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Research Paper

Mapping wilderness in China: Comparing and integrating Boolean and WLC approaches

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ABSTRACT

Wilderness protection is increasingly important in the era of the Sixth Extinction and the Anthropocene. Mapping environmental indicators along a continuum of human modification provides key information for wilderness protection. However, uncertainty may occur in identifying wilderness areas by reclassifying wilderness continuum maps. In this study, an approach integrating both Boolean overlay and Weighted Linear Combination (WLC) is used to identify discrete wilderness patches and evaluate their relative wilderness quality. This approach is applied to China with a resolution of 1 km^2. The wilderness patches are first identified using Boolean overlay with discrete thresholds for land use, distance from settlements and roads. A Wilderness Quality Index is then created using a WLC model by weighting and combining six wilderness quality indicators including biophysical naturalness, population density, remoteness from settlements, remoteness from roads/railways, settlements density and roads/railways density. An integrated wilderness map is then created by combining the results from the Boolean and WLC models. It is found that China is a highly wild country in parts, containing over 86,000 wilderness patches, with varying relative wilderness qualities, which covers approximately 42% of China's terrestrial area. About 77% of the existing wilderness patches are not covered by nature reserves, indicating the obvious conservation gaps of China's wilderness areas. The wilderness maps presented here could potentially support new wilderness protected area designation, connectivity conservation, and monitoring programs. This integrated approach of wilderness mapping is potentially useful for other countries in conducting their own wilderness inventories and developing wilderness conservation policies.

1. Introduction

We are currently in the Sixth Extinction and a new geological epoch, known as the Anthropocene (Lewis & Maslin, 2015). Wilderness areas are shrinking rapidly, which in turn may have catastrophic effects on conserving biodiversity and maintaining ecosystem services. Over the past 20 years, approximately 9.6% of the remaining terrestrial wilderness has been lost globally (Allan, Venter, & Watson, 2017; Watson et al., 2016) and only 13.2% of the oceans can still be classified as marine wilderness (Jones et al., 2018). With ongoing anthropogenic threats, including climate change, pollution and habitat loss, wilderness protection and restoration (rewilding) are increasingly important both present and future (Casson et al., 2016).

Robust, reliable and repeatable mapping is crucial to the development of better wilderness protection policies since it provides basic information about the location, size and quality of these areas (Carver & Fritz, 2016). In the past 30 years, several wilderness mapping projects have been conducted at global scale, which have revealed patterns and trends in the world's remaining wilderness (McCloskey & Spalding, 1989; Sanderson et al., 2002; See et al., 2016; Watson et al., 2016). However, limitations in the scale (generalization), completeness and resolution of global datasets indicate that global-scale assessments often do not include many locally important wilderness areas which have high conservation value at national and local levels. In order to address this issue, national wilderness mapping studies based on national datasets have been conducted in several countries including Australia (Lesslie & Maslen, 1995), the United States (Aplet, Thomson, & Wilbert, 2000), the United Kingdom (Carver, Evans, & Fritz, 2002), Iceland (Olafsdottir & Runnström, 2011), Denmark (Müller, Bøcher, & Svenning, 2015), Scotland (Carver, Comber, McMorran, & Nutter, 2012), Austria (Plutzar, Enzenhofer, Hoser, Zika, & Kohler, 2016), China (Cao, Long, & Yang, 2017) and Switzerland (Radford, Senn, & Kienast, 2019). A summary of previous wilderness mapping projects is shown in Appendix (Table S1).

China is the world's fourth largest country, covering terrestrial area of 9.6 million km^2, and is the world's most populous country with 1.4 billion people. Despite its population and long history, China is one of the 17 mega-biodiverse countries identified by Conservation International (Mittermeier, 1997), and contains significant areas of wilderness (McCloskey & Spalding, 1989; Sanderson et al., 2002). China can therefore be defined as one of the "mega-wild" countries in the world (Watson et al., 2018). However, with China's recent rapid

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economic development and associated urbanization, wilderness areas have been threatened as land is converted for agriculture, urbanization and infrastructure projects (especially road construction) as well as facing threats from improper management of tourism activities, poaching, and resource exploitation such as the damming of rivers, forestry and mining.

To date, China's protected areas cover 18% of the total terrestrial area (Cao, Peng, & Liu, 2015; Miller-Rushing, Primack, Ma, & Zhou, 2017; Xu et al., 2017), just exceeding the 17% terrestrial target set by the Aichi Targets (CBD, 2010). The overall system consists of various types of protected areas including Nature Reserves, Scenic Areas, Forest Parks, Geological Parks, Water parks, Wetland Parks and Desert Parks (Zhao, Peng, & Yang, 2016). Within this system, nature reserves protect over 15% of the total land area and therefore represent the main component within the protected area system (Xu et al., 2017). According to the regulations, there are three types of functional zones in nature reserves. These include core, buffer and experimental zones, of which the core and buffer zones are designed to protect ecosystems in their natural state and therefore human access is strictly prohibited except for scientific research purposes. In this way, China's nature reserves serve as the main protection mechanism for its wilderness areas.

In addition, China's national policy of "Eco-civilization" creates new opportunities for wilderness protection. China is currently undergoing a process of establishing a new national park system and reorganizing the existing protected area system (Huang et al., 2018; Yang, 2017; Zhao et al., 2016). In 2017, China unveiled the general plan for the national park system, which called for the strictest measures to protect the country's natural ecosystems, the first of which will be set up in 2020 (The General Office of the CPC Central Committee and the General Office of the State Council, 2017). This plan states that the key role of Chinese national parks is to "protect the authenticity and integrity of the natural ecosystem". The authenticity of ecosystems in this context refers to landscapes and ecosystems with high degree of wildness, free from human disturbance and lack of human artefacts (Ouyang et al., 2018; Yu, Zhong, & Zeng, 2018). Additionally, the latest guidelines suggest that national park should be composed of Core Protection Zone (CPZ) and General Control Zone (GCZ), in which human activities are prohibited in the CPZ and restricted it in the GCZ (The General Office of the CPC Central Committee and the General Office of the State Council, 2019). In this context, national parks and nature reserves will together serve as the main protection mechanism of China's wilderness areas in the future (Yang, Shen, & Ma, 2019). A new proposal has been made to establish a *Chinese Wilderness Preservation System* (CWPS), consisting of the core protection zones of nature reserves and national parks, as a sub-system of the new protected area system (Cao & Yang, 2017). In this context, there is an urgent need to identify specific wilderness areas with discrete and clear boundaries based on widely acknowledged international wilderness definitions and criteria (Casson et al., 2016). This information can support protected area planning in general, and especially the designation and zoning of new national parks and nature reserves.

There is currently no official definition of wilderness in China, though the word "Huāng-Yě" is commonly used (Tin & Yang, 2016), and so Category 1b "Wilderness Area" identified by the International Union for Conservation of Nature (IUCN) is used as a preferred frame of reference. IUCN Category 1b wilderness areas are defined as "*A large area of unmodified or slightly modified land, and/or sea, retaining its natural character and influence, without permanent or significant habitation, which is protected and managed so as to preserve its natural condition*" (Casson et al., 2016). According to this definition, wilderness area should be a clearly defined geographical space with a clear boundary (Dudley, 2008), with no permanent human settlements and mechanized vehicle roads within its boundary, and its land cover should be in its natural state. This clearly calls for robust and reliable wilderness maps to support decisions about the location, extent, and designation of China's wilderness areas under the proposed CWPS.

However, little research on mapping wilderness patches with clear boundaries at national scale has been done in China. Previous studies have notable limitations including poor data quality, subjective indicator weights and classification of wilderness quality (Cao et al., 2017; Cao, Yang, Long, & Carver, 2018). In addition, only the wilderness continuum itself was mapped, leaving wilderness patches with clear boundaries to be identified. While the initial inventory in these previous studies is useful in showing the overall geographical patterns in wilderness quality at national level, it remains difficult to apply the wilderness concept in relevant landscape planning policies without identifying specific wilderness patches with discrete and easily applied boundaries. It is important that this knowledge gap is closed before the new protected areas system is fully designed and implemented. Therefore, this paper aims to:

1. Compare and integrate Boolean and WLC approaches in order to identify wilderness patches with clearly defined boundaries, while also quantifying the wilderness quality within these patches.
2. Apply this approach to China's terrestrial area at national scale by creating a new integrated wilderness map, which can be used to refine the result in the previous study by Cao et al. (2017) and serve as the baseline for monitoring changes of wilderness quality in the future.
3. Assess to what extent these wilderness areas are protected in China's existing nature reserve system, which could then further inform and strengthen wilderness protection policies in China.

2. An integrated approach for mapping wilderness

2.1. Advantages and limitations of the WLC approach

In the book "*Wilderness and the American Mind*", Roderick Nash proposes that wilderness is just one extreme on a scale of environmental modification continuum from the "paved to the primeval" (Nash, 1993). This emphasizes the transition of landscapes from urban areas to "pristine" nature resulting from varying levels and types of human modification. Using this as a model, Lesslie firstly proposed the use of the wilderness continuum concept in creating the Australian Wilderness Inventory (Lesslie & Taylor, 1985). This has subsequently been regarded as the main theoretical basis of mapping wilderness and has been widely used across various spatial scales and locations (Aplet et al., 2000; Cao et al., 2017; Carver, Comber, McMorran, & Nutter, 2012; Carver, Evans, & Fritz, 2002; Carver & Fritz, 1995; Comber et al., 2010; Hou, Zhai, Qiao, & Walz, 2019; Kuiters et al., 2013; Lin et al., 2016; Mc Morran, Price, & Warren, 2008; Müller, Bøcher, & Svenning, 2015; Olafsdottir & Runnström, 2011; Radford, Senn, & Kienast, 2019). The wilderness continuum is usually mapped using spatial indicators of naturalness and remoteness wherein it is assumed that if an area is more natural and more remote from human disturbance, then it is likely to be relatively wilder in comparison to those areas which are more developed and easily accessible.

To date, the most commonly used method in wilderness quality mapping is Weighted Linear Combination (WLC) which is one of the classic approaches of GIS-based Multi-Criteria Evaluation (MCE) models (Carver, 1991; Malczewski & Rinner, 2015). The principal advantage of the WLC approach is that it recognizes the relative nature of the wilderness concept and maps the wilderness continuum by considering the full range of the data inputs, which then identifies both the wildest and least wild locations and all points in between(Carver et al., 2012; Lesslie & Taylor, 1985; Orsi, Geneletti, & Borsdorf, 2013; Radford et al., 2019). Using this method, several wilderness indicators can be weighted according to their relative importance and combined to produce a wilderness continuum showing the variation in wilderness quality across the chosen area of interest. By reclassifying the wilderness continuum using statistical methods, the areas with the highest wilderness quality (i.e. the wildest areas) can be highlighted and used to define candidate wilderness protected areas. For example, Kuiters et al. (2013) selected the top 1%, 5% and 10% wildest cells for Europe by reclassifying a wilderness continuum based on remoteness from settlement and roads and naturalness of land cover. In another example Lin et al. (2016) segmented the wilderness continuum for the Three Parallel Rivers Region of China into 10 levels using the unsupervised classification method, with level 1 identified as wilderness areas to be protected. In a study covering the mainland China, Cao et al. (2017) reclassified the wilderness continuum to divide all lands into five types, including high-quality, relatively-high-quality, medium-quality, low-quality wilderness areas and all non-wilderness areas. Elsewhere Radford et al. (2019) identified two types of wilderness areas in Switzerland, which lie within the top 10% and top 25% wilderness quality by segmenting the wilderness continuum. As demonstrated in these examples, the thresholds used to reclassify the wilderness continuum are usually quite arbitrary and clearly exert a significant influence on the areas identified.

In this paper it is suggested that there are two major limitations in identifying wilderness areas by reclassifying the wilderness continuum. Firstly, it ignores many local *de facto* wilderness patches (without permanent human settlements, mechanized vehicle roads, and unnatural land cover), which could not reach the top percent in terms of overall wilderness quality at the broad scale. For instance, if a threshold of the top 10% wildest areas is used in selecting the wilderness areas to be protected across the whole area of interest, all other wilderness patches below this threshold will be ignored, regardless of their regional and local conservation value. Secondly, this approach may conversely include some localized non-wilderness areas where permanent human settlements, mechanized vehicle roads, and unnatural land covers exist within larger wilderness areas. Again, this may cause improper delineation of protected area boundaries resulting in increased management costs, or elevated conflict with local, affected communities.

2.2. Integrating the Boolean overlay and WLC approaches

To overcome the above limitations, we suggest integrating the Boolean and WLC approaches. The Boolean approach results in a simple map defining wild or not wild and, despite being a less common approach, has previously been used in creating a wilderness map of Norway (Brun, 1986) and the first global wilderness inventory (McCloskey & Spalding, 1989). Because defined boundaries are required for legal purposes, the Boolean overlay approach can be very useful in producing maps that clearly demarcate areas as either wild or non-wild when drawing up protected areas designation and zoning. However, Boolean overlay often results in the loss of information on overall patterns when determining relative wilderness quality, whereas the WLC approach maps the full spectrum of wildness by considering the full range of the data inputs, together with the relative importance of the indicators using user-defined weights.

By integrating the two approaches, their own strengths can be maintained, and weaknesses avoided or minimized. The main advantage of using such an approach is that, in a single project, researchers can identify both discrete boundaries of specific wilderness patches, while also quantifying the wilderness quality within them. As a result, this integrated approach can be used in identifying potential wilderness protected areas and thereby significantly enhance the planning of potential new national parks and nature reserves.

3. Methodology

To achieve the research goal, two GIS-based models were used. Boolean overlay was used to identify the wilderness patches, and a WLC model was used in quantifying variations in the wilderness quality of these patches. This integrated wilderness model is shown in Fig. 1. Before processing, data were converted to raster format and projected using Albers Equal Area Conic projection, with pixel size 1 km × 1 km. This resolution is deemed sufficiently fine for mapping wilderness at national scale in China.

3.1. Data collection

Data quality is extremely important in any spatial analysis, and the best available data are used here. Data sources are described in Table 1, including land use, railway, roads, settlements, population density, and boundaries of nature reserves. Data for the province of Taiwan that were currently lacking in mainland China datasets, were obtained and merged with that for mainland China to produce a single dataset for the whole study region. In addition, data outside of China were included within a 20 km buffer to avoid edge effects along the national border. Before processing, all data were cross-checked for consistency using overlay methods and visual comparison.

Settlements and roads were classified into different levels based on careful comparison and interpretation between different datasets and classification standards across China. Settlements were classified into three types based on the size and level according to the classification standard in the datasets. Level 1, 2, 3 settlements represent urban built area, towns, and villages or hamlets respectively. Specific information on settlement types is shown in Appendix (Table S2). Roads were classified into three types by function and traffic volume. Level 1 roads are national important roads or highways, while level 2 and level 3 represent regional and locally important roads. Specific information of road types is shown in Appendix (Table S3).

3.2. Identifying wilderness patches using Boolean overlay

Although there is no single definition of wilderness or method for identifying wilderness patches, most wilderness definitions have treated wilderness as undeveloped land with minimal human impact or influence (Lesslie & Taylor, 1985) and thus emphasize the presence of natural land cover types, lack of human settlements and absence of mechanized access from roads and railways (Casson, Martin, Watson, Stringer, & Kormos, 2016; European Wilderness Society, 2019; Fisher et al., 2010; Kormos, 2008; Leopold, 1921). These could be regarded as minimum basic requirements for wilderness areas and thus form the basis for a Boolean analysis. These are explained as follows:

1. Wilderness areas should contain only natural land cover. The IUCN 1b guidelines state that wilderness areas are unmodified or slightly modified areas, retaining their natural character and influence (Casson et al., 2016). According to the Land Management Law and land use classification in China, artificial land cover includes construction land and agricultural land. Construction land consists of urban land, rural settlement and other modified lands (including mines, large industrial areas, oil fields, quarries, roads and airports), while agricultural areas consist of rice paddy and arable fields (Liu et al., 2014). Thus, those areas with artificial land cover were excluded in identifying wilderness patches.
2. Wilderness areas should be roadless. The WILD Foundation defines wilderness areas as the most intact, undisturbed wild natural areas where human control is largely absent and there are no roads, pipelines or other industrial infrastructure (Kormos, 2008). Being free of mechanized vehicle roads/railways is seen as a key wilderness attribute in many wilderness mapping studies (Aplet et al., 2000; Hawes, Dixon, & Bell, 2018; Ibisch et al., 2016; Olafsdottir & Runnström, 2011; Selva et al., 2011) due to their varying adverse effects on natural areas (Forman & Alexander, 1998). After reviewing 282 scientific papers which provide information on the spatial effect of various roads, Ibisch et al. (2016) suggest that most of the impact of roads on natural areas declines significantly at distances greater than 1 km from the roadway. Roadless areas were therefore defined here as areas at least 1 km away from all types of roads and railways.

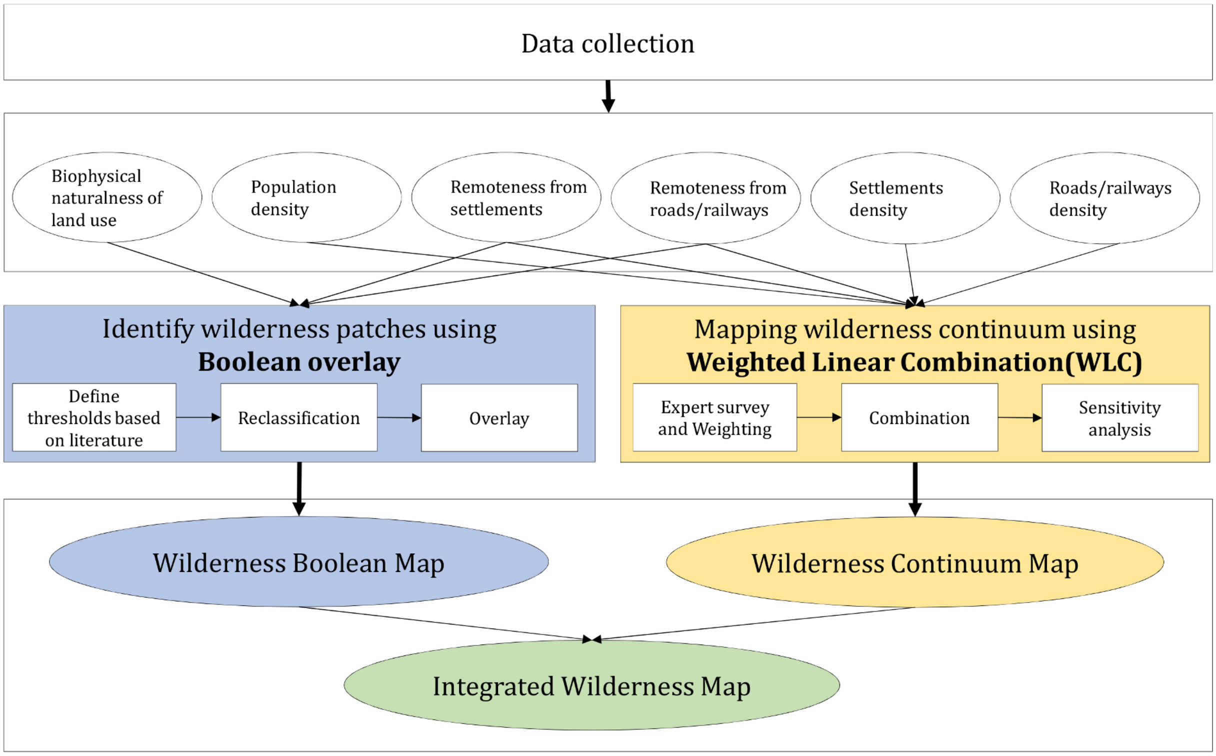

Fig. 1. Flow Chart of GIS-MCE Wilderness Model in China.

Table 1
Data sources.

Layer	Dataset	Resolution	Source	Year
Land use	Land use/Land cover	1 km	Data Center for Resources and Environmental Sciences, Chinese Academy of Sciences (RESDC) (http://www.resdc.cn)	2015
Settlements	Level 1 settlements	Vector	National Catalogue Service for Geographic Information (NCSFGI) (www.webmap.cn)	2015
	Level 2 settlements	Vector	NCSFGI	2015
	Level 3 settlements (mainland China)	Vector	NCSFGI	2015
	Level 3 settlements (Taiwan)	Vector	Open Street Map (OSM) (https://download.geofabrik.de/asia.html)	2018
Railway	Railway	Vector	NCSFGI	2015
Roads	Roads	Vector	NCSFGI	2015
	Roads	Vector	Open Street Map	2018
Population density	Population density (mainland China)	1 km	RESDC	2015
	Population density (Taiwan)	1 km	Socioeconomic Data and Applications Center (SEDAC). Gridded Population of the World (GPW version 4) (http://sedac.ciesin.columbia.edu/data/collection/gpw-v4)	2015
Protected areas	Protected areas boundary	Vector	World Database on Protected Areas (WDPA) (https://www.protectedplanet.net/)	2016

3. Wilderness areas should be free from permanent human settlements. IUCN 1b guidelines state that wilderness areas should be without permanent or significant human habitation (Casson et al., 2016). Human settlements (including built-up areas, towns and other small settlements) affect the natural environment in many ways. It has been found that human settlements exert negative effects on protected areas up to 1 km away through direct pressures including habitat loss, noise, trampling, firewood collection, exotic species establishment, and edge effects on microclimate (Decker et al., 2017; Mcdonald et al., 2009; McDonald, Kareiva, & Forman, 2008; Theobald, Miller, & Hobbs, 1997). We therefore excluded all types of human settlements with a 1 km buffer in identifying wilderness patches. It should be noted that some types of indirect effects of urban areas may influence natural places at distances much greater than 1 km (e.g. air pollution can be transcontinental) (Mcdonald et al., 2009). For the purposes of this study, these indirect effects that are regional to global in scale are not included in defining the minimum basic requirements for the identification of wilderness patches.

Using these three basic minimum requirements, all areas were classified into either "wilderness patches" or "non-wild" areas using Boolean overlay. Importantly, no minimum size (area) was included as a requirement for wilderness in this study. Although several wilderness definitions emphasize that wilderness areas should be "large", there is no universally accepted size or area threshold for wilderness. Considering the spatial heterogeneity of China, and the need to maintain the raw information of the wilderness areas, it was deemed more appropriate to include all wilderness patches at this stage since even the smallest wilderness patches might be ecologically important in a local or regional setting. This is particularly true in eastern China where the landscape is more heavily populated and highly modified. However, it is suggested that an area threshold could be applied later in the planning process according to specific policy objectives. For example, home-range sizes can be used to filter out smaller patches in modelling habitat suitability for conservation of wilderness-dependent species.

3.3. Mapping wilderness continuum using Weighted Linear Combination

3.3.1. Wilderness indicators mapping

Indicators which appropriately reflect variations in wilderness across China's varied landscapes were selected using previous studies as a guide (Aplet et al., 2000; Carver et al., 2002, 2012; Carver, Tricker, & Landres, 2013; Hawes et al., 2018; Kuiters et al., 2013; Lesslie & Maslen, 1995; Müller et al., 2015; Olafsdottir & Runnström, 2011; Plutzar et al., 2016; Radford et al., 2019). These include biophysical naturalness of land use (BN), population density (PD), remoteness from settlements (RS), remoteness from roads/railways (RR), settlements density (SD) and roads/railways density (RD). The above six indicators, which were deemed effective to reflect the wilderness quality from different perspective, were combined using the WLC approach to generate a wilderness continuum map. The selected six indicators are explained in the following paragraphs together with details on their meaning and measurement.

Biophysical naturalness of land use (BN) reflects the degree to which an ecosystem has been changed from its original state due to human modification by settlement, deforestation, and agriculture. This is often determined by assigning values to land use types based on expert knowledge (Carver et al., 2002, 2012; Kuiters et al., 2013; Liu et al., 2014; Müller et al., 2015; Radford et al., 2019). In this study, different naturalness scores (from 1 to 10, with 10 being the highest degree of naturalness) were assigned to different land-use types by 25 Chinese landscape experts, and the mean value was used to assign the naturalness score to each land use type (See Table 2, and details in Appendix Table S4). To account for the influence on naturalness caused by the local pattern of land use immediately adjacent to the observer (Carver et al., 2012), and following Lin et al. (2016), the mean value was calculated for each central cell within a moving window of 3 × 3 cells, so that the naturalness value varies smoothly across landscape.

Population density (PD) is an effective indicator of human disturbance on natural landscapes (Ge & Feng, 2009; Liu et al., 2014; Müller et al., 2015). Population density is supplied as a 1 km resolution raster. The mean value was calculated for each central cell within a moving window of 3 × 3 km cells to smooth the data and avoid edge-effects.

Remoteness from settlements (RS) is a commonly used wilderness indicator since it is widely regarded as a defining characteristic of wilderness (Fritz & Carver, 1998; Kuiters et al., 2013; Lesslie & Maslen, 1995; Olafsdottir & Runnström, 2011; Plutzar et al., 2016). This was calculated using Euclidean distance from the nearest settlement in this study. As different settlements have different relative importance, weights for the three levels of settlements were derived from the expert survey (Appendix Table S5) and the remoteness from settlements was calculated using a WLC sub-model such that it took their different impacts into consideration (Formula (1)).

$$\text{Remoteness} = \sum_{1}^{n} R_i * \beta_i \tag{1}$$

where n = 3, R_i represents the Euclidean distance from level-i settlements, β_i are weights for different levels of settlements.

Remoteness from roads/railways (RR) is also a commonly used wilderness indicator (Carver et al., 2002, 2012; Kuiters et al., 2013; Lesslie & Maslen, 1995; Olafsdottir & Runnström, 2011; Plutzar et al., 2016), since roads have the single largest impact on wilderness by means of fragmentation, connecting human settlements and giving access to land along their length and so facilitating its exploitation (Ibisch et al., 2016). Considering the large spatial scale of China and the resolution of the analysis, remoteness from roads and railways (RR) was calculated using Euclidean distance from the nearest roads/railways weighted by type. Higher level roads carrying higher traffic volume therefore have greater impact than lower level roads. The weights for the railway and three types of roads were derived from the expert survey (Appendix Table S6). Formula (1) was used, where n = 4, R_i represents the Euclidean distance from railway and different levels of roads, β_i are weights for different levels of roads and railways.

Settlements density (SD) reflects apparent naturalness, or absence of human artefacts which is related to perception of wilderness and visual impact (Carver et al., 2012; Radford et al., 2019). Considering the distance decay effect, a kernel density function was used with a search radius of 20 km. This is assumed to be the maximum visual distance on a clear day (Bishop, 2002), and is also the distance an individual can reasonably walk in a day over a rough terrain (Lesslie & Maslen, 1995). The resulting kernel density raster is based on a quadratic formula with the highest value at the center of the surface and tapering to zero at the full extent of the search radius thus taking the distance decay effect into consideration. Overall settlements density was calculated by combining the kernel density raster for Level 1, Level 2 and Level 3 settlements in a WLC sub-model (Formula (2)).

$$\text{Density} = \sum_{1}^{n} D_i * \beta_i \tag{2}$$

where n = 3, D_i is settlements density, β_i are weights for different levels of settlements derived from the expert survey.

Roads/railways density (RD) reflects the density of the transportation infrastructure and associated human artefacts such as bridges, dams, power lines, etc. (Carver et al., 2013; Radford et al., 2019). Roads/railways density was again calculated using a 20 km radius kernel density filter for all railways together with Level 1, Level 2 and Level 3 roads. The same formula (2) as settlement density (SD) was used, where n = 4, β_i are weights for different levels of road/railways derived from the expert survey.

3.3.2. Indicator weighting based on expert survey

Following Müller et al. (2015) and Radford et al. (2019), an expert

Table 2
Biophysical naturalness of land use (0 = lowest, 10 = highest).

Land-use type (Land-use code)	Biophysical naturalness	Land-use type (Land-use code)	Biophysical naturalness
Paddy field (11)	3.04	Intertidal zone (45)	8.76
Dry field/Arable crops (12)	2.88	Bottomland (46)	8.48
Woodland (21)	7.20	Urban land (51)	1.28
Shrubbery (22)	7.16	Rural settlement (52)	2.12
Open forest land (23)	6.88	Other construction land (53)	1.24
Other woodland (24)	4.72	Sand land (61)	8.68
High coverage grassland (31)	7.56	Gobi land (62)	9.12
Medium coverage grassland (32)	7.48	Saline land (63)	8.36
Low coverage grassland (33)	7.44	wetland (64)	8.84
River canal (41)	4.36	Bare land (65)	7.48
Lake (42)	8.12	Bare gravelly land (66)	8.44
Reservoir pond (43)	3.60	Other unutilized land including alpine desert and tundra (67)	9.52
Permanent glacier and snowfield (44)	9.76		

survey was used to derive a robust set of weights based on professional knowledge. Twenty-five Chinese landscape experts familiar with the wilderness concept and with research experience in protected areas were asked to complete a survey designed to establish weights which were used in the WLC model.

Before starting the survey, the meaning of the six wilderness indicators were explained in detail to make sure the experts understood these correctly. They were then asked to conduct the importance rating for: (1) the relative importance of the six wilderness indicators; (2) the relative importance of different levels of settlements in calculating remoteness from settlements and settlements density; and (3) the relative importance of different levels of roads and railways in calculating remoteness from roads/railways and roads/railways density.

After collecting the data from the expert survey, the weights were calculated using Formula (3). The final indicator weight was produced based on the average value of the importance rating given by the 25 experts, which could reflect the collective expert opinion.

$$W_i = \frac{IR_i}{\sum_1^n IR_i} \tag{3}$$

where W_i is the indicator weight, IR_i is the importance rating (the average value of the 25 experts) for the i-th indicator, and n is the number of indicators (n = 6 in this case). The details of weights from the expert survey are shown in Appendix (Table S7).

3.3.3. Combining the wilderness indicators using Weighted Linear Combination

The six indicator maps (BN, PD, RS, RR, SD and RD) were used to calculate a wilderness continuum using the WLC model and the weights derived from the expert survey. Each indicator was normalized due to the different measurement units and data ranges. Following Lin et al. (2016) and recognizing that human disturbance on landscapes are limited and substantially unnoticeable after reaching a certain threshold, a logarithmic function (Formula (4)) was used to normalize the wilderness indicators so that all normalized values range from 0 to 1.

$$NI_i = \frac{\lg(a_i + 1)}{\lg(a_{imax} + 1)} \tag{4}$$

where NI_i is the normalized indicator, a_i is the value of the i-th indicator.

The Wilderness Quality Index (WQI) was then calculated according to Formula (5) using a WLC model.

$$\text{WQI} = \sum_1^n X_i * w_i \tag{5}$$

where n = 6, X is the normalized wilderness quality indicator, w_i is the weight of the i-th indicator derived from the expert survey, in this case, w_i = (0.192, 0.170, 0.155, 0.155, 0.164, 0.164).

3.3.4. Sensitivity analysis

The uncertainty of the wilderness continuum map mainly comes from the indicator weights. Therefore, it is necessary to conduct a sensitivity analysis to show the influence of the indicators weights on the results. Following Carver et al. (2013) and Radford et al. (2019), sensitivity analysis on the uncertainty of the indicator weights was conducted (Feizizadeh, Jankowski, & Blaschke, 2014). We calculated 25 sets of weights (reflecting the opinion from each expert) as randomized weights. Twenty-five wilderness continuum maps were then created by running the WLC model 25 times using different sets of weights. To demonstrate the overall sensitivity of the model and identify areas of localized sensitivity, the mean and standard deviation of the 25 result maps were calculated. This shows those regions that are most likely to be affected by the uncertainty related to the indicator weights and where the opinions of experts on the estimation of wilderness quality are much more consistent and robust.

3.4. Integrating and comparing wilderness continuum with wilderness patches

After identifying the wilderness patches from the Boolean overlay and generating the wilderness continuum from the WLC model, the mean value of Wilderness Quality Index (MWQI) within each wilderness patch was calculated to create an integrated wilderness map where the MWQI value reflects the general status of wilderness quality of each wilderness patch. The wilderness patches were then classified into ten levels based on the MWQI value using the Natural Breaks (Jenks) method. As a result, wilderness patches were identified according to minimum basic requirements using Boolean analysis and were also differentiated according to their wilderness quality using information derived from WLC methods.

To better illustrate the difference of the Boolean and WLC approaches, we quantitatively compared the wilderness continuum map with the wilderness patches map. First, the wilderness map from the previous study (Cao et al., 2017) and the wilderness patches map obtained in this study were quantitatively compared. In the previous study, the wilderness continuum was reclassified using certain thresholds to define wilderness areas (including high-quality, relatively high-quality, medium-quality and low-quality wilderness areas). Here we calculated the area of *de facto* wilderness patches and non-wild patches contained in the four types of wilderness areas identified by the previous study. Second, the new wilderness patches map and the wilderness continuum map were further compared. We reclassified the wilderness continuum into 10 categories using the equal area method and labelled them as top 10% to top 100%. We then calculated the area of wilderness patches and non-wilderness patches in each of these 10 categories, to further illustrate the limitations of reclassifying the wilderness continuum and the advantages of an integrated Boolean and WLC approach.

3.5. Assessing the conservation status of wilderness areas

Nature reserves in China are currently the main component of the protected areas system, which has the strictest protection mechanisms for wilderness areas. To date, there are 2644 terrestrial nature reserves of different levels (including 474 national nature reserves) which take up 14.94% of total land area (Xu et al., 2017). These are well represented within the World Database on Protected Areas (WDPA) (Chen, Tang, & Fang, 2009) and comprise 13.75% of the total land area of China, which is 92% of the officially reported nature reserves by area. This data is not complete, but is the best available data which is enough to represent most of the nature reserves in China. These were overlaid with the wilderness patches map to assess the conservation status of wilderness areas in China.

4. Results

4.1. Wilderness patches

Just over 86,000 wilderness patches were identified by Boolean overlay with a total area of just over 4 million square kilometers, which comprises approximately 42% of China's terrestrial area (see Fig. 2). The individual patches were classified into five types according to patch size (area), varying from Extra-small, Small, Medium through to Large and Extra-large wilderness patches (see Table 3). With increased patch size class, there is a corresponding and successive decrease in the number of patches in each class. There are over 70,000 Extra-small wilderness patches (smaller than 10 km^2) though these account for only 3% of the existing total wilderness by area, while there are only 19 Extra-large wilderness patches (larger than 10,000 km^2) accounting for nearly 23% of the existing total. It can be seen from Fig. 2 that the Extra-large wilderness patches are found only within the provinces of Xinjiang, Tibet, Qinghai and Inner Mongolia. Large wilderness patches

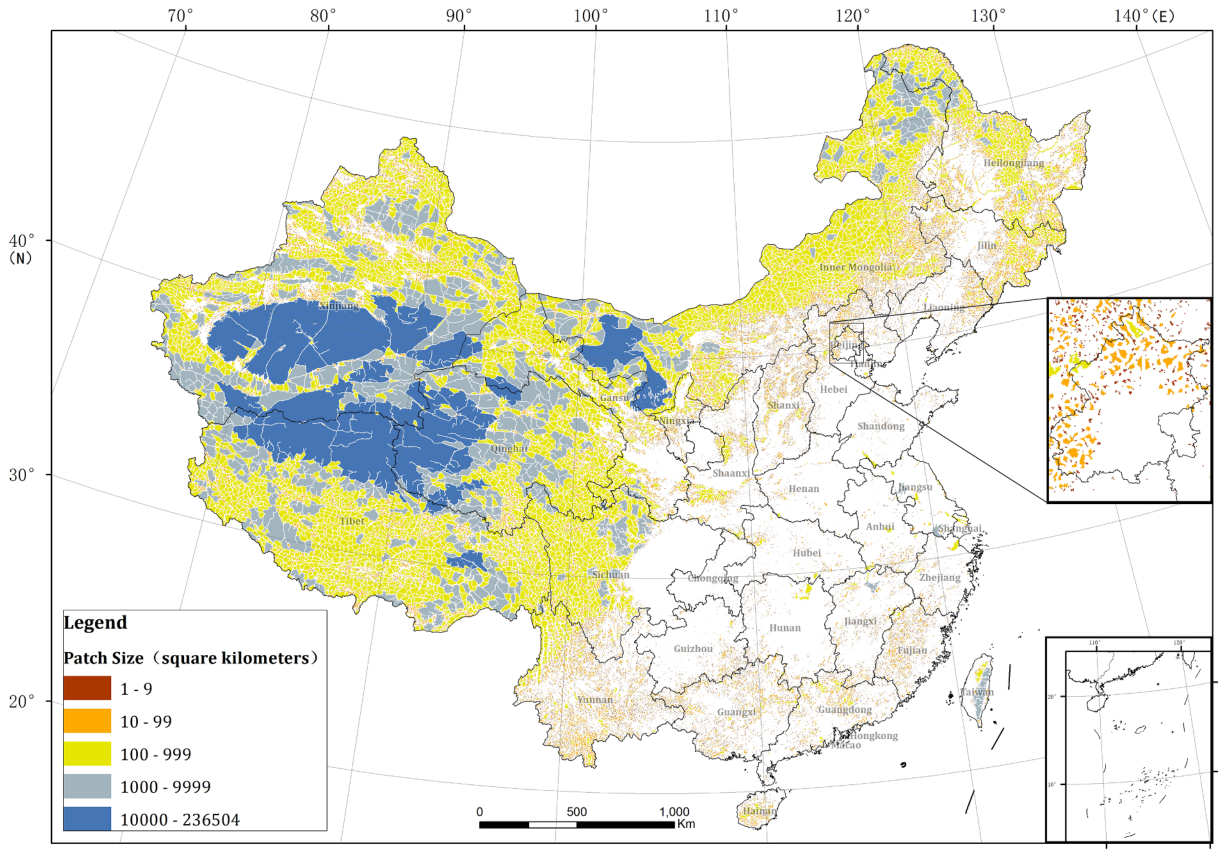

Fig. 2. Spatial distribution of wilderness patches identified by the Boolean overlay.

Table 3
Classification of wilderness patches based on patch size.

Wilderness patches type	Patch size (km^2)	Patch number	Ratio of patch number (%)	Total area	Ratio of total area (%)
Extra-small	1–9	70,223	81.57	124,328	3.08
Small	10–99	10,181	11.83	310,634	7.69
Medium	100–999	5203	6.04	1,649,980	40.85
Large	1000–9999	464	0.54	1,028,025	25.45
Extra-large	≥10000	19	0.02	925,773	22.92
Total	–	86,090	100	4,038,740	100

are mainly distributed in western China, while Medium, Small and Extra-small wilderness patches are distributed throughout most of the provinces, but crucially these can still be found in the densely populated and developed east of China. This is an important finding for maintaining a sample of protected wilder areas in eastern China.

4.2. Wilderness indicators and the wilderness continuum map

The spatial pattern of the six wilderness indicators are shown in Appendix (Fig. S1). These maps show the distribution and spatial patterns of biophysical naturalness of land use, population density, remoteness from settlements, remoteness from roads/railways, settlements density and roads/railways density. The different indicators share the same broad pattern at the national scale, reflecting the significant difference in landscapes between east and west China wherein the degree of human influence and landscape modification in the west of China is far lower than that in the east. Despite the similarity at the national scale, the precise patterns in the six wilderness indicators are significantly different at regional and local scales.

The wilderness continuum map of China combining the six indicators with the collective expert weights using the WLC model, is shown in Fig. 3. The regions with the highest wilderness quality are distributed in the northern part of Tibet, the western part of Qinghai, the southern part of Xinjiang and the western part of Inner Mongolia, while the regions with the lowest wilderness quality are distributed in coastal areas, north China plain, Sichuan basin, and other urban agglomeration regions.

The sensitivity to indicator weight uncertainty in the WLC model is shown in Appendix (Fig. S2). The maximum standard deviation is around 0.034 and as such is quite low, indicating that the estimation of wilderness quality is hardly affected by the uncertainty related to indicator weights. Specifically, regions with higher standard deviation are found principally in the regions with low wilderness quality highlighting the areas affected by human settlements, mechanized roads and artificial land covers. While in areas maintaining high wilderness quality, the standard deviation is much lower, demonstrating general agreement between the experts concerning the regions that are of highest wilderness quality. This indicates the robustness of the method in wilderness quality mapping using weights derived from the expert survey.

4.3. Integrated wilderness map

The integrated wilderness map is shown in Fig. 4. This is a combination of the Boolean wilderness patch map and wilderness continuum map derived using WLC model. This shows not only the spatial distribution of wilderness patches, but also the variation of wilderness quality within these patches. The wilderness patches are classified into

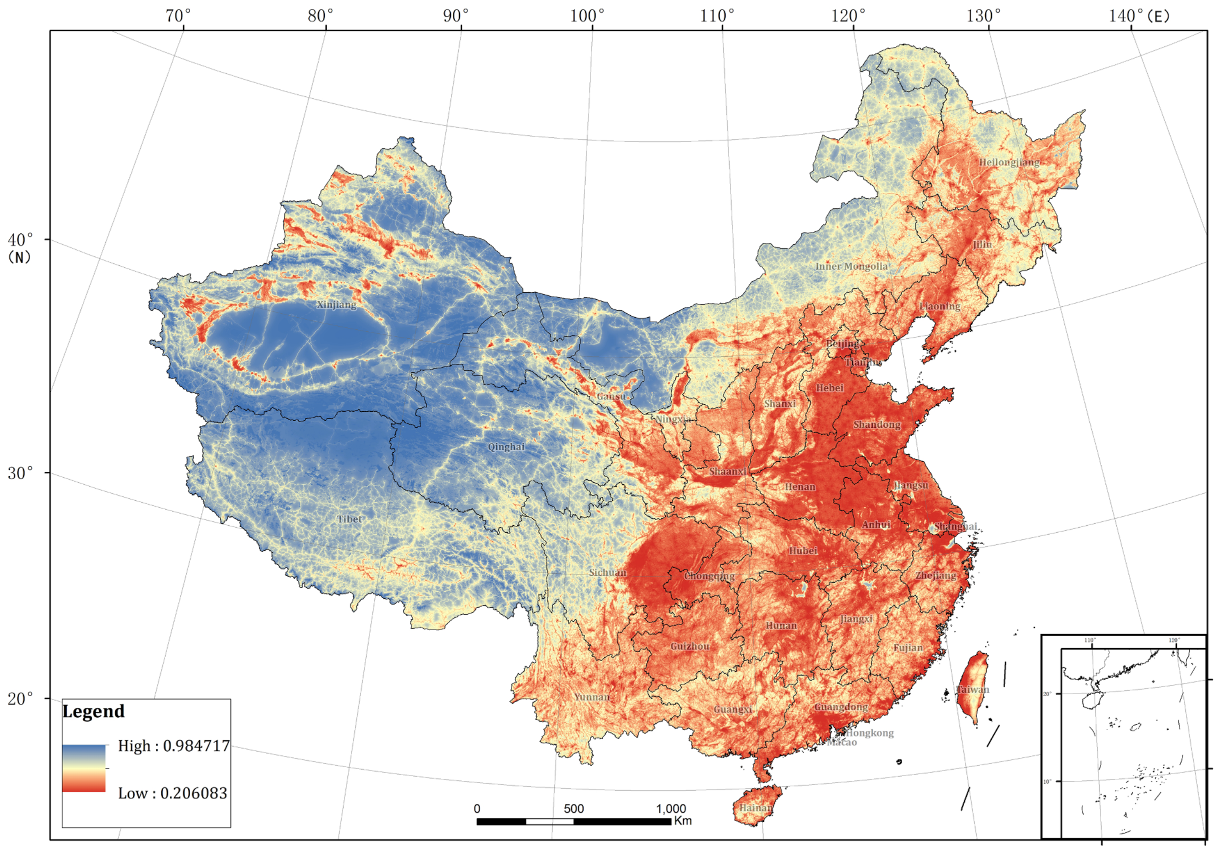

Fig. 3. Wilderness continuum map of China.

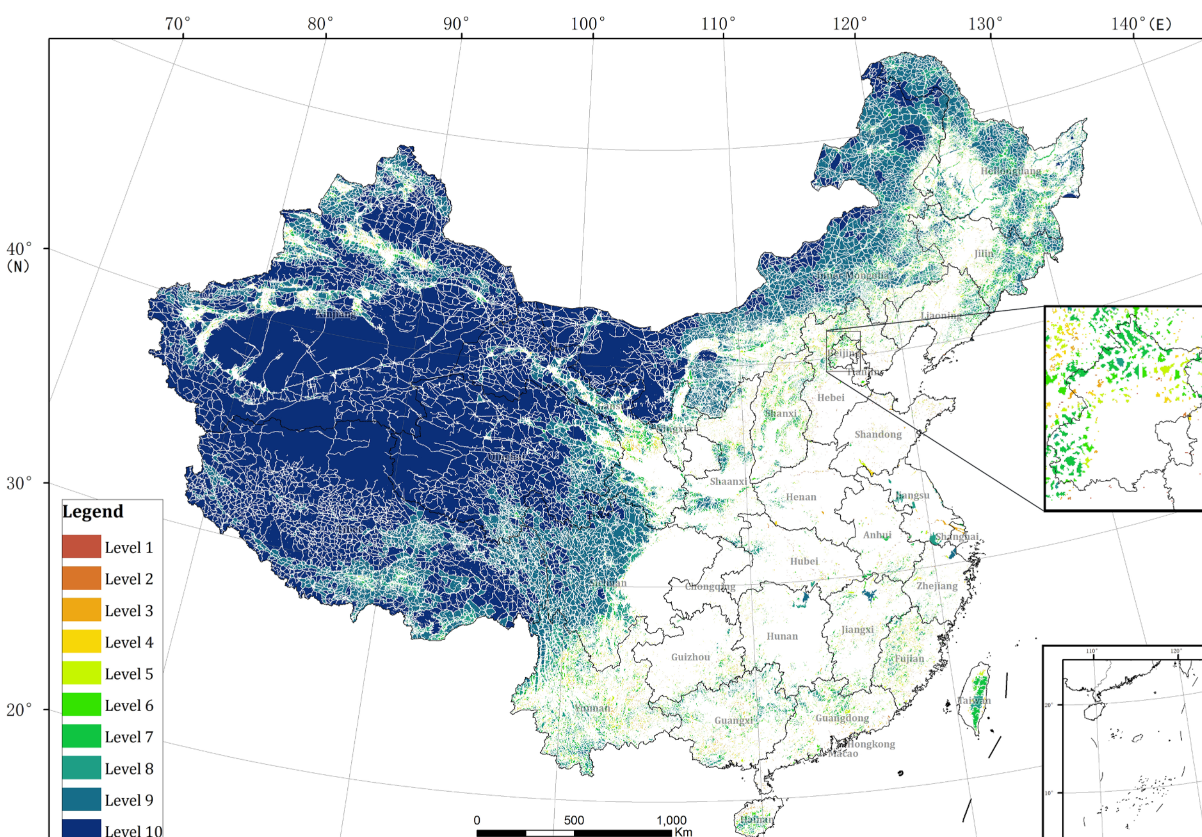

Fig. 4. Integrated wilderness map of China.

Table 4
Classification of wilderness patches based on mean value of Wilderness Quality Index.

Patch type	Mean WQI	Number of patches	Ratio of patches (%)	Total area	Ratio of total area (%)
Level1	0.524052-0.679224	1411	1.64	1899	0.05
Level2	0.679225-0.718797	4025	4.68	6097	0.15
Level3	0.718798-0.746559	7393	8.59	14,383	0.36
Level4	0.746560-0.769291	10,774	12.51	23,890	0.59
Level5	0.769292-0.789720	13,187	15.32	36,891	0.91
Level6	0.789721-0.809536	14,371	16.69	60,134	1.49
Level7	0.809537-0.830253	13,454	15.63	116,252	2.88
Level8	0.830254-0.854041	9542	11.08	252,002	6.24
Level9	0.854042-0.882121	8079	9.38	930,508	23.04
Level10	0.882122-0.954130	3854	4.48	2,596,684	64.29

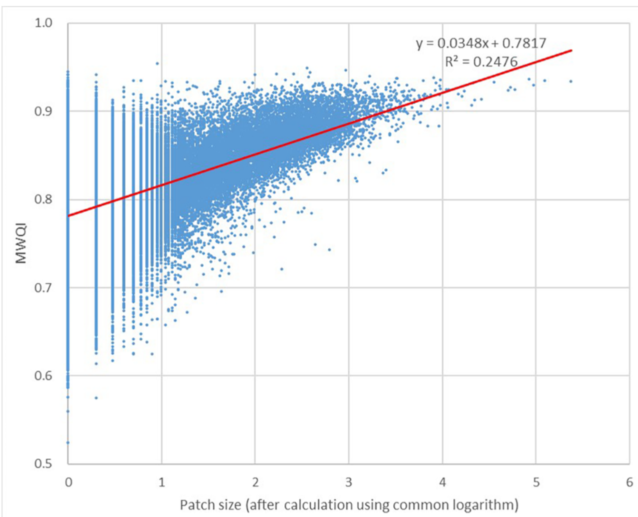

Fig. 5. Scatterplot between patch size and MWQI.

ten levels based on the MWQI value using the Natural Breaks (Jenks) method. Level 1 patches have the lowest wilderness quality and the Level 10 patches have the highest wilderness quality. Table 4 shows the MWQI value range, patch number and total area for each level of wilderness patches.

To illustrate the relationship between wilderness patch size and MWQI value, a scatterplot and linear regression line between patch size and MWQI are shown in Fig. 5. This shows that when the patch area of wilderness is smaller, the value range of MWQI is larger. In addition, there is a statistically significant positive correlation between wilderness patch size and mean MWQI value (Pearson's $r = 0.498$, the number of cases $N = 86090$, and correlation is significant at the 0.01 level), which means the larger the wilderness patch is, the higher its overall wilderness quality will be.

4.4. Comparison of Boolean and WLC approaches

The comparison between the previous study and the wilderness patches map is shown in Fig. 6. The wilderness map from the previous study (Cao et al., 2017) using WLC alone is shown in Fig. 6(a) while Fig. 6(b) shows the differences in identifying wilderness areas in the previous study when compared to the Boolean approach used here (see Table 5). Of the wilderness areas identified by the previous study (which account for up to 52.6% of the country's land area), 64.3% are *de facto* wilderness patches, but 35.7% are non-wilderness patches and so were potentially misidentified as wilderness in the previous study. The misidentified wilderness areas in the previous study mainly occur in the east of China. On the other hand, of those areas which were not defined as wilderness areas in the previous study, 79.7% are non-wilderness patches, but there are 20.3% of wilderness patches which were missed. These missed patches from the previous study mainly occur in the west of China. This demonstrates a level of potential uncertainty in the previous study resulting from defining wilderness using a WLC-based wilderness continuum without considering Boolean factors in a country with marked differences in wilderness attributes between regions.

The comparison of the new wilderness continuum map and wilderness patches map generated in this study is shown in Fig. 7. The higher the wilderness quality index, the larger the area of the wilderness patches, and the smaller the area of the non-wilderness patches. This in turn reflects the consistency of the wilderness continuum map and the wilderness patches map. However, while non-wilderness patches exist even in the top 10% (3.04% in area), wilderness patches also exist in each category. For example, there are 8.52% of wilderness areas exist even in the top 70% category (with relatively low wilderness quality). This further illustrates the limitations of identifying wilderness areas by reclassifying the wilderness continuum, where there are large differences between regions.

4.5. Conservation status of wilderness areas in China

The protection status of wilderness areas in China is shown in Fig. 8. This shows the spatial distribution of wilderness areas that are currently protected and not protected by nature reserves. Of all wilderness patches (accounting for 42% of China's total land area), about 23% of these wilderness areas are covered by nature reserves, leaving the remaining 77% outside existing reserves. The 77% contain large areas of “no man's land” and low productivity land including the Taklimakan desert, Badain Jaran desert, southern Tibetean plateau, etc. The result shows the obvious conservation gaps in China's wilderness areas and indicates the potential for future expansion of the protected areas system. However, there may be an overestimation of the wilderness conservation gap due to the incomplete dataset of nature reserves. Besides, the ongoing process of reorganizing and expanding the protected areas system in China, especially the delineating of national park pilot areas, ecological space, ecological red-line areas and other types of protected areas, may provide other forms of protection for wilderness areas. This could be systematically assessed in the future when data becomes available. It should be also noticed that not all wilderness patches identified here should be strictly protected which is neither necessary nor realistic, calling for identifying conservation priorities for these wilderness patches in the next steps.

To facilitate wilderness protection strategies at provincial level, we calculated the area of the protected (*de jure*) and non-protected wilderness areas (*de facto*) for each provincial administrative region. Detailed information is shown in Table 6, which could be used in protected areas system planning and wilderness protection at provincial level.

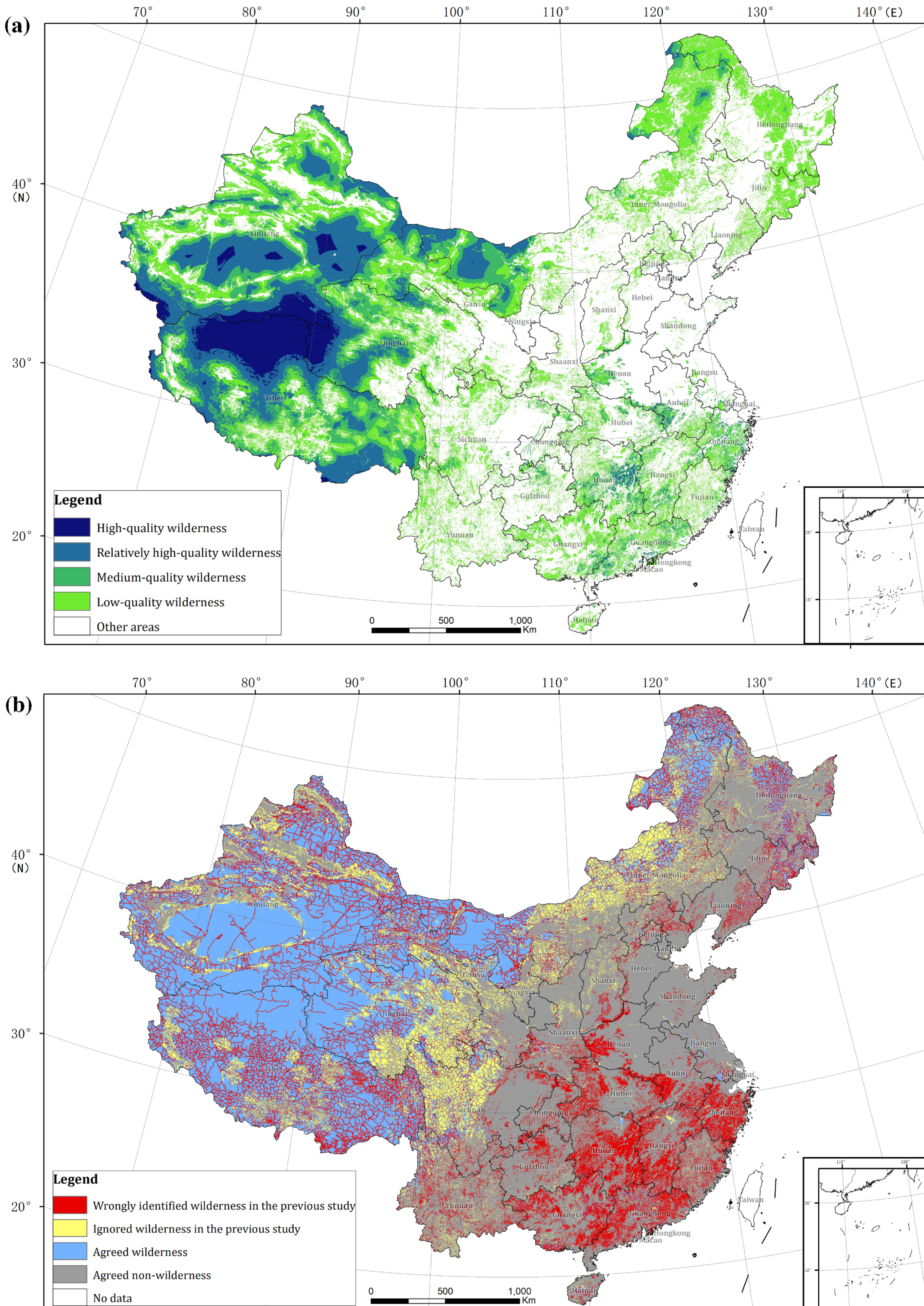

Fig. 6. (a) China wilderness map produced in the previous study (Cao et al., 2017). (b) Errors in identifying wilderness areas in the previous study.

Table 5
Comparison of the result map in the previous study and the new wilderness Boolean map.

	Area of defacto Wilderness patches	Proportion of defacto Wilderness patches (%)	Area of defacto non-wilderness patches	Proportion of non-wilderness patches (%)	Total area
High-quality wilderness	336,087	91.88	29,694	8.12	365,781
Relatively high-quality wilderness	863,944	80.60	208,009	19.40	1,071,953
Medium-quality wilderness	704,335	65.16	376,651	34.84	1,080,986
Low-quality wilderness	1,179,151	51.86	1,094,619	48.14	2,273,770
Other areas	939,633	20.26	3,699,241	79.74	4,638,874

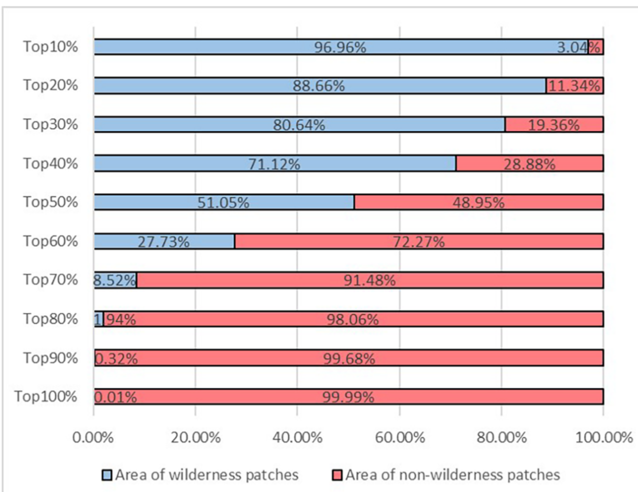

Fig. 7. The area proportion of wilderness patches and non-wilderness patches in 10 categories with different wilderness quality.

5. Discussion

5.1. Improvements compared to the previous study

The previous study on identifying wilderness areas in China has highlighted limitations in data quality and methods (Cao et al., 2017, 2018). This study provides significant improvements to the overall wilderness map for China in two principal areas: improvements in data quality/handling, and improvements to modelling wilderness across large, spatially heterogeneous areas using integrated Boolean overlay and WLC model for the purposes of supporting planning and policy decisions on protected areas and ecological networks.

In terms of data quality, the best available national scale data were used in this study, including population density, the level 2 and 3 settlements, level 3 roads, and updated land use data, all of which were not used in the previous study. In addition, the work described here integrates data for Taiwan, and avoids edge effects by including data for a buffer of 20 km outside the Chinese national border. In terms of indicator weighting, the previous study did not distinguish between different levels of settlements and roads, and the wilderness indicators were treated with equal weights. This study considered the different

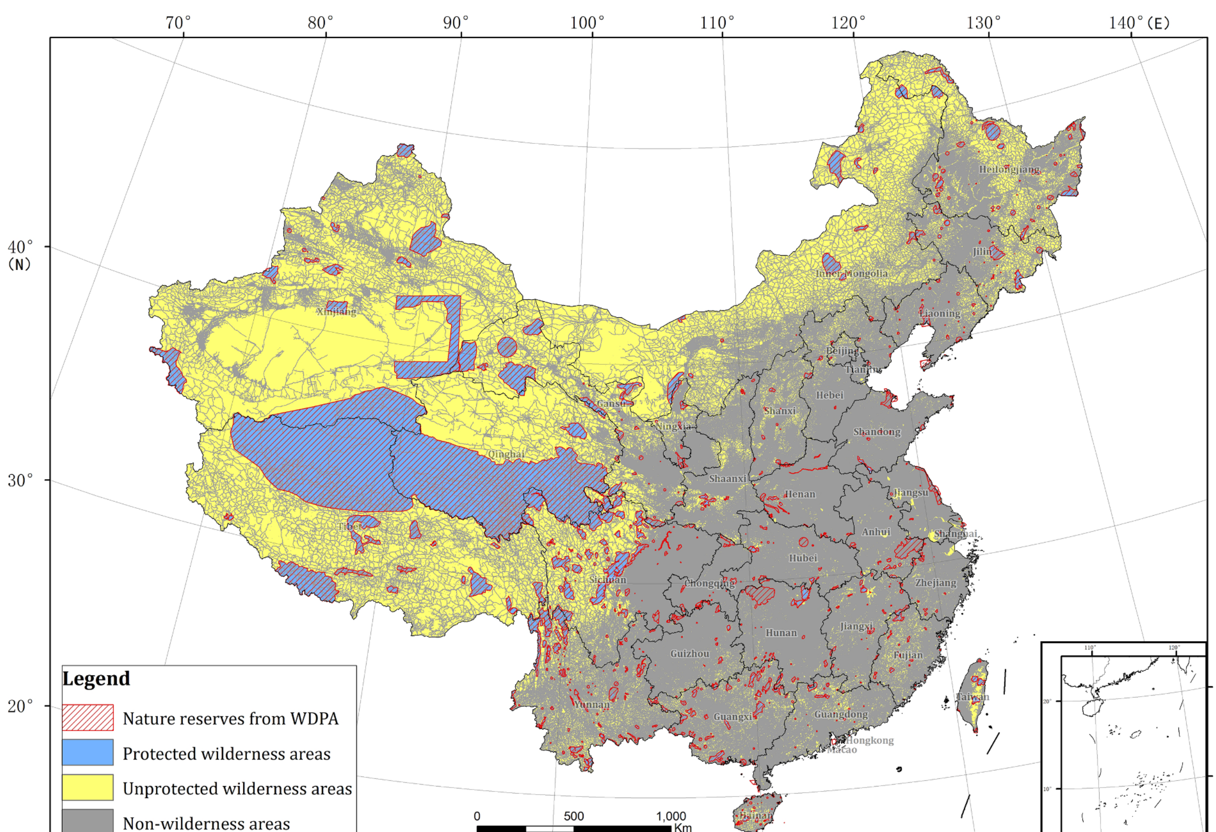

Fig. 8. Conservation status of wilderness areas in China.

Table 6
Conservation status of wilderness areas at provincial level.

Provincial Administrative Regions	Total Area (km^2)	Wilderness areas (km^2)	Ratio of wilderness areas (%)	Area of protected wilderness areas	Ratio of protected wilderness areas (%)
Xinjiang	1,660,000	1,190,653	71.73	171,855	14.43
Tibet	1,228,000	859,270	69.97	327,393	38.10
Inner Mongolia	1,183,000	636,985	53.84	19,136	3.00
Qinghai	722,300	523,621	72.49	269,621	51.49
Gansu	454,400	200,981	44.23	44,387	22.09
Sichuan	481,400	177,689	36.91	45,481	25.60
Heilongjiang	473,000	155,946	32.97	11,559	7.41
Yunnan	383,300	70,500	18.39	16,181	22.95
Jilin	187,400	43,600	23.27	3946	9.05
Guangxi	236,000	20,752	8.79	3751	18.08
Shaanxi	205,600	20,466	9.95	1333	6.51
Shanxi	156,300	16,611	10.63	619	3.73
Guangdong	180,000	13,178	7.32	654	4.96
Hebei	187,700	12,901	6.87	317	2.46
Liaoning	145,900	11,829	8.11	544	4.60
Fujian	121,300	11,603	9.57	668	5.76
Ningxia	66,400	10,478	15.78	1271	12.13
Taiwan	36,000	9482	26.34	2095	22.09
Jiangxi	167,000	9190	5.50	1022	11.12
Hunan	211,800	5734	2.71	2179	38.00
Jiangsu	102,600	5487	5.35	299	5.45
Hainan	34,000	5424	15.95	727	13.40
Guizhou	176,000	4919	2.79	579	11.77
Anhui	139,700	3986	2.85	750	18.82
Hubei	185,900	3975	2.14	870	21.89
Zhejiang	102,000	3924	3.85	110	2.80
Shandong	153,800	2947	1.92	1081	36.68
Henan	167,000	2298	1.38	285	12.40
Beijing	16,800	2220	13.21	72	3.24
Shanghai	6300	769	12.21	52	6.76
Chongqing	82,300	562	0.68	143	25.44
Tianjin	11,300	470	4.16	2	0.43
Hongkong	1101	36	3.27	0	0.00
Macao	25.4	0	0.00	0	0.00

impacts of different levels of settlements and roads and obtained the robust wilderness indicator weights through the expert survey and sensitivity analysis.

In terms of the uncertainty in defining wilderness areas, whereas the previous study (Cao et al., 2017) used the standard WLC modelling approach on its own, this paper addressed the problem using an integrated approach combining both Boolean and WLC methods. According to the comparison with the previous study using only WLC model, possible problems may exist in two aspects. One is the neglection of wilderness areas with relatively low wilderness quality, which may result in gaps in conservation networks. Another is that, many non-wilderness patches will be included, resulting in unreasonable boundaries of wilderness protected areas and even community conflicts. By integrating the Boolean approach and MCE models, the integrated map can effectively identify wilderness patches as well as assessing the relative wilderness quality levels of these in a single analysis. Therefore, it is recommended to use this integrated approach to wilderness mapping instead of simply reclassifying the wilderness continuum to avoid the problems we have identified, especially in countries where different regions exhibit large, spatially heterogeneous differences in patterns of wilderness quality.

5.2. Potential applications in wilderness conservation

The data and maps produced here provide the basis for a wider discussion of approaches to wilderness mapping as well as for looking more closely at the wilderness patterns across China. These maps can also inform ongoing conservation efforts within the country.

Firstly, the integrated wilderness map could be used in setting wilderness conservation target areas, especially in protected area designation or zoning of national parks, nature reserves and World (Natural) Heritage Sites (Kormos et al., 2016). Because large gaps in wilderness protection exist, there is an urgent need to designate new national parks and more nature reserves that will cover these existing *de facto* wilderness areas. This should be based on the further assessment of conservation value of the wilderness patches, by incorporating datasets reflecting the ecological values in terms of biodiversity and ecosystem services.

Secondly, the integrated wilderness map and wilderness continuum map could be used together to better model ecological connectivity, which is an important aspect of modern landscape-scale conservation (Soule & Noss, 1998; Worboys et al., 2010). Here ecological connectivity between the core wilderness patches can perhaps be best evaluated using the continuous wilderness map as a resistance surface in Linkage Mapper and Circuitscape (Kupfer, 2012). Using such an approach, the fragmentation and isolation of the existing wilderness areas can be assessed, and ecological connectivity mapped to identify likely wildlife movement corridors. This is especially helpful in identifying any barriers and pinch-points in the network that need to be addressed through land use changes and creation of intermediate “stepping-stone” refugia or built infrastructure such as wildlife bridges and underpasses.

Thirdly, both the integrated wilderness map and the wilderness continuum map can be used for long-term monitoring of changes in wilderness quality. Once mapped at the beginning of a protected areas program, datasets can be updated at set intervals in the future and remapped using the same approaches to create new wilderness maps. Comparing the new maps with the old maps will highlight areas of change (loss and gain) and so help inform landscape planning policy and management decisions in wilderness protection and rewilding.

5.3. Limitations and future research

While the integrated approach to wilderness mapping has clear advantages, it needs to be recognized that the approach still has certain limitations. As with any GIS-based analysis that relies on combinations of off-the-shelf data, there are concerns with data quality associated with resolution, generalization and uncertainty. This is especially true of any country the size of China where data quality varies between different datasets and regions. Like their global counterparts, such national mapping projects are limited by difficulties of ground-based validation (Stokes & Morrison, 2003), which may then cause overestimation or underestimation of wilderness areas.

In geographically diverse countries such as China, it is necessary to apply and adjust the proposed method at regional and local scales to support on-the-ground wilderness protection projects in the future (Adhikari & Hansen, 2018; Carver et al., 2012, 2013; Ceauşu, Gomes, & Pereira, 2015; Flanagan & Anderson, 2008; Lin et al., 2016; Măntoiu et al., 2016; Orsi et al., 2013; Tricker & Landres, 2018). At a local scale, more accurate datasets with on-the-ground validation are required. Additionally, more realistic models to map wilderness indicators at very high resolutions are needed. For example, at the national scale, remoteness from roads and settlements are based on simple Euclidean distance functions, whereas at the local scale a range of factors that influence on-foot travel times such as barrier features, topography, and vegetation can be incorporated to produce non-linear or anisotropic remoteness models (Carver et al., 2012, 2013). In addition, a wilderness perception survey could be incorporated in modelling wilderness (Flanagan & Anderson, 2008; Kliskey & Kearsley, 1993; Kliskey, 1998; Larkin & Beier, 2014). This is especially true in regions where social and cultural factors are important for nature conservation.

6. Conclusion

This paper improves on previous work by Cao et al. (2017) and confirms that the total area of wilderness in China accounts for 42% of its terrestrial area, with over 70% of the existing wilderness areas left outside of the nature reserves. While the concept of wilderness is not "black and white", discrete boundaries are nonetheless required for planning and policy for the legal protection of wilderness. To this end, an integrated approach combining Boolean overlay and WLC models is proposed to map both discrete wilderness patches and internal variations in wilderness quality. We suggest that the updated maps could be used in further developing national wilderness protection policies. Besides, this approach could easily be adapted and modified for use in other countries. Should the *Nature Needs Half* and *Half Earth* visions (Locke, 2014; Wilson, 2016) be realized, and protected area targets met (Butchart et al., 2015), further work using this approach will be required to support policy and management decisions crucial for future wilderness protection.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.landurbplan.2019.103636.

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