and wetlands. The reserves in the east are mainly for special species, such as Eld's deer, harbor seal and waterfowl.

Discussion

In this study, 29 human activity records were used as a threshold to identify wilderness (less than one recorded count per day on average in February 2016). The human activity threshold was also checked by using other recorded counts in every grid square.

Using conventional GIS and MCE methods, the spatial distribution of wilderness areas was identified at the national scale on the Chinese mainland in 2018 (Cao et al. 2018), prior to the new data approach being suggested in this article. In that study, a set of indicators and measures that reflect remoteness and naturalness were used, including remoteness from settlement, remoteness from access, biophysical naturalness, and apparent naturalness, as the basis for wilderness mapping (see Fig. 7a–d). Data inputs were

Table 2 The top 10 and bottom 10 nature reserves according to their wilderness ratio

	Top 10	Province	Ratio %	Area Km^2		Bottom 10	Province	Ratio %	Area Km^2
1	Qiangtang Nature Reserve	Xizang	99.3	319,328	1	Rongcheng Swan Nature Reserve	Shandong	23.6	34
2	Sanjiangyuan Nature Reserve	Qinghai	98.8	299,150	2	Zhangjiangkou Mangrove Nature Reserve	Fujian	25.1	11
3	Mount Qomolangma Nature Reserve	Xinjiang	98.3	18,403	3	Xiamen Rare Marine Species Nature Reserve	Fujian	26.2	33,088
4	Altun Mountain Nature Reserve	Xizang	98.2	53,738	4	Shishou Wapiti Nature Reserve	Hubei	36.4	1567
5	Lop Nor Camel Nature Reserve	Xinjiang	98.0	54,921	5	Dazhou Islands Nature Reserve	Hainan	36.8	7000
6	Yanchiwan Nature Reserve	Gansu	98.0	13,600	6	Zhanjiang Mangrove Nature Reserve	Guangdong	37.7	193
7	Hoh Xil Nature Reserve	Qinghai	97.3	54,818	7	Yellow River Wetlands Nature Reserve	Henan	41.2	238
8	Xilingol Grassland Nature Reserve	Neimenggu	96.7	6624	8	Datian Nature Reserve	Hainan	42.5	43
9	Tarim Populus Euphratica Nature Reserve	Xinjiang	96.6	5670	9	Qingliang Peak Nature Reserve	Anhui	45.1	42
10	Qinghai Lake Nature Reserve	Qinghai	96.6	5944	10	Beipiao Bird Fossil Nature Reserve	Liaoning	47.2	4630

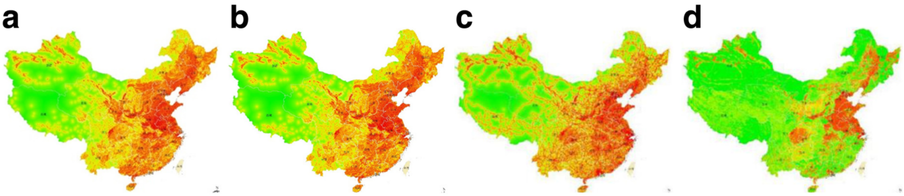

Fig. 7 The four indicators using the MCE method. **a** Remoteness from settlement. **b** Remoteness from access. **c** Biophysical naturalness. **d** Apparent naturalness. From red to green, the value decreases (Cao et al. 2018)

given the same weight to reflect their importance in reflecting wilderness characteristics and a resolution of one square kilometer measuring units was applied. The result of Cao et al. (2018) is illustrated in Fig. 8. A total of 52.6% of national land was classified wilderness, among which high-quality wilderness and relatively high-quality wilderness occupy 16.7%, mainly located in western China, and medium quality and low-quality wilderness occupy 35.9%, located in western, middle and eastern parts of China. The proportion of wilderness is smaller than in the straightforward new data mapping approach presented in the current research, which is 71.8%. Comparing the wilderness map generated by a conventional MCE method to the new data approach, it can be seen from two figures (see Figs. 4 and 8) that the difference between the two methods mainly is in the identification of wilderness in the central part of China. More precisely, in three provinces in central China: Shanxi, Jilin and Heilongjiang. The difference in the value of wilderness between these two approaches are over 20%. According to the MCE method, the wilderness occupies 10.2% of the total province area in Shanxi, while this percentage is 55.7% through the big LBS data approach. This difference value is 45.5% which is the biggest amongst all Chinese provinces when comparing these two methods. In addition,

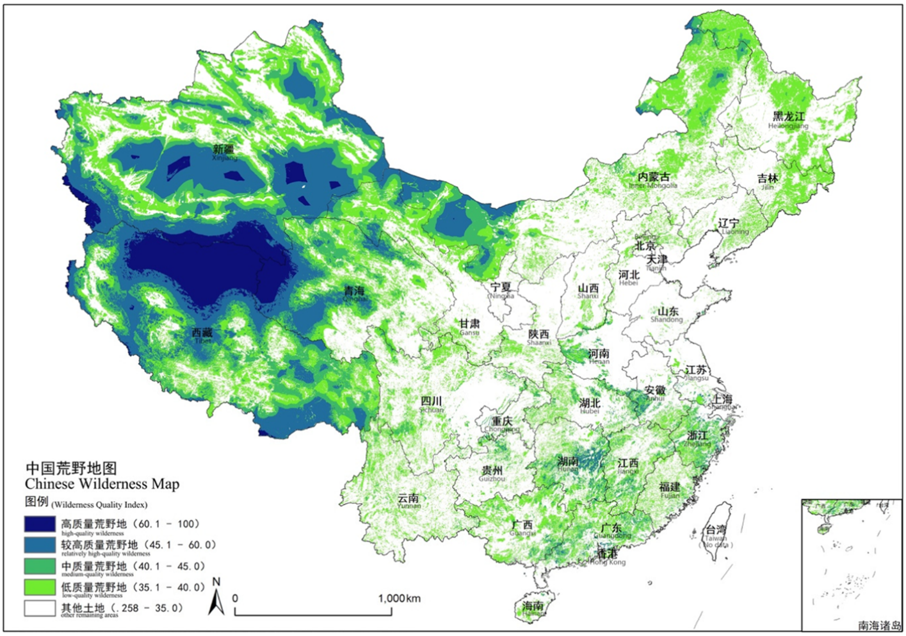

Fig. 8 Wilderness map in China based on the MCE method (Cao et al. 2018)

using the new data approach, the wilderness percentages in Qinghai and Sichuan, which are located in western China, are much larger than that identified using the MCE method. For example, the wilderness area covers around 119,477km^2 in Sichuan Province according to the MCE approach, but this area is around 334,880 km^2 based on the new approach.

The MCE method and new data method both have their drawbacks and advantages. Due to the data missing and subjectivity in indicators and statistical approaches, wilderness mapping will always have a deviation from the practical reality to some extent. Therefore, it is necessary to consider more than the final outcomes and attention should also be paid to the reasons behind the outcomes so that bias can be identified and decreased, and a delineating approach can be chosen according to practical requirements. For instance, the big data approaches based on LBS data, cellular signaling data, Flickr photos and other crowdsourced data can reflect human mobility and supervise the immediate change of perceived wilderness, however, the big data approaches lack other ecological restrictions which may lead to the identified wilderness being larger. Moreover, the MCE method may be overly restrictive with many layers of data and many uninhabited areas with no human data traces being identified as wilderness area.

This article also integrates the big LBS approach with the MCE approach. The LBS approach could work as a tool to revise the outcomes of wilderness mapping based on MCE. In this article, the authors use the LBS approach to revise the Chinese wilderness map delineated by Cao et al. (2018). The wilderness map drawn based on the LBS method gives attention to human activity, but lacks consideration of ecological factors. Integrating the LBS approach with conventional an MCE approach can integrate ecological factors along with the perceived wilderness to identify a more accurate wilderness pattern.

Through weeding out the wilderness areas that are not delineated by the LBS approach, in the wilderness identified by the MCE approach, a new Chinese wilderness map can be drawn (see Fig. 9). The percentage of each category: high-quality wilderness, relatively high-quality wilderness, medium-quality wilderness and low-quality wilderness is 4.4, 12.2, 11 and 20.9% respectively. The high-quality wilderness and relatively high-quality wilderness which occupy 16.7% of total area in the MCE method decrease only 0.1% after revision, and the medium quality and low-quality wilderness which occupy 35.9% in the MCE method drop 4%. This means that for the wilderness with low quality, the human activity is more crucial for wilderness mapping apart from remoteness and naturalness. The wilderness map covers 4,911,562 km^2 for the whole China after revising using LBS data, and occupies 92% of the wilderness delineated by the MCE method. Through integrating a wilderness map delineated by LBS data with the MCE method, it offers a much clearer wilderness map. A big data approach works as a tool to revise and can be expected to be widely used in the future in practical wilderness mapping.

Conclusions

In this article, a novel straightforward new data approach is developed to identify wilderness across China using Tencent LBS data. This approach is derived from the

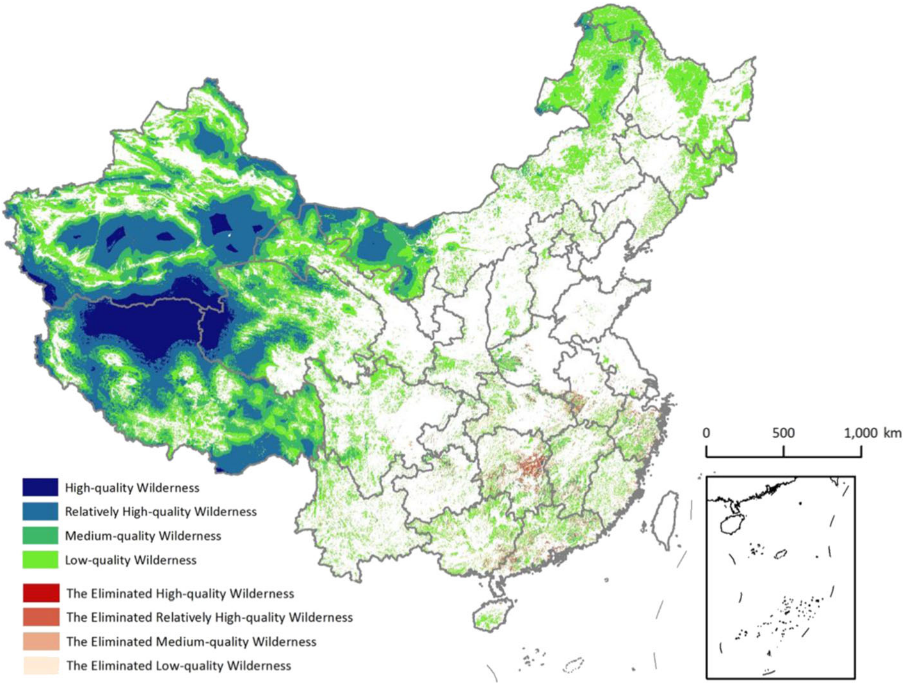

Fig. 9 Wilderness map in China based on the MCE method after revising by LBS method

observation of human activity rather than from the evaluation of wilderness through MCE methods based on their naturalness (land cover, biophysical naturalness, etc.) and remoteness (distance from nearest settlements, lack of human infrastructure, etc.) and recognizes that the wilderness consists of those areas with no human electronic traces. This method can directly inform protection schemes for national nature reserves from human activity aspects and lead efficient management.

In this study, Tencent LBS data is used to generate a wilderness map which has a wilderness area of 6.9 million square kilometers for the whole of China (see Fig. 4). To the west of the Heihe–Tengchong Line, the wilderness is at very high proportion. The wilderness ratios to the east of this line by contrast are lower than those of cities situated to the west. The wilderness mapping is also combined with national nature reserves by calculating the wilderness ratio of every national nature reserve. Through illustrating the top 10 and bottom 10 nature reserves by wilderness ratio, the best nature reserves based on protection condition, and the worst nature reserves that require immediate improvement, are revealed. These outcomes can be applied by informing the local land managers of existing protection areas. Using six typical national nature reserves, the wilderness patterns as well as the sizes and habitat types in these national nature reserves are illustrated. In the discussion section, the difference between wilderness mapping using a traditional MCE approach was discussed. A total of 52.6% of national land was classified wilderness by the MCE approach, which is 19.2% lower than the wilderness identified by LBS data. In three provinces in central China, Shanxi, Jilin and Heilongjiang, this difference value is larger than 20%. In addition, this study integrates the MCE method and LBS data method and uses the wilderness delineated by LBS to revise the wilderness map made by MCE. After revising, the wilderness map which covers 4,911,562 km^2 for the whole China is generated. It occupies 92% of the wilderness delineated by the MCE method (see Fig. 9).

The potential applications of this study include the following: to evaluate conservation conditions for existing nature reserves and identify possible locations and patterns of wilderness, to dynamically monitor protection areas and implement policies for other eco-space and optimize protection area system planning. In addition, the wilderness map delineated by LBS data in this study can work as a tool to revise the MCE method with GIS, and with the boom of new data creation, this work will contribute to wilderness identification at various spatial scales and geographical areas.

One limitation is that only limited amounts of data were captured (in 1 month, February), and other sets of data were contrasting. In addition, though the Tencent LBS data represent China's largest databases of online footprints, those people who do not have traceable devices are not considered. Moreover, in this article, wilderness areas are identified by observing where people are not recorded, while other restrictions are not considered, this may lead the total wilderness area to be larger than in reality. The 1km^2 resolution grids also hinder wilderness identification at detailed scales. It is acknowledged there are potential biases in this study and more comprehensive data will be used in future studies, with more exploration of wilderness mapping over longer time periods.

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Compliance with Ethical Standards

Conflict of Interest The authors declare that they have no conflict of interest.

Appendix 1

Table 3 The wilderness ratio in provincial administrative regions (excluding Macao)

Provincial Administrative Regions	Wilderness Area (km^2)	Total Area (km^2)	Ratio (%)
Anhui	29,636	139,700	21.2
Beijing	5218	16,800	31.1
Chongqing	27,879	82,300	33.9
Fujian	58,590	121,300	48.3
Gansu	317,579	454,400	69.9
Guangdong	63,048	180,000	35
Guangxi	98,355	236,000	41.7
Guizhou	63,428	176,000	36
Hainan	13,889	34,000	40.9
Hebei	72,778	187,700	38.8

Table 3 (continued)

Provincial Administrative Regions	Wilderness Area (km^2)	Total Area (km^2)	Ratio (%)
Heilongjiang	349,586	454,800	76.9
Henan	37,138	167,000	22.2
Hong Kong	289	1101	26.3
Hubei	60,389	185,900	32.5
Hunan	67,046	211,800	31.7
Jiangsu	16,714	102,600	16.3
Jiangxi	67,150	167,000	40.2
Jilin	110,838	187,400	59.2
Liaoning	52,639	145,900	36.1
Neimenggu	1,038,564	1,183,000	87.8
Ningxia	32,593	66,400	49.1
Qinghai	697,077	722,300	96.5
Shaanxi	115,124	205,600	56
Shandong	27,077	153,800	17.6
Shanghai	801	6300	12.7
Shanxi	86,998	156,300	55.7
Sichuan	334,659	481,400	69.5
Taiwan	20,394	36,000	56.7
Tianjin	1910	11,300	16.9
Xinjiang	1,568,569	1,660,000	94.5
Xizang	1,194,741	1,228,000	97.3
Yunnan	231,139	383,300	60.3
Zhejiang	34,903	102,000	34.2
Average	**213,692**	**292,345**	**46.8**

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