land

Article

Classification and Distribution of Traditional Grass-Roofed Dwellings in China Based on Deep Learning

Jin Tao [1,2], Yuxin Zeng [1], Xiaolan Zhuo [3,*], Zhibo Wang [1], Jihang Xu [1] and Peng Ren [1,2]

1 School of Architecture, South China University of Technology, Guangzhou 510641, China; arjtao@scut.edu.cn (J.T.)
2 State Key Laboratory of Subtropical Building and Urban Science, Guangzhou 510641, China
3 College of Architecture and Urban Planning, Guangzhou University, Guangzhou 510006, China
* Correspondence: zhuoxl@gzhu.edu.cn

Abstract: Traditional grass-roofed dwellings are important components of Chinese vernacular architecture. Building a comprehensive nationwide database of traditional grass-roofed dwellings is crucial for the inherence of this cultural heritage and its traditional ecological technologies. This study proposes classifying traditional Chinese grass-roofed dwellings into three types according to recognizable appearance features. Based on the YOLOv8 deep learning framework, a recognition model is constructed to recognize and spatially locate various grass-roofed dwellings from the image dataset on a county-level. Further, by conducting spatial overlap analysis with a variety of natural and socio-environmental factors on ArcGIS, their influences on the distribution pattern of traditional grass-roofed dwellings were examined. The study findings are as follows: (1) Traditional grass-roofed dwellings are concentrated on the southeast side of the Hu Line with different distribution patterns according to their types. (2) The natural environment influences the original construction and distribution of traditional grass-roofed dwellings in terms of the growth of grass resources and the ecological adaptability of grass material. (3) The development of economy, population, and urbanization pose challenges to the retention of grass-roofed dwellings. This research provides useful references for the precise preservation of various grass-roofed dwellings and introduced a novel approach for the classification of traditional buildings.

Keywords: grass materials; traditional dwellings; deep learning; distribution pattern; GIS; China

Citation: Tao, J.; Zeng, Y.; Zhuo, X.; Wang, Z.; Xu, J.; Ren, P. Classification and Distribution of Traditional Grass-Roofed Dwellings in China Based on Deep Learning. *Land* **2024**, *13*, 1595. https://doi.org/10.3390/land13101595

Academic Editor: Michael Hensel

Received: 18 August 2024
Revised: 27 September 2024
Accepted: 28 September 2024
Published: 30 September 2024

1. Introduction

For a long time, for the study of Chinese vernacular architectural roofing materials, researchers have mainly focused on stone, tile, raw earth, and wood, while grass building materials, as non-mainstream materials, are less involved. In fact, as a lightweight material, grass is widely used in the construction of traditional houses. Using various kinds of grass plant as the main material for building (mainly folk dwellings) roof coverings is one of the typical ways of grass utilization in building construction (Figure 1). We collectively refer to this type of folk building as "grass-roofed dwellings", which were once widely distributed around the world. They reflect the use of environmental resources by the inhabitants of farming societies and have important historical and cultural values [1]. However, with the development of urbanization, this architectural cultural heritage is in a state of rapid extinction globally and has become endangered or even extinct in some regions. Therefore, we need to find a way to quickly understand the overall retention status of grass-roofed dwellings before they are replaced by modern buildings and to draw the attention of a greater protection force of cultural heritage.

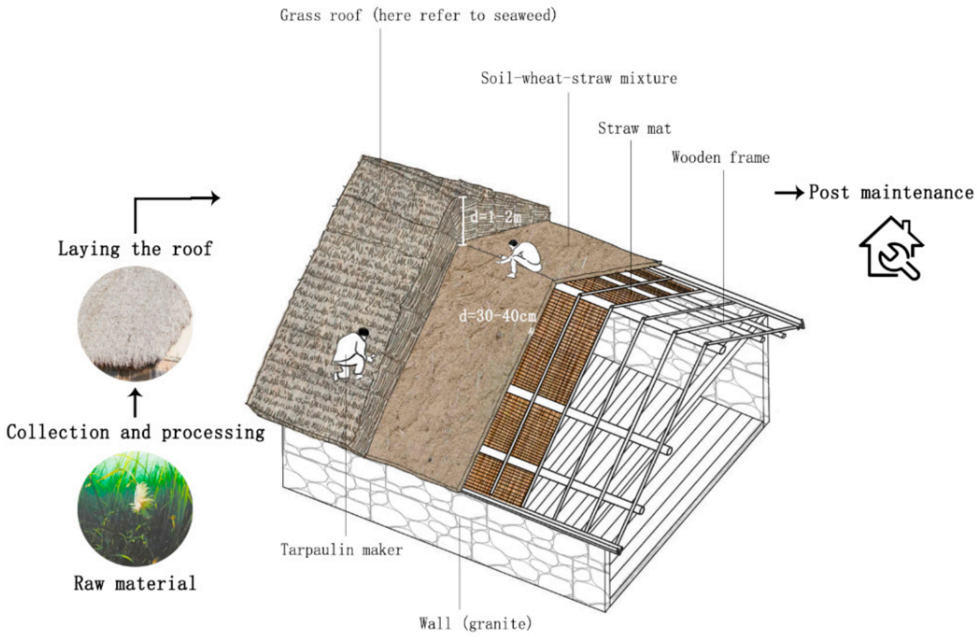


Figure 1. Construction of traditional grass-roofed building. Note: The construction of traditional grass-roofed building dwellings reflects the knowledge and experience in using herb-based local materials. It generally requires four steps: processing of grass, fixing, laying, and post-maintenance.

Typically, the collection of data on the distribution of traditional Chinese dwellings is based on traditional field survey techniques, which rely on a certain degree of technical expertise and a large number of human resources, making it a time-consuming, labor-intensive, and costly task. Traditional techniques have also been shown to suffer from a lack of granularity in data collection. For example, Wang Wen-qing roughly delineated the building material zoning map of traditional Chinese dwelling construction patterns according to climate, topography, and materials, which involved the spatial distribution of grass-roofed dwellings [2]. Using building materials as cultural factors, Wang Lei produced a cultural zoning map of traditional residential roofing material techniques in the Northeast and found that grass-roofed dwellings are mainly concentrated in central Heilongjiang Province and central Jilin Province [3]. These studies have produced some results on the spatial distribution and zoning of grass-roofed dwellings. However, due to the difficulty in obtaining complete data across the country, only a small number of studies have conducted distribution studies at the provincial scale, while most studies have been limited to the municipal or sub-municipal scales or have involved only case studies. In other words, at present, we only have a very vague and rough knowledge of the distribution of traditional grass-roofed dwellings in a nationwide vision. There still lies a huge gap between the information we have and the actual remains of grass-roofed dwellings, which is very unfavorable for the research and protection of these built heritages. As a result, a comprehensive database of traditional Chinese grass-roofed dwellings has yet to be established, and the update and registration of these heritage lists are also lagging behind. There is a huge information gap from the information we had and the actual remains of thatched roof dwellings, which is very unfavorable for the research and protection of endangered traditional grass-roofed dwellings.

Compared with traditional data collection methods, advanced artificial intelligence technology can integrate richer data sources, bringing possibilities for more comprehensive and refined data collection, database construction, and data analysis. These technologies have been widely applied in the field of construction engineering. Seung-Yeul Ji et al. used deep learning mainstream models for traditional East Asian building form and type recognition [4], Wang et al. automated the damage detection of brick masonry structures of historic buildings based on ResNet deep learning models [5], and Konstantina Siountri et al.

used a YOLO network to identify Athenian cultural heritage building categories [6]. In fact, for grass-roofed buildings, due to the special appearance of grass materials, their material information can be directly obtained from the two-dimensional appearance image data of the building [7]. Therefore, deep learning models such as image classification, target detection, and object segmentation can be well adapted to the visual features of grass-type materials, providing efficient means for the automated extraction and analysis of grass-roofed buildings.

There is also a lack of granularity regarding the definition of grass-roofed dwellings, lacking a detailed differentiation of various grass materials. In fact, grass-roofed dwellings in different regions utilize a diverse array of grass materials, as documented in literatures, including seagrass, thatch, wheatgrass, reed, Ula grass, goat grass, etc. [1]. It is worth noting that there are significant differences in the physical attributes and visual appearance of these grass materials. For example, wheatgrass is yellow and more flammable than seagrass, which is white [8]. The differences in grass materials reflect the differences in the natural environment, climatic conditions, and social structure of different regions. At the same time, the technical feasibility, accessibility of construction materials, and climate were decisive factors for shaping the style of the constructions of a place [6]. Subdividing the material types of grass-roofed dwellings allows us to explore the relationship between external factors and the choice of roofing materials and to analyze the reasons for the differences in the distribution of grass-roofed dwellings according to different factors, so as to enhance the relevance of the research on the protection measures for grass-roofed dwellings.

A wealth of research has been revealed on the link between the environment and the use of materials in grass-roofed dwellings. Paul Oliver examined palm-leaf-roofed dwellings in the Americas, coconut-straw-roofed dwellings in Oceania, rectilinear straw-roofed dwellings in Zambian, and straw-roofed dwellings in East and Southeast Asia, and noted that unique construction skills that adapted to the local environment were the key to understanding these dwellings [9]. Indeed, the local reed and cogon-roofed dwelling of the Ivatan of Bataan Islands, Philippines is designed to withstand strong typhoons, and the thatch-roofed dwelling in central Vietnam is featured to adapt to hot and humid climates [10,11]. In China, traditional grass-roofed dwellings also reflect an imprint of their surroundings. Zhang Jie found that building roofs using sorghum straw handle and cereal grass for dense and thick pavement can be better adapted to the high local temperature and rainy climate [12]. According to Wang Jiang et al., thatched cottages in Asia using easily accessible materials like bark, thatch, or palm leaves for roofing are convenient for demolition and reconstruction, and are therefore representative of local simple folk dwellings, reflecting the characteristics of certain regional economic environments [13]. In addition, Chen Ruixin believes that, due to its remote location, inconvenient transportation, and poor communication with the outside world, villagers in Baicha village, Hainan will continue their traditional habit of regular maintenance of thatch-roofed boat houses, which can effectively maintain the regional characteristics and vitality of the buildings [14]. As seen from these studies, traditional grass-roofed dwellings not only reflect their adaptability to the natural environment but are also influenced by the humanistic environment. By choosing appropriate materials and designs responding to local climatic and socio-economic changes, these buildings have demonstrated the wisdom and adaptability of local residents, thus effectively perpetuating their unique cultural and historical values.

In view of the problems of small scale, large granularity, and limited access to data sources in the existing research on the distribution and classification of traditional grass-roofed dwellings, this study aims to construct a nationwide fine-classified grass-roofed dwelling distribution database through rapid identification and large-scale collection of traditional grass-roofed dwelling samples by means of deep learning methods and the abundant open image resources. On this basis, the spatial characteristics of traditional grass-roofed dwellings and their intrinsic correlations with natural and human environmental factors can be explored. The significance of this study is as follows:

(1) Refinement of the classification of grass-roofed dwellings. By reassessing the differences between various grass-roofed dwellings and drawing a classification map, the study provides a basis for the conservation of diversity and sustainable construction of different types of grass-roofed dwellings.
(2) Efficient construction of a large-scale distribution database of traditional grass-roofed dwellings. Through the development of a deep learning model, image data of grass-roofed buildings are collected through computer networks, and grass-roof features are extracted directly from the images for type recognition. This method overcomes the limitations of local data collection and realizes the construction of a nationwide classification and distribution database of traditional grass-roofed dwellings.
(3) Improving the classification accuracy of different types of grass-roofed dwellings. By re-evaluating their distinctions and drawing distribution maps, this research provided a basis for the precise preservation of various grass-roofed dwellings and introduced a novel approach for the classification research of other traditional building materials.

2. Materials and Methods

2.1. Research Scope and Data Sources

The scope of this study is the whole region across China. The granularity of the data is based on county-level administrative divisions according to the Rules for Preparation of Zoning Codes and Urban and Rural Delineation Codes for Statistical Purposes officially issued by the National Bureau of Statistics (NBS) in 2022. On this basis, data collection, quantity statistics, and spatial distribution analysis are carried out.

This study involves two types of data. The first type of data is 2D image used for deep learning model training and prediction. For model training, the dataset must encompass all kinds of grass-roofed dwelling types, ensuring a sufficient sample size. Images in the prediction dataset should include their location information to facilitate subsequent spatial analysis. To ensure the recognizability of visual features in the images and enhance model accuracy, the images in the training dataset need to fulfill the following criteria:

(1) Using ground-level perspective images that have rooflines and horizons exposed intact.
(2) Ensure that the content of the images primarily focuses on traditional grass-roofed dwellings rather than other objects.
(3) Grass material should be used as the main enclosure structure for roofs. Instances where grass are used as auxiliary materials to enhance adhesion and toughness will be excluded, e.g., flat roofs constructed of a mixture of sheep grass and clay, as seen in the Tun-domed dwelling in northeast China, should be avoided. This is because the use of such mixtures may not exhibit obvious herbaceous characteristics in visual features and could be misjudged as loess materials, thus affecting the effectiveness of the recognition model.

The second type of data comprise the basic data used for spatial correlation analysis. This includes statistic data and thematic data sourced from the Chinese Resource and Environment Science and Data Center (RESDC). These data were primarily employed to examine the natural and social factors that influenced the type differentiation and the spatial distribution of traditional grass-roofed dwellings.

A detailed description of all the data is shown in Table 1.

Table 1. List of data used in this study.

Data Type	Data Sources	Data Volume and Format		Note
Training dataset	Public images collected from Bing web search platform based on the known cases of grass-roofed dwellings listed in authoritative sources	342 pieces of raw JPG images	1400 pieces of enhanced JPG images	
Prediction dataset *	Public images in 2853 county-level units obtained on the web search engine Bing by python script	Adopting the first 100 images obtained for each county, making a total of 258,300		Search images using "administrative district + traditional folk dwellings" as keywords
Filtered dataset	Filtered from the predicting outcomes	474 JPG images in total		Screening images of traditional grass-roofed dwellings and removing images containing modern dwellings
Vagetation type	RESDC	raster data		Nationwide
Annual precipitation	RESDC	raster data		Nationwide in 1970
Moisture index	RESDC	raster data		Nationwide
Annual average temperature	RESDC	raster data		Nationwide in 1970
Digital elevation model	RESDC	raster data		Nationwide
Spatial distribution of GDP	RESDC	raster data		Nationwide in 1995
Spatial distribution of Population	RESDC	raster data		Nationwide in 1990
Road network	Web crawler	vector data		Nationwide in 1990

* Note: The use of county-level administrative units is mainly based on the following considerations. Firstly, the purpose of this study is to reveal the distribution pattern of grass-roofed dwellings across the country, so the images need to have the geographic coordinates information. Since the name of each county-level unit in the country will not be repeated, this will reduce the confusion of information and improve the recognition accuracy. Secondly, the exterior features of traditional dwellings vary little at the county scale, so data collected at this level can be representative. In comparison, the greater diversity of dwelling types within larger scale geographic units such as a prefecture-level city or province may result in incomplete samples, while the greater homogeneity of dwellings in smaller-scale geographic units like township or village will result in data redundancy and reduced efficiency.

2.2. Research Framework

As shown in Figure 2, the framework of this study mainly includes four stages: (1) The classification criteria of traditional grass-roofed dwellings are proposed to categorize the grass-roofed dwellings into three types. (2) A deep learning model for rapid and automatic identification of the distribution of traditional grass-roofed dwellings is established to construct a national database of traditional grass-roofed dwellings. (3) The database is linked to the GIS platform to analyze the overall distribution characteristics of traditional grass-roofed dwellings across China. (4) The relevant factors of the distribution of traditional grass-roofed dwellings are analyzed.

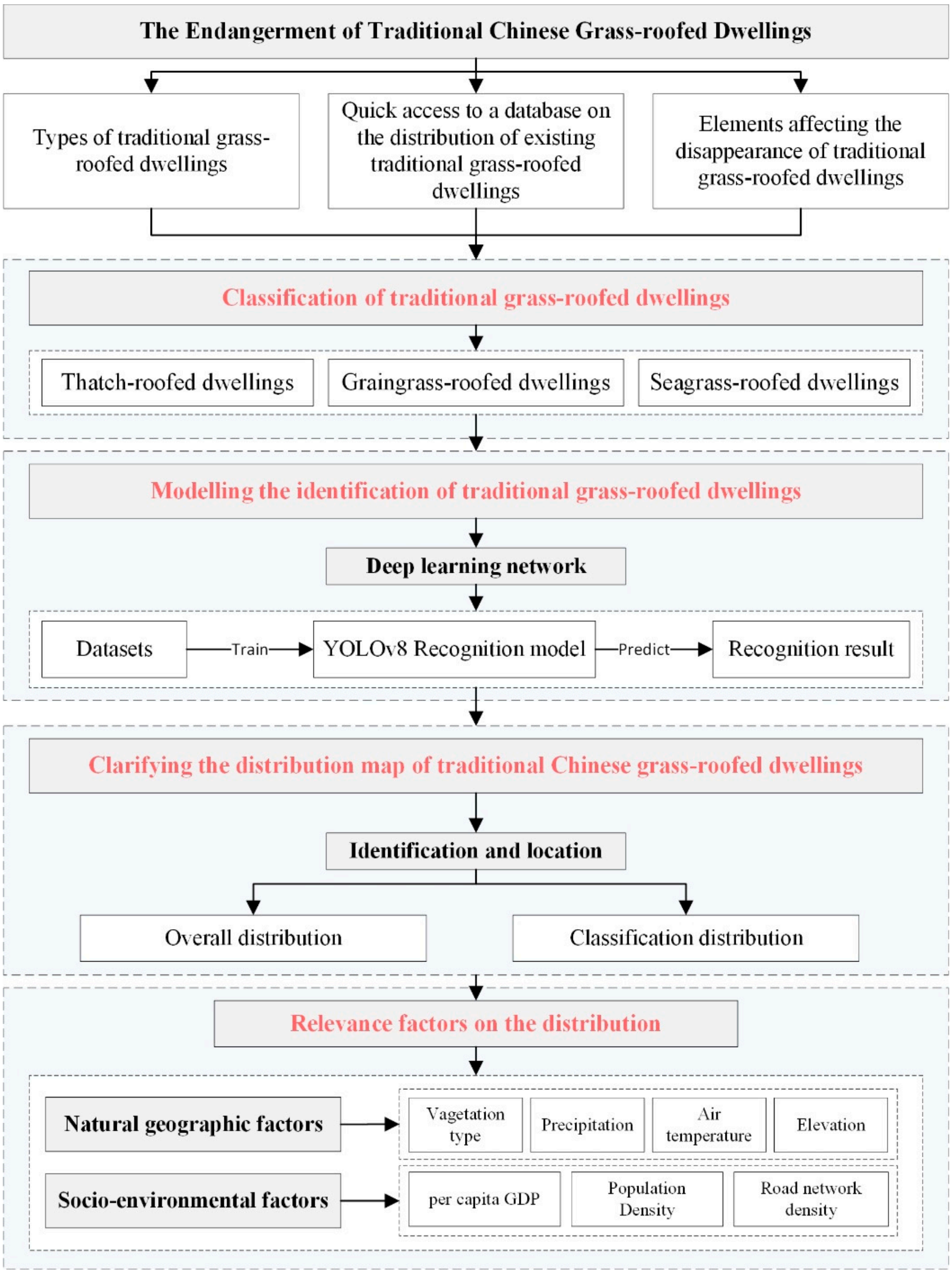


Figure 2. Research framework.

2.3. Methods

2.3.1. Classification of Traditional Grass-Roofed Dwelling Based on Grass Plant Family

The classification of grass-roof materials is often complex and varied in existing studies, with generic or ambiguous terms like "grass thatch roof" commonly being used. For instance, Cara Steger categorized the 205 species globally used for grass-roof into three types: Gramineae, palms, and other families, considering grass-roofed buildings to occur in grass-like or palm-like forms [15]. Similarly, Zamolyi roughly classified grass roofs into three categories according to their appearance and characteristics: those using branches with leaves, those using leaves only, and those made of rods such as reeds or straw [16].

In fact, despite varying interpretations among scholars regarding grass-roofed dwelling types, their classification principles primarily involve the morphological features of the plants. Therefore, this study proposes a comprehensive classification approach, namely, based on the differentiation of plant families, grass material with similar structures and appearance were classified into the same category. On this basis, combined with references to the classic bibliography "Typological Collection of Traditional Chinese Dwellings" [17], we categorized the grass materials used in all grass-roofed dwellings into three types: thatch, grain-grass, and seagrass, each of them including several specific materials from the same grass plant family. Accordingly, we obtained the corresponding three types of grass-roofed dwellings: thatch-roofed dwellings, grain-grass-roofed dwellings, and seagrass-roofed dwellings, each using the abovementioned three types of grass as major roof-laying materials (see Table 2). This classification criterion takes into account both the recognizability of physical attributes and the appearance features of different grass material types, providing clear objectives and an effective dataset for training of the deep learning model.

Table 2. Traditional grass-roofed dwelling types and features.

Type	Material Family	Material Properties	Appearance Characteristic	The Morphology of Raw Materials	Typical Example
Thatch-roofed dwellings	Herbs, perennial, with long stout rhizomes	Anti-corrosion Pest control Moisture proof	Mostly green when fresh, with stiff, straight stems, turning yellow when dried off the soil, with hairy spikes on the roof and protruding leaves.		
Grain-grass-roofed dwellings	Stems, leaves, or stalks of food crops [18]	High toughness Heat insulation Damp-proof Soundproof	Yellow at maturity, black after oxidation off the soil. The roofs are chaffy with rough texture.		
Seagrass-roofed dwellings	Higher angiosperms that survive in seawater	Anti-corrosion Flame retardant Heat insulation High strength colloidal fibers	Green when fresh, purple–brown when dried, and then gradually whitening due to the chemical reaction of the gel in the seagrass species with the environment. The roofs are neat with soft texture.		

2.3.2. Spatial Database Construction Based on Deep Learning

YOLO is a deep learning model that implements an end-to-end detection neural network based on the regional recommendation algorithm [19]. This study uses the YOLOv8 version of the YOLO family for recognition model construction. The device we used to run this algorithm is DELL EMC DSS 8440 equipped with 10*A40 GPUs for accelerating the training process, which is manufactured in Xiamen, China by Dell (China) Co.

Figure 3 depicts the specific building process, which consists of 4 main steps.

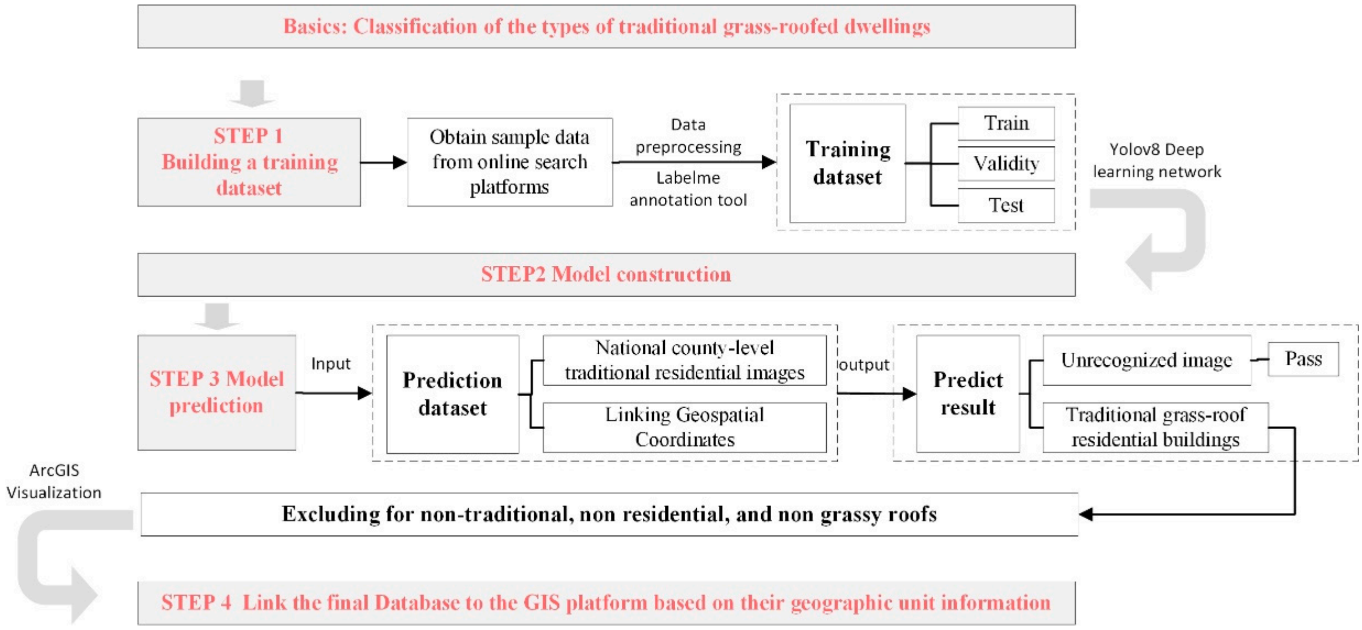


Figure 3. YOLOv8 recognition model building process.

(1) Building the training dataset

The first step was to build a training dataset. Based on the literature review, a total of 342 images of known samples were collected through a search engine (www.bing.com, accessed on 2 April 2024). These images were manually annotated according to the three types of traditional grass-roofed dwellings by the tool "Labelme". In order to enhance the learning of the model, data enhancement methods such as adjusting image brightness and contrast, rotating, scaling, cropping, and noise removal were performed on the original 342 images to expand the dataset to a total of 1400 images. The data situation of the training set is shown in Table 3.

Table 3. The data situation of the training set.

Data	Valid Image Amount	Total Valid Amount	Enhanced Image Amount	Final Image Amount
Thatch-roofed dwellings	122	342	490	1400
Grain-grass-roofed dwellings	102		405	
Seagrass-roofed dwellings	118		505	

(2) Model construction and evaluation

The YOLOv8 framework was employed to develop a recognition model for intelligently recognizing various types of grass-roofed dwellings from images. The training set was fed into the neural network as a priori knowledge about the characteristics of various types of grass-roofed dwellings for the model learning.

To assess the performance the model, the Recall and Precision metrics are used, which are calculated as follows:

$$recall = \frac{TP}{(TP + FN)} \quad (1)$$

$$precision = \frac{TP}{(TP + FP)} \quad (2)$$

In these two formulas, the variables TP, TN, FP, and FN represent the sum of predictions for different samples specifically as follows:

TP: The number of actually positive samples that are correctly predicted to be positive;

TN: The number of actually negative samples that are correctly predicted to be negative;

FP: The number of actually negative samples that are mistakenly predicted to be positive;

FN: The number of actually positive samples that are mistakenly predicted to be negative.

The mAP (mean Average Precision) metric is also used for the results evaluation, which is widely adopted for assessing the performance of object detection algorithms across multiple classes. In this paper, we considered mAP50, which calculates the average precision for all classes at a threshold of 0.5 [20].

(3) Image recognition and database construction

In order to obtain comprehensive coverage of candidate residential image data as much as possible, a Python script was used to automatically gather images of traditional dwellings from the open website (www.bing.com), with a quantity of 100 images per county-level unit. These gathered images, serving as the prediction dataset, were fed into the constructed recognition model. Finally, a national database of grass-roofed dwellings with location information (county) and type information was constructed, with images that cannot recognize the target objects, i.e., non-traditional grass-roofed dwellings, filtered out. It should be noted that during the experiments, recognition screening was performed by trying to incorporate different numbers of search results to ensure that the first 100 alternative images currently used for screening had sufficient coverage. In addition, we consider these data as the reflection of all available historical situations and analyze them on a synchronic platform that does not involve analysis on a timeline.

In order to visualize the distribution analysis of the recognition results on the map, the database was linked to an attribute table on ArcGIS based on the geographic information of the counties they located. The type of grass-roofed dwellings of each image were binary differentiated in the attribute table, with 1 or 0 representing the presence or absence of a certain grass roof material.

2.3.3. Distribution Analysis Based on ArcGIS

(1) Nearest neighbor index

The spatial distribution of point elements is typically classified into three types: uniform distribution, random distribution, and agglomeration distribution [21]. This can be assessed by the nearest neighbor index, which serves as a geographical indicator of the proximity among point-like entities. The specific formula is as follows:

$$R = \frac{\overline{r_i}}{\overline{r_E}} = 2\sqrt{D} \quad (3)$$

where $\overline{r_i}$ represents the actual nearest neighbor distance, $\overline{r_E}$ represents the theoretical nearest neighbor distance, and D represents the point density. The point elements are considered to be randomly distributed when $R = 1$, uniformly distributed when $R > 1$, and clustered when $R < 1$. By utilizing the Average Nearest Neighbor tool in ArcGIS (10.6.1) for calculation, we can derive the nearest-neighbor point index for each type of grass roof material. Subsequently, the macro-distribution characteristics of the building materials across the whole country can be assessed.

(2) Kernel density analysis

Kernel density analysis is a method that effectively illustrates the dispersed or discrete characteristics of elements. This approach acknowledges that a geographic event can potentially occur at any spatial location, but the probability of occurrence varies across different locations. The denser the distribution of points, the greater the likelihood of the geographical event occurring, and vice versa. In this study, traditional grass-roofed dwellings served as the center of the circle, with the input values determining the radius of the circle. The Rosenblatt–Parzen function was utilized to estimate the probability of occurrence of the grass roof material point element F within the circle [22]. The equation is

$$F(x) = \frac{1}{nh}\sum_{i=1}^{n} k\left[\frac{d(x-x_i)}{h}\right] \quad (4)$$

In this equation, $k\left[\frac{d(x-x_i)}{h}\right]$ represents the kernel function, h represents the search radius, $d(x-x_i)$ represents the distance from the estimated point to the observation point, and n represents the number of data points for a single class of grass roof material. After the kernel density analysis, the distribution density of various materials in geographic space can be revealed.

2.3.4. Relevance Factor Analysis Based on Map Overlaying

Overlay analysis is the operation of overlaying two or more map features based on coordinate alignment to create a new feature layer. Specifically, this study superimposes the point elements of traditional grass-roofed dwellings with the polygonal elements in the patch maps of various factors. Then, by performing intersection operations based on the spatial relationship between elements on the two layers (i.e., the inclusion relationship between points and polygons), the information of the relevance factor can be assigned to the corresponding grass-roofed dwellings though generating new attributes for them.

3. Results

3.1. The Recognition Results

Upon completion of the previous training, our recognition model was evaluated using the metrics mentioned in Section 2.3.2. In general, the model exhibited distinguished outcomes (Table 4), with each mAP value reaching 0.8 or more, characterizing the suitability of the model for grass-roofed dwelling type recognition. The best-performing model during the training process was adopted for the recognition of three types of traditional grass-roofed dwellings from raw images collected from a website (Figure 4).

Table 4. Model performance evaluation.

Assessment of Indicators	Overall Recognition Model (Box *, Mask *)		Recognition Results of Single Type (Box *, Mask *)					
			Thatch-Roofed Dwellings		Grain-Grass-Roofed Dwellings		Seagrass-Roofed Dwellings	
Recall	0.76	0.753	0.729	0.729	0.681	0.66	0.869	0.867
Precision	0.876	0.867	0.837	0.837	0.881	0.854	0.909	0.909
mAP	0.879	0.866	0.825	0.807	0.843	0.847	0.97	0.945

* Note: Box refers to the rectangle marked by the algorithm in the image to frame the target object it recognized. Mask refers to the irregular patches mask of the entire roof shape that the algorithm recognized and marked in the image.

A total of 526 images were recognized as eligible traditional grass-roofed dwellings from the prediction set of traditional dwellings images (a total of 285,300) from 2853 counties in China. Due to the identification of a small number of false positive samples and misclassifications, these 526 images were manually inspected, screened, and type-corrected, resulting in a total of 474 valid images covering a range of 246 counties. The quantity of the recognition result and the final database are detailed in Table 5. We also statistically sort out all the cases involved in the existing studies. It can be seen that the distribution database constructed in this paper is significantly improved compared to those of existing studies, especially in term of scope coverage.

Figure 4. Prediction set data identification results (partial).

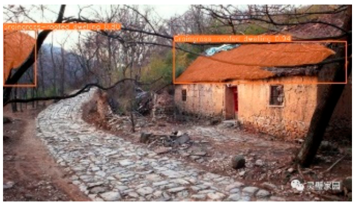
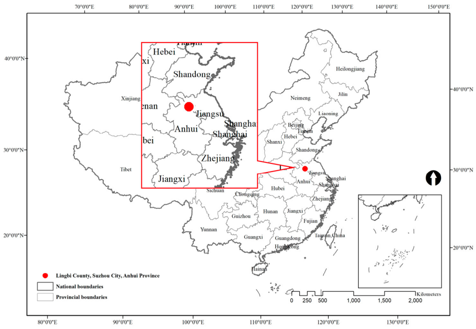
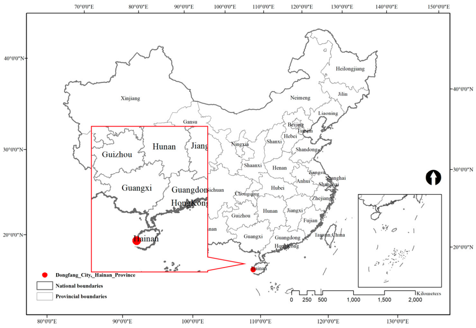
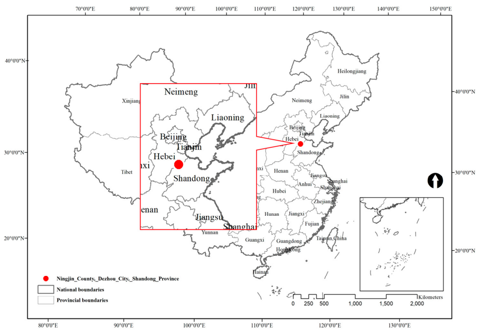
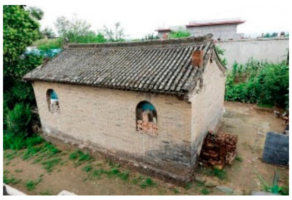
Table 5. The quantity of the recognition result and the final database.

Category	Recognition Results		Valid Results after Manual Screening		Cases Covered by Existing Studies	
	Num of Images	Coverage (Num of Counties)	Num of Images	Coverage (Num of Counties)	Num of Specific Cases	Coverage (Num of Counties)
Thatch-roofed dwellings	239	135	208	136	22	41
Grain-grass-roofed dwellings	201	130	188	131	7	12
Seagrass-roofed dwellings	86	28	81	23	5	9
Total	526	293	474	290	34	62

3.2. Spatial Distribution of Traditional Grass-Roofed Dwellings in China

The GIS platform was used to link the previously obtained 474 images to the corresponding county administrative units, where they are located to generate a visualized distribution map. Table 6 shows the information of example samples of the three types of grass-roofed dwellings recognized by the model.

Table 6. Recognition results (examples) of the prediction dataset.

Name and Number of the Image	Recognition Results		Map Points and Remarks	
	Marking	Labeling and Photograph	X	Y
Lingbi_0	1	Grain-grass-roofed dwelling 	117.531189 	33.686076
Dongfang_52	1	Thatch-roofed dwelling 	108.839842 	18.994769
Ningjin_39	1	Seagrass-roofed dwelling 	116.801001 	37.679721
Fugu_10	0	- 	- Image of non-traditional grass-roofed dwellings	-

3.2.1. Overall Spatial Distribution Showing Agglomeration

On a national scale, by calculating the nearest neighbor index of traditional grass-roofed dwellings in China according to Equation (3), the following results were yielded: the average observed distance is 70.5 km, and the predicted average distance is 102.8 km. Consequently, the nearest neighbor index (R) is 0.685697, with a Z score of −9.373071 and a significance of $p < 0.01$, indicating that traditional grass-roofed dwellings show obvious agglomeration characteristics in geographic space (Figure 5).

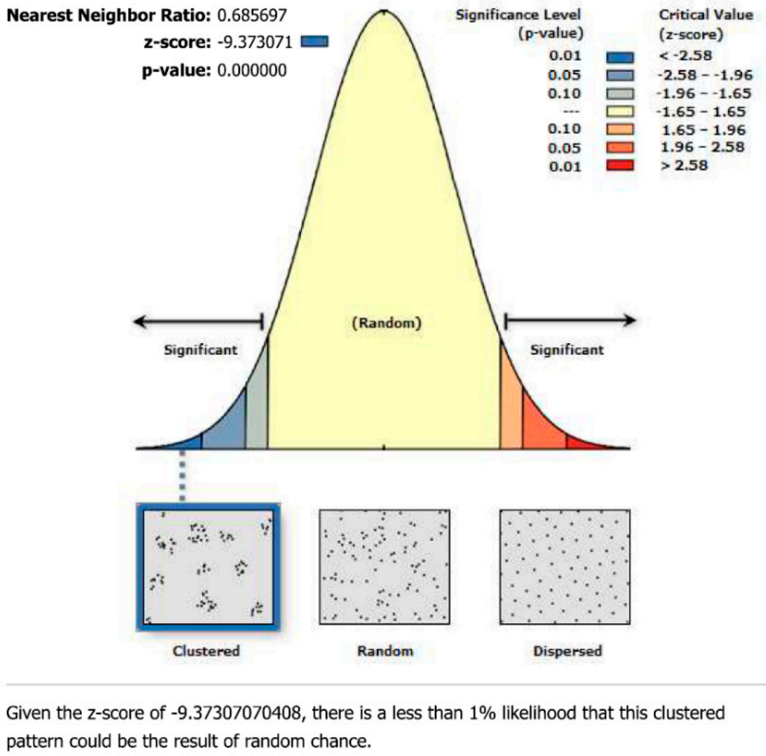


Figure 5. The Average Nearest Neighbor test report of the grass-roofed dwellings of all types.

According to the kernel density map (Figure 6), it can be seen that the distribution points meander across Yunnan, Guizhou, Sichuan, Shaanxi, Henan, Hebei, Shandong, Anhui, Liaoning, and Heilongjiang Provinces, forming strong intensity centers in fringe areas like Yunnan, Hainan, and Shandong. It is worth noting that the areas where the grass-roofed dwellings are distributed cover different typical topographic landscapes such as mountains, plains, and coasts, as well as climatic regions with great differences such as cold, hot and humid, which means that grass-roofed dwellings exist in natural environments with great differences. More importantly, the distribution of traditional grass-roofed dwellings shows a pattern characterized by a major concentration in the southeastern part of the Hu Line. The Hu Line, stretching from Aihui in Heilongjiang to Tengchong in Yunnan in the northeastern–southwestern direction, serves as a significant national geographic demarcation line in China. It reveals differences in demographic, economic, and natural geographic factors between the eastern and western regions of China [23]. The distinctive characteristics of both sides of this line, as well as fringe areas, exert a significant influence on the distribution of traditional grass-roofed dwellings. This issue will be discussed in the following section.

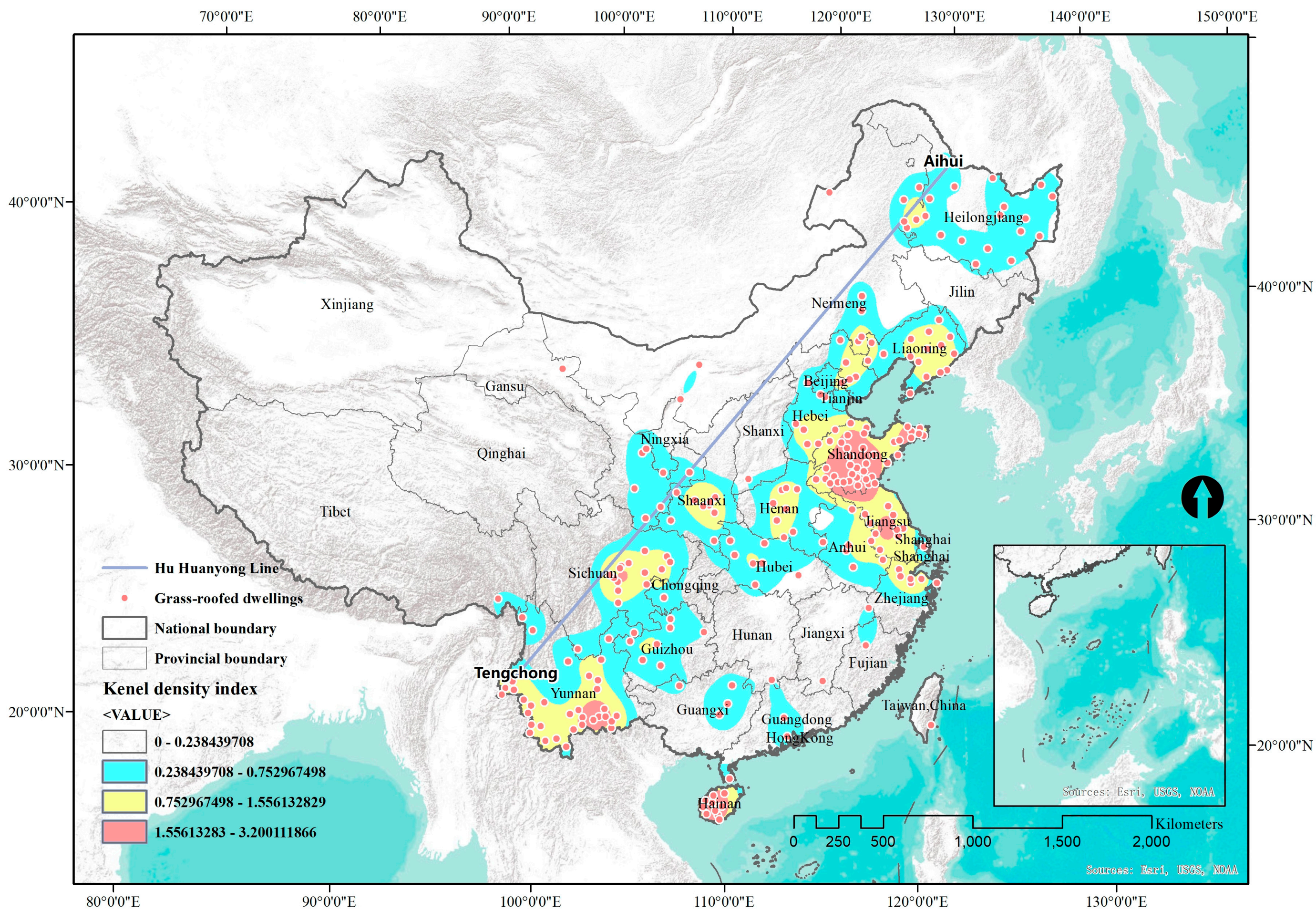


Figure 6. The kernel density distribution of traditional grass-roofed dwellings in China.

3.2.2. Spatial Distribution Difference of Grass-Roofed Dwelling Types

Further, we explore differences in the spatial distribution of different types of grass-roofed dwellings. In terms of quantity, the thatch-roofed dwellings constitute the majority, scattered across 25 out of 28 provinces that have grass-roofed dwellings in China, of which Yunnan Province has the most, accounting for more than 1/5 of the total. Slightly less than the thatch-roofed dwellings in quantity, the grain-grass-roofed dwellings are distributed in 23 provinces, being the most abundant in Shandong, Heilongjiang, and Yunnan. Compared to the first two, the seagrass-roofed dwellings are relatively rare in number and only distributed in the four coastal provinces, of which about 2/3 are clustered in Shandong (Figure 7).

According to the calculation of the nearest neighbor index (Table 7), both thatch-roofed and grain-grass-roofed dwellings showed significant clustering characteristics in geo-space, while the seagrass-roofed dwellings failed to form a distribution pattern of clustering. Figure 8 shows the distribution of kernel density for each type:

(1) The thatch-roofed dwellings form multiple cluster regions in Yunnan, Guizhou, Hainan, Sichuan, Shaanxi, northern Zhejiang, and Shandong–Henan junction, presenting a pattern of multi-center distribution, and the most clustered areas are primarily located at provincial boundaries, far away from provincial administrative centers (Figure 8a).

(2) The grain-grass-roofed dwellings are clustered in three main regions: Jiangsu–Shandong, southern Yunnan, and eastern Liaoning. While Heilongjiang Province in northeastern China lacks a prominent center of clustering, it still hosts a considerable number of grain-grass-roofed dwellings evenly distributed across the province (Figure 8b).

(3) Unlike the first two, seagrass-roofed dwellings did not form a significant clustered pattern in spatial distribution but were mainly distributed in the south of the Bohai Sea, i.e., from the Bohai Strait to the tip of the Shandong Peninsula, and a small number of them spread southward to Jiangsu Province, while no distribution was found in other coastal areas of China (Figure 8c).

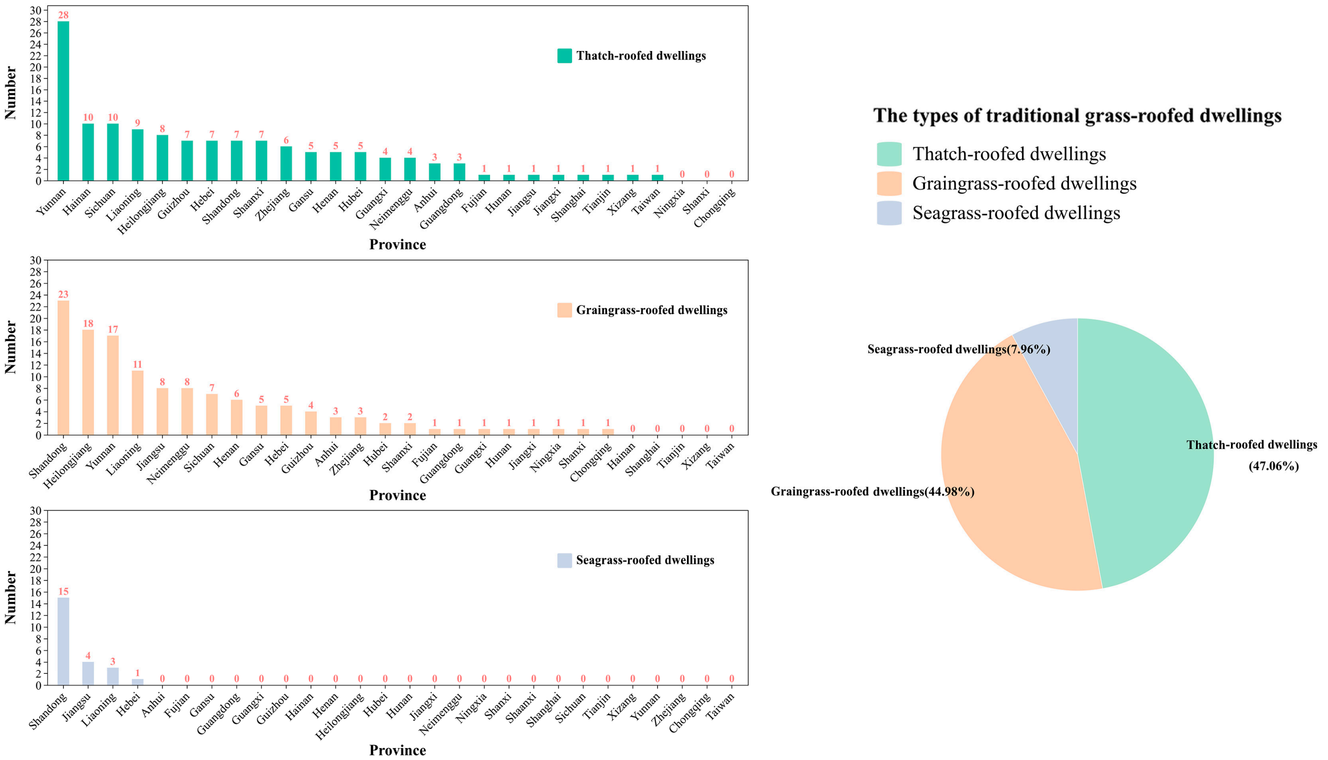
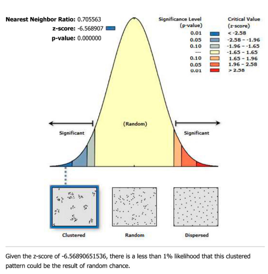
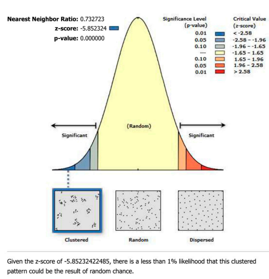
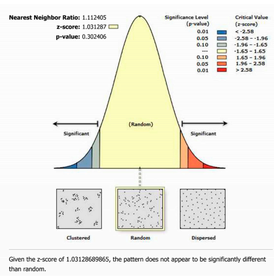
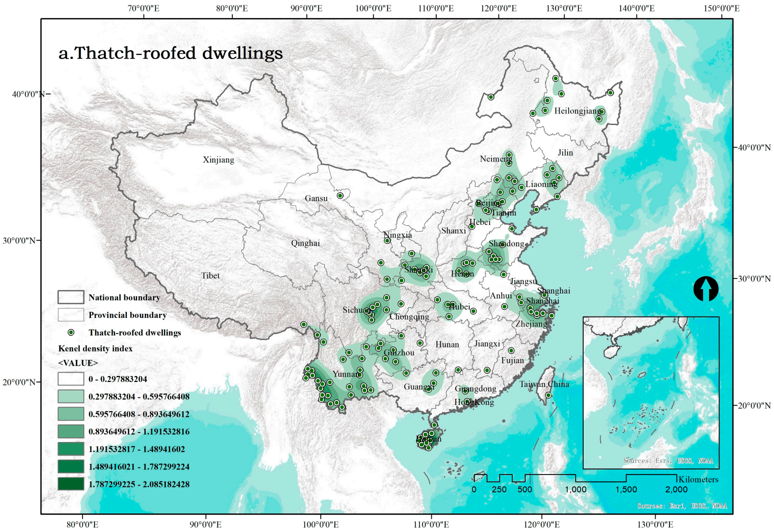


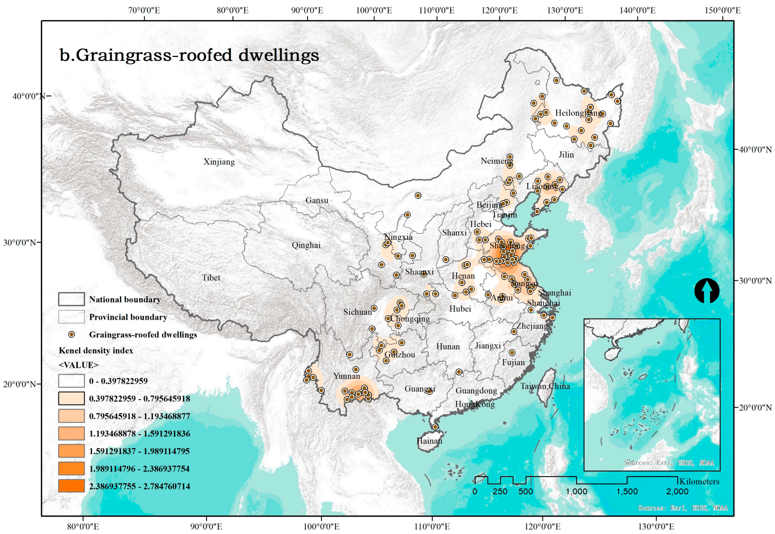
Figure 7. The number of the three types of grass-roofed dwellings in each province.

Table 7. Calculation results of the nearest neighbor index of traditional grass-roofed dwellings.

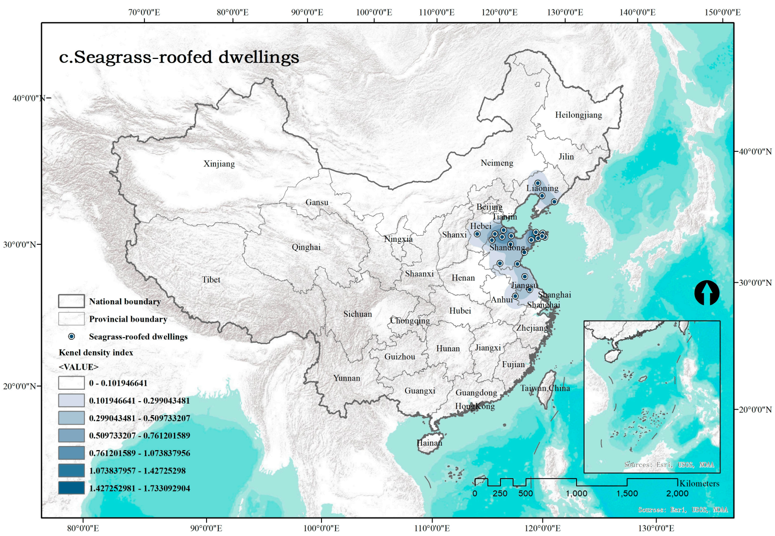
	Thatch-Roofed Dwellings	Grain-Grass-Roofed Dwellings	Seagrass-Roofed Dwellings
Observed mean distance (m)	95,998.38	85,318.87	91,902.39
Expected mean distance (m)	136,059.31	116,440.85	82,615.96
Nearest neighbor index R	0.705563	0.732723	1.112405
Z-score	−6.568907	−5.852324	1.031287
Significance *p*	<0.01	<0.01	>0.1
Clustering test report			



(**a**) Distribution map of thatch-roofed dwellings



(**b**) Distribution map of grain-grass-roofed dwellings



(**c**) Distribution map of seagrass-roofed dwellings

Figure 8. The kernel density distribution of three types of traditional grass-roofed dwellings.

In addition, the distribution of different types of grass-roofed dwellings is not mutually exclusive; 2–3 different types of grass-roofed dwellings may coexist in the same province or even the same county unit, which is related to the compatibility of growing environments for different types of grass materials and will also be specifically discussed in the next section.

3.3. Factors on the Distribution of Grass-Roofed Dwellings

Based on the results obtained in the previous experiments, such as the database of traditional grass-roofed dwellings and its corresponding distribution map obtained by new method, we will continue to explore the distribution pattern and reveal the regularity of traditional grass-roofed dwellings remains so as to provide inspirations for the protection and inheritance of this special architectural heritage.

In the introduction of this study, it was mentioned that classification and distribution are the final results of this study but they are not the final mission of traditional grass-roofed dwellings conservation; therefore, we continue to explore the distribution pattern of traditional grass-roofed dwellings in the discussion section, hoping to provide inspiration for the policy response to the conservation of traditional dwellings.

In the previous experiments, we obtained a new method of constructing the database information of traditional grass-roofed dwellings and distribution maps, and the core agglomeration centers of each type of grass-roofed dwellings have distribution differences, which means that the degree of protection of grass-roofed dwellings is affected by the role of external factors. Previous analysis indicates that grass-roofed dwellings are mainly distributed on the southeastern side of the Hu Line and in fringe areas. The Hu Line serves as a delineation for various socio-environmental factors, including population distribution, urbanization levels, and production modes. It also marks a distinction in natural geographic factors such as annual precipitation exceeding 400 mm and differences in topography between plateaus, plains, and hills. Based on this perception, the paper proposes to investigate the distribution patterns of traditional grass-roofed dwellings through the lens of both natural geographic and socio-environmental factors.

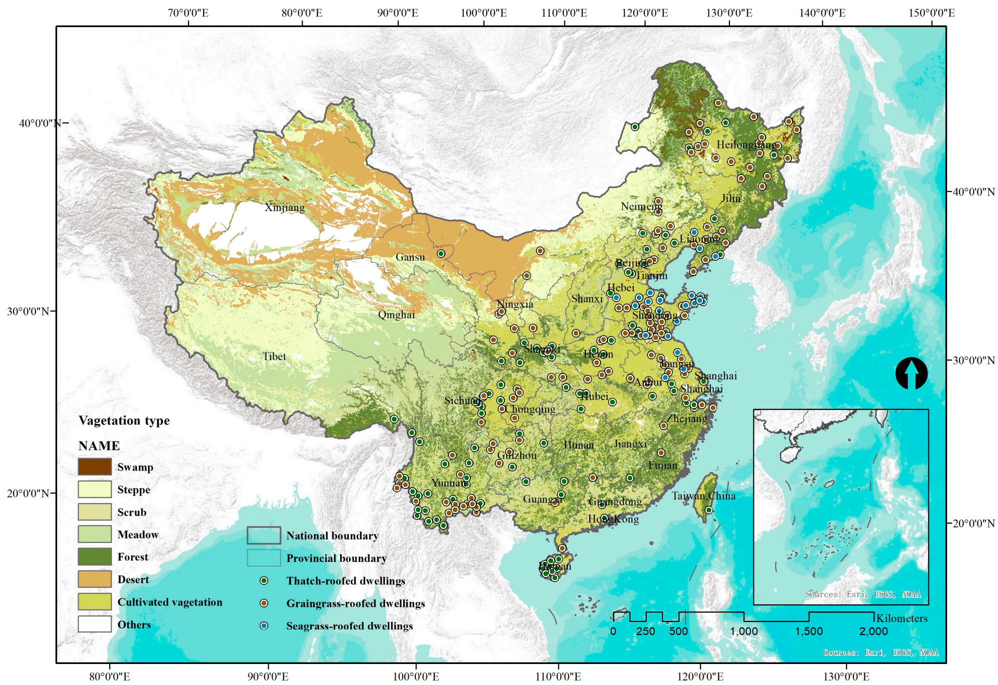
3.3.1. Natural Geographical Factors

Natural systems have shaped the orderly distribution and structure of herbaceous ecosystems, in which only specific grass species from specific regions are suitable as materials for house construction. Based on this understanding, we superimposed the map data of various types of natural geographic factors with the distribution maps of different types of grass-roofed dwellings for spatial analysis and data statistics, which explains in detail how the natural geographic factors affect the distribution of traditional grass-roofed dwellings.

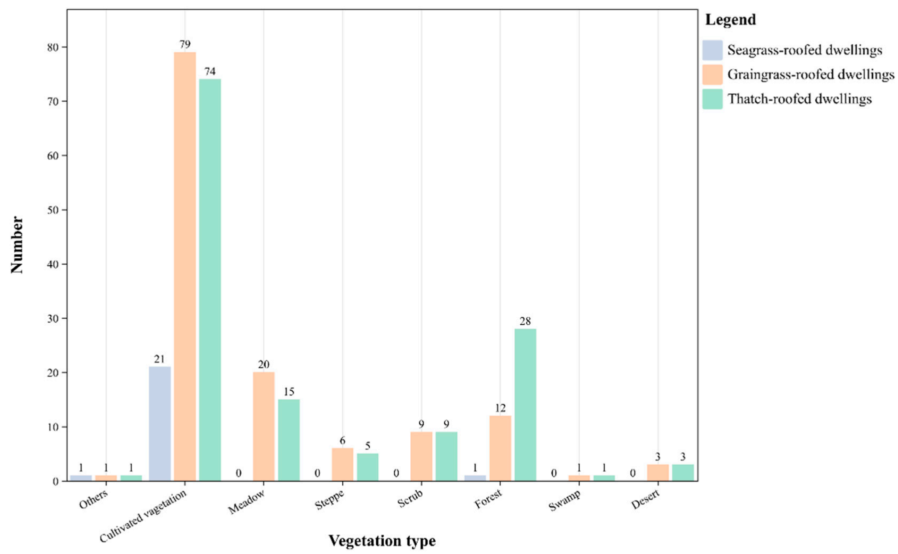
Traditional grass-roofed dwellings are a product of history and have a service life of between 30 and 50 years. Grain-grass-roofed dwellings using wheat or straw as the main material generally have a service life of 20–30 years [24], while seagrass material can last for 40 years or more [15]. Therefore, the construction of existing traditional grass-roofed dwellings can be traced back to the 1970s and 1990s. Therefore, geospatial data from the corresponding period are employed, aiming to establish a more reasonable understanding.

(1) Resource distribution pattern: acquisition of the grass materials

The differences in the distribution of the three types of grass-roofed dwellings are, first of all, directly related to the distribution pattern of the raw material, i.e., the grass plants themselves. From the superimposed map of grass-roofed dwellings and vegetation types (Figure 9), most of the grass-roofed dwellings are distributed in areas of cultivated vegetation, which are closely related to human activities. In fact, the acquisition of construction materials should not simply be a passive extraction from nature but rather an organic integration with human production and efficient utilization of resources in order to achieve the goal of sustainable construction. For example, Heilongjiang, Shandong, Yunnan, Liaoning, and Jiangsu are China's major grain-producing provinces, with crops such as soybeans, rice, maize, and wheat, which, while providing grain, also provide rich building materials for the construction of grain-grass-roofed dwellings [25,26]. A different story is that in the coastal areas of Shandong, due to the early consumption of a large amount of vegetation materials by the coastal salt industry, the local people turned to collecting seagrass that surged ashore with seasonal tides to build roofs [12]. However, due to the deterioration of the natural environment and excessive human excavation, the main material of seagrass-roofed dwellings, the large leaf algae, has been listed as "vulnerable" in the Red List of Threatened Species by the International Union for Conservation of Nature [27,28]. Therefore, the survival of the seagrass-roofed dwelling heritage also inevitably needs to be closely related to the ecological protection and restoration projects of the seagrass resources that have been initiated [29].



(**a**)

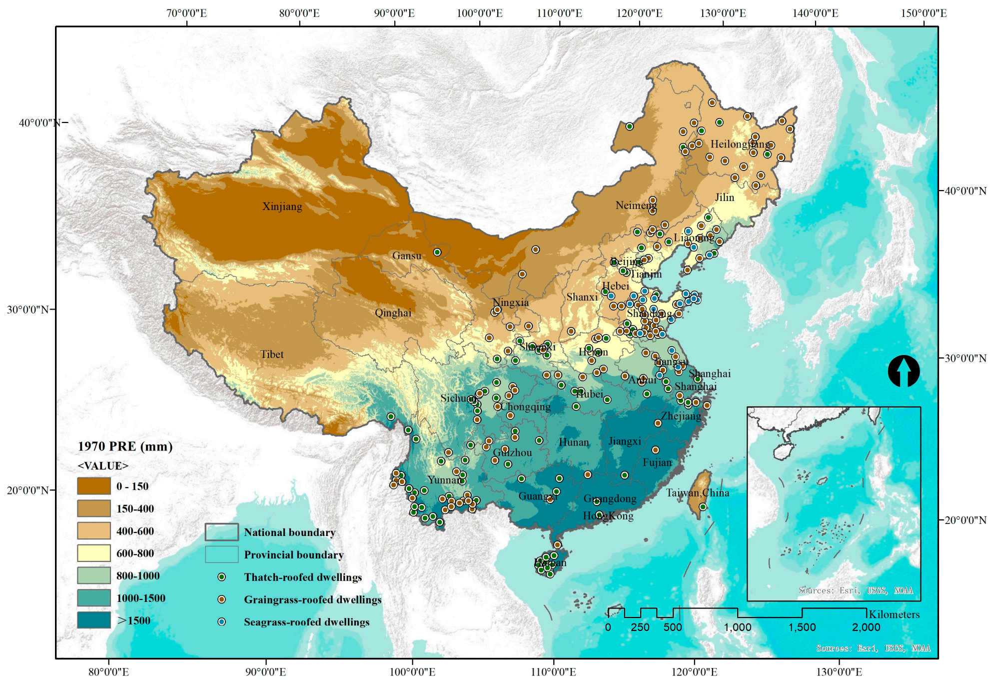


(**b**)

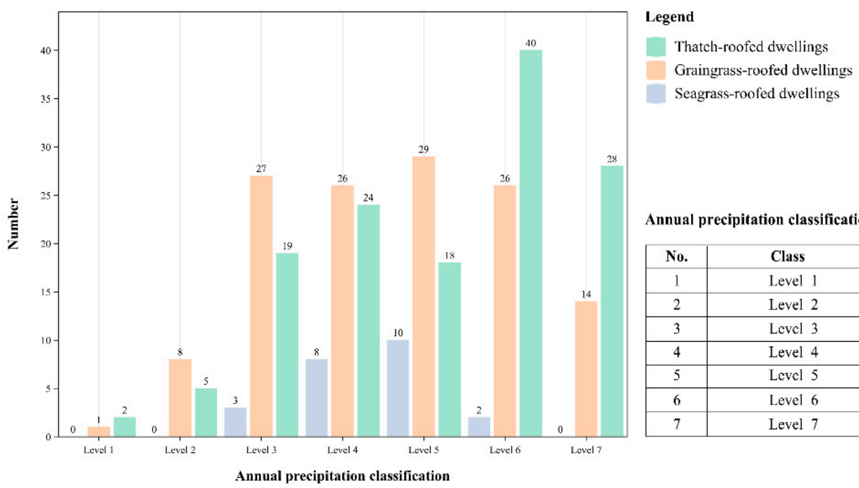
Figure 9. (**a**) Spatial distribution relationship between grass-roofed dwellings and vegetation types. (**b**) Quantitative statistics of grass-roofed dwellings in areas with different vegetation types.

(2) Precipitation: Grass growth environment and waterproof performance

Precipitation, on the one hand, is directly related to the growing conditions of grasses and, on the other hand, poses different demands on the roofs of buildings for rain protection. Figure 10 reflects the distribution of traditional grass-roofed dwellings in relation to the annual precipitation in 1970 across the country. The traditional grass-roofed dwellings in different precipitation levels are roughly normally distributed, mainly concentrated in L3–L7 (precipitation of 400 mm–2000 mm), with only a sporadic distribution in the L1 with precipitation below 200 mm. Among them, grain-grass-roofed dwellings are evenly distributed in the L3–L6 section with an annual precipitation of 600–1500 mm, while half of the thatch-roofed dwellings are distributed in the area with annual precipitation of more than 1500 mm.



(**a**)



Annual precipitation classification criteria

No.	Class	Index range (mm)
1	Level 1	less than 150
2	Level 2	150-400
3	Level 3	400-600
4	Level 4	600-800
5	Level 5	800-1000
6	Level 6	1000-1500
7	Level 7	more than 1500

(**b**)

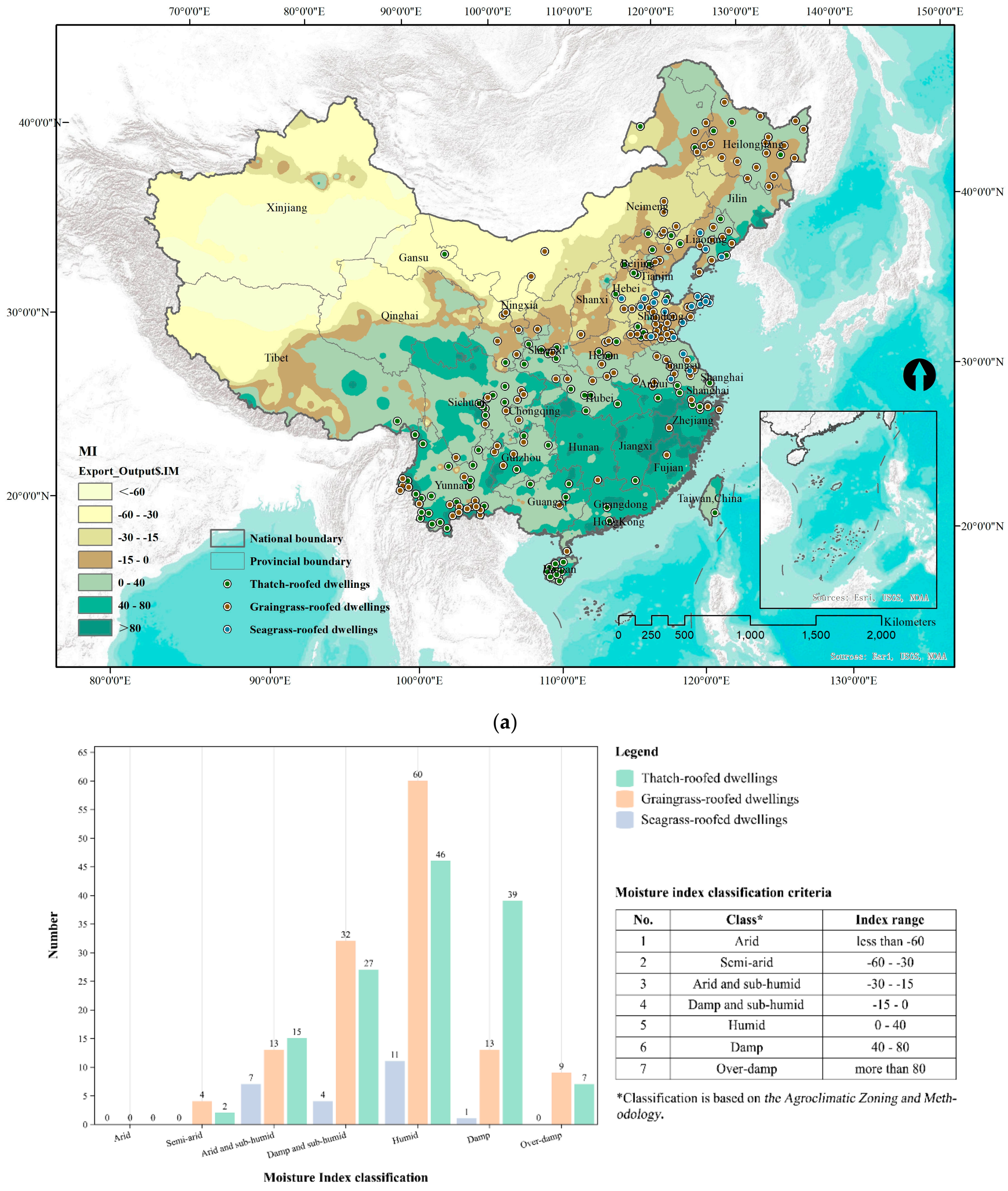
Figure 10. (**a**) Spatial distribution relationship between grass-roofed dwellings and precipitation[1]. (**b**) Quantitative statistics of grass-roofed dwellings in areas with different levels of precipitation.

Of the three grass roofing materials, thatch and grain-grass are both biologically inclined to loose and moist soil, with the exception of seagrass, which grows on the seashore. Higher precipitation can provide more water to the soil and satisfy the growth demand of thatch and grain-grass. Therefore, in the context of building houses with local materials, areas with higher precipitation can provide more raw materials for the construction of grass-roofed dwellings.

However, it should be noted that the number of grass-roofed dwellings is not linearly positively correlated with precipitation. The increase in precipitation not only nourishes the growth of grass but also brings requirements for rainproofing of the building roofs. According to a previous study, in order to meet the rainproof requirements, the grass roof needs to be thatched to a thickness of at least 15 cm by a thick paving technique [1]. In addition, it is also necessary to incorporate a variety of techniques to enhance drainage and rain protection, including increasing the slope of the roof, increasing the smoothness of the roof by planting moss or surface dressing, and special paving. For example, in Hainan Island, where annual precipitation exceeds 2000 mm, local materials such as white thatch, hemp bamboo, and sunflower leaves are adopted by the Li people to build the roofs [30]. During the construction process, thatched grass is clipped into thin bundles after drying. These bundles are then laid along the eave line in a zigzag line from bottom to top. This ensures that the roofs maintain firmness, preventing leaks or collapse, even in adverse weather conditions [31]. Another example is the grass-roofed mushroom houses of the Hani ethnic group concentrated in Honghe Prefecture in Yunnan Province, which also has a rainy climate. According to the research of ethnologists, the grass roofs of those mushroom houses with a steep slope of up to 60° were an improved device made specifically for rain protection after the transplantation to rainy areas of the Tu-zhang houses, a type of flat top rammed earth building commonly found in dry and hot areas of Yunnan [1]. However, compared to roofs made of other waterproof materials such as stone and tiles, grass roofs in the same area require a greater slope to meet the rainproof requirements, which makes excessive rainfall a greater constraint for the construction of grass-roofed dwellings [32]. In conclusion, precipitation has a bi-directional effect on the distribution of grass-roofed dwellings in terms of growth suitability and rainproof requirement, resulting in the distribution of grass-roofed dwellings being concentrated in areas with moderately high levels of precipitation. At this point, the three types of grass-roofed dwellings have certain commonalities.

(3) Humidity: Insect and fire prevention

Due to the strong correlation between precipitation and wetness index, we analyzed these two factors together. As can be seen from Figure 11, the distribution of the three types of grass-roofed dwellings on different moisture index levels all peak at “humid”. Both grain-grass-roofed and thatch-roofed dwellings show a normal distribution, but the former has more distribution below the peak than above it, while the latter is the opposite, i.e., more distributed in wetter areas. This situation basically corresponds to their distribution in correlation with the precipitation. As has been discussed above, grass roofs can reduce the accumulation of rainwater by strengthening surface drainage, but still have a certain degree of water absorption. If the air environment itself is not conducive to drying the roof, especially in warm and humid conditions, it will promote the development of microorganisms and fungi in the grass materials, attracting insects to feed and subsequently attracting birds, who may take the materials away from the roof for nesting. All of these factors will accelerate the decay and damage of the roof [9]. It can be seen that the provinces in the south where the temperature is higher and most humid, including Hunan, Jiangxi, Fujian, and Guangdong, have very few distributed grass-roofed dwellings. On the contrary, an overly arid environment obviously increases the risk of fire, and flammability is the biggest drawback in the performance of grass materials compared to other materials.



Moisture index classification criteria

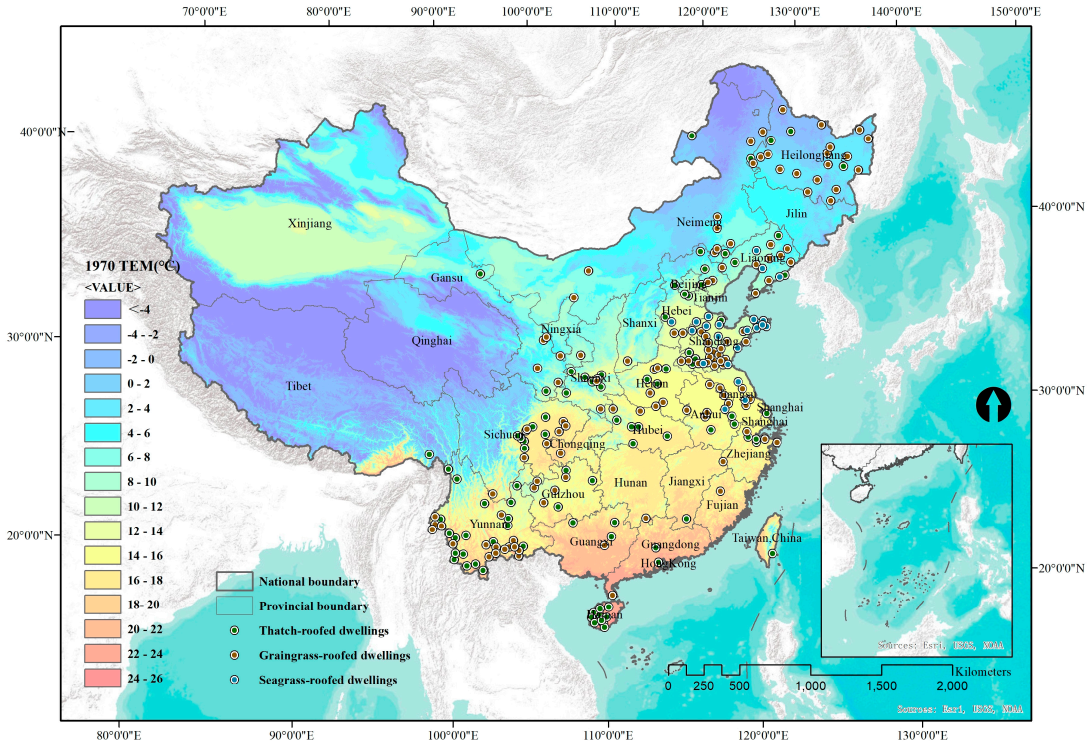
No.	Class*	Index range
1	Arid	less than -60
2	Semi-arid	-60 - -30
3	Arid and sub-humid	-30 - -15
4	Damp and sub-humid	-15 - 0
5	Humid	0 - 40
6	Damp	40 - 80
7	Over-damp	more than 80

*Classification is based on *the Agroclimatic Zoning and Methodology*.

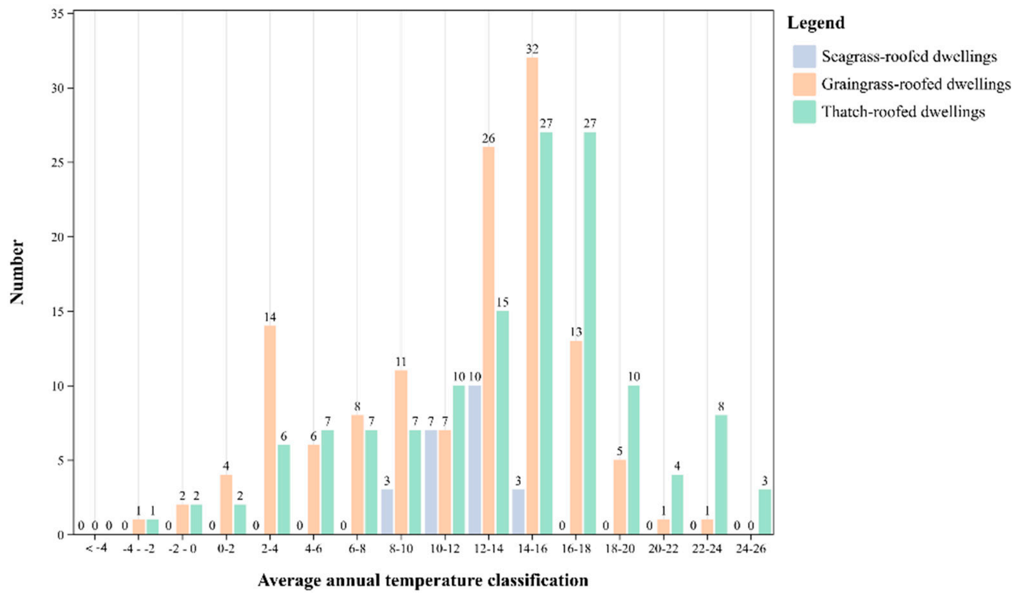
Figure 11. (**a**) Spatial distribution relationship between grass-roofed dwellings and humidity (moisture index)[2]. (**b**) Quantitative statistics of grass-roofed dwellings in areas with different levels of moisture index.

(4) Air Temperature: Grass growth environment and thermal performance

Similar to the precipitation factor, temperature is also related to the construction of grass-roofed dwellings in terms of both the growing environment of grass and the temperature adaptation of buildings. Figure 12 reflects the correlation between the distribution of traditional grass-roofed dwellings and the average annual temperature of various places in China in 1970. It can be seen that grass-roofed dwellings are distributed in the area with an average annual temperature ranging from −4 to 24 °C. Seagrass-roofed dwellings are distributed in areas with 8–16 °C, grain-grass-roofed dwellings are more distributed in areas with 2–4 °C and 12–18 °C, and thatch-roofed dwellings are distributed in areas with 14–18 °C. Among them, thatch-roofed dwellings have the widest distribution range in different temperature levels. The distribution of the three types of grass-roofed dwellings in different temperature conditions reflects not only the growth environment pattern of various grass species but also the differences in adapting and adjusting temperature as building materials.



(**a**)



(**b**)

Figure 12. (**a**) Spatial distribution relationship between grass-roofed dwellings and air temperature[3]. (**b**) Quantitative statistics of grass-roofed dwellings in areas with different levels of temperature. Note: The temperature grading is based on the classification of the annual average temperature map of China (1951–1980 data) published by China Map Publishing House.

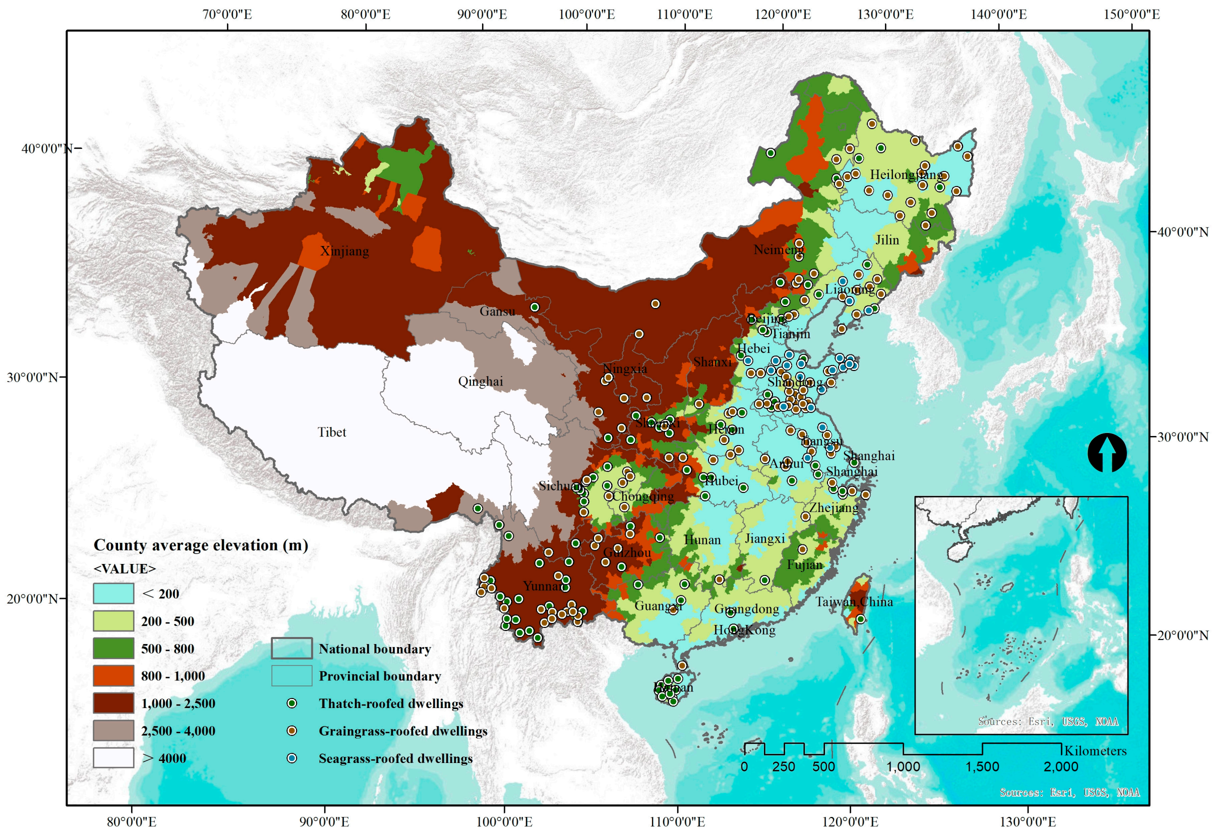
The distribution of seagrass-roofed dwellings is a significant example of the effect of temperature on the spatial pattern of raw material growth. The fact that seagrass-roofed dwellings are concentrated only in North China and not in South China along the coastline is precisely related to the differences in seagrass species under different temperatures. According to the distribution zoning, seagrasses in China are mainly distributed in the Indo-Pacific Tropical Seagrass Distribution Area and the North Pacific Temperate Seagrass Distribution Area [33]. The Jiaodong Peninsula, where seagrass-roofed dwellings are concentrated, belongs to the latter. Its main roofing material, eelgrass, belongs to the macrophyte family of temperate seagrasses, with rhizome diameters of 2–4 mm, some even only 0.15 mm, and internode lengths of 5–70 mm, which is very suitable for use in roof coverings. In contrast, the seagrass grown in the coastal areas of South China is mainly typical tropical seagrass such as Tylophora and Acorus calamus, which have stout fibrous roots with diameters of 15–20 mm, resulting larger gaps after cascading or bundling; thus, they are unsuitable to be used as a roof covering [34,35]. Therefore, there is no distribution of seagrass-roofed dwellings in these areas. Coincidentally, on the other side of the globe, on the island of Rais in Denmark, which is located in the same latitude and temperature zone as the Jiaodong Peninsula, there are also seagrass-roofed dwellings made of macroalgae and dwarf macroalgae grown on the local coast [36].

On the other hand, the biological properties of grasses make the grass roofs have a certain degree of climate adaptability. For example, the raw material, straw—used in the roof of the grain-grass-roofed dwellings—has a typical closed thin-walled cavity structure, which is light and fluffy, with a lower thermal conductivity than general roof materials such as wooden boards and stone slabs [37,38]. It has good thermal insulation performance and can effectively maintain the balance of indoor microclimate. Another example is the commonly used Wula sedge in thatch-roofed dwellings in Northeast China. The chemical composition of its grass fibers has superior thermal insulation properties [39].

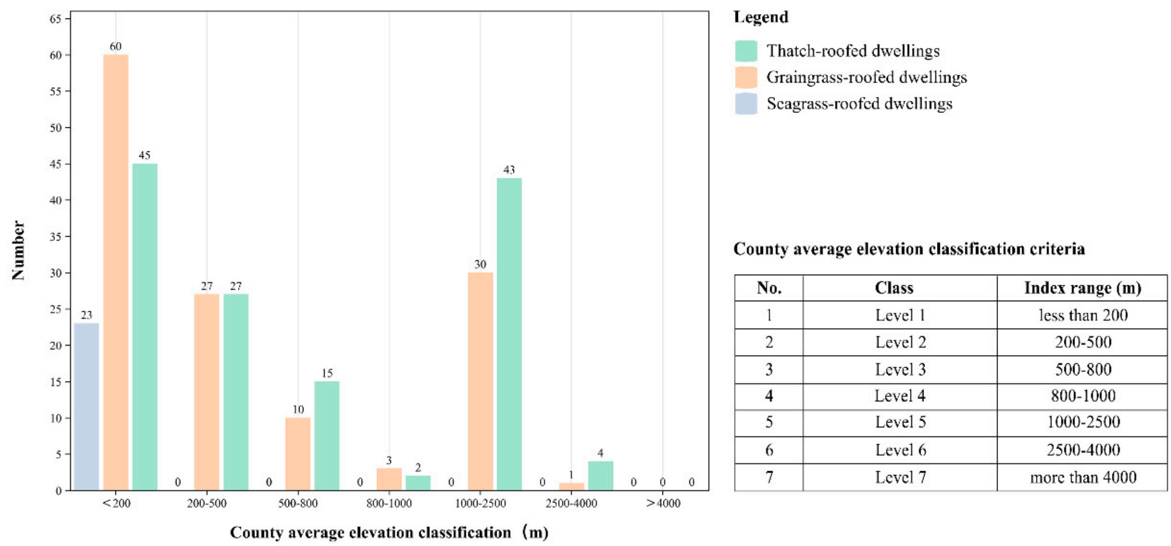
Grass roofs can also be adapted to different climates by flexibly adjusting the thickness and angle of the roof covering, e.g., the thickness of roof is about 20 cm in warmer areas in South China, while that in the colder areas in North China can be up to 30–50 cm [39]. More extreme examples, such as the Shirakawa-go Hapu houses in Japan, with grass roofs as thick as 1 m and as steep as 60°, are able to achieve better thermal insulation and reduce snow cover with lighter weight compared to other materials [1]. On the contrary, in high-temperature environments, grass roofs can help to enhance heat reflection and absorption, and reduce indoor heat accumulation through higher breathability [40].

(5) Elevation: Vertical landscape differences and wind protection

Figure 13 reflects the distribution of traditional Chinese grass-roofed dwellings at different elevations. It can be seen that within the range of elevation below 1000 m, the distribution of grass-roofed dwellings shows a significant decreasing trend from low elevation to high elevation, with the vast majority (>70%) distributed in areas below 800 m. However, it is interesting to note that in the section of elevation at 1000–2500 m, the grass-roofed dwellings have a considerable amount of distribution, even becoming the second most abundant section. Observing the locations of the grass-roofed dwellings distribution points in Figure 13a, these high-elevation grass-roofed dwellings are mainly located in Shaanxi and Ningxia in Northwest China as well as the Yunnan–Guizhou Plateau region in Southwest China. However, as the elevation continues to rise above 2500 m, the distribution of grass-roofed dwellings once again decreases to very few.



(**a**)



No.	Class	Index range (m)
1	Level 1	less than 200
2	Level 2	200-500
3	Level 3	500-800
4	Level 4	800-1000
5	Level 5	1000-2500
6	Level 6	2500-4000
7	Level 7	more than 4000

(**b**)

Figure 13. (**a**) Spatial distribution relationship between grass-roofed dwellings and elevation. (**b**) Quantitative statistics of grass-roofed dwellings in areas with different levels of elevation.

The pattern of distribution of grass-roofed dwellings in relation to elevation is influenced by the distribution of human settlement density on the topographic gradient itself, but in addition to this, due to the vertical differences in climate, different elevation also affects the growth pattern of grass resources. Take the Red River region of Yunnan, which is the highest elevation section in the distribution area of grass-roofed dwellings, as an example. Both its natural and humanistic landscapes have the typical characteristics of vertical distribution differences. In the main human settlement area at an elevation of 1000–2000 m, rice terraces, bamboo forests, tea plantations, forests, and upland grasslands are distributed from low to high, respectively. In the Hani ethnic settlement areas at lower elevation, people use crops grown in terraced fields to build grain-grass-roofed dwellings, forming the unique Hani "mushroom house", while the high-elevation forest areas provide a large amount of timber and thatch, and the Yi people living there use these materials to build double-sloped thatch-roofed dwellings [41].

In addition to the environmental disadvantages of aridity and coldness in the high-elevation regions of Northwest China as mentioned before, the excessive wind speeds also bring higher requirements for the structural stability of the dwellings. Grass roofs are lighter than other roofing materials such as stone and tile, which makes their wind protection problem more severe. A study has found that the slope of grass roofs in coastal areas, where they are more frequently affected by windy or typhoon weathers, is generally steeper than in inland areas. For example, the roof slope of the thatch-roofed dwellings in Leizhou Peninsula, South China is about 50°, while that of the seagrass-roofed dwellings in Jiaodong Peninsula is as high as nearly 70° [39]. Therefore, it is obvious that the grass roofs will face too severe a threat of wind damage and lose their safety and suitability in areas with high wind speeds, such as the Tibetan Plateau [42].

3.3.2. Socio-Environmental Factors

Social environment reflects the intensity of human activities and the level of social development. With the deepening of urbanization and land expansion, the survival of traditional grass-roofed dwellings were affected in different ways [43]. Based on the knowledge that factors such as population, economic development, and facility construction have differential effects on the distribution of traditional dwellings, this study extracts the distribution of population density, GDP per capita, and road density and superimpose them with the distribution of traditional grass-roofed dwellings in order to explore in what ways the socio-environmental factors affect the preservation status of grass-roofed dwellings.

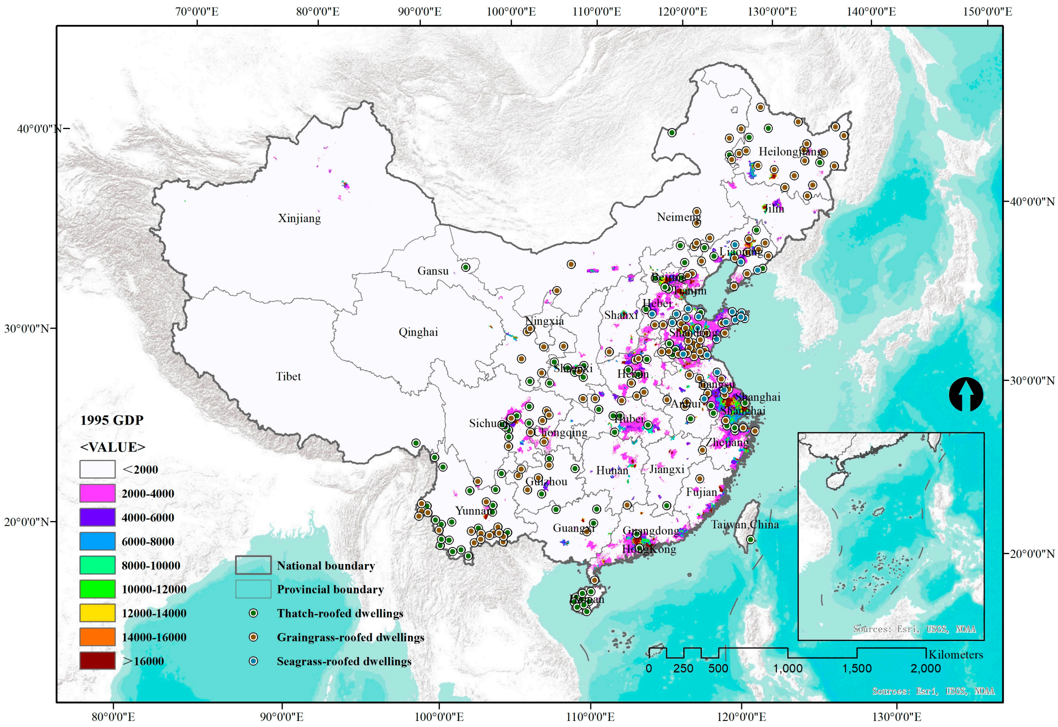
(1) Per capita GDP

Figure 14 illustrates the spatial distribution of China's per capita GDP in 1995, revealing that most of the grass-roofed dwellings are distributed in regions with a per capita GDP below the national average [44].

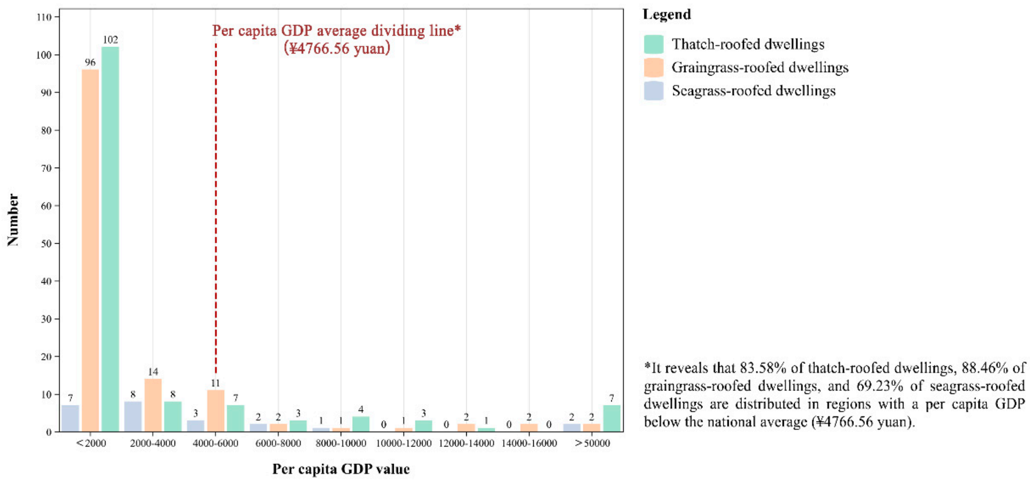
The relatively backward economic conditions in these areas have led to simpler rural dwelling construction. Grass-roofed dwellings, combined with locally available materials such as loess and stones, are cost-effective for the accommodation of large populations. Furthermore, the relatively lower degree of modernization in these regions has fostered a conservative attitude among residents, who tend to maintain traditional architectural styles and lifestyles, thus exhibiting a slower pace in replacing or updating traditional built environments. Consequently, grass-roofed dwellings are more likely to be preserved and perpetuated as one of the traditional building forms in these areas.

Comparatively, in Hunan, Hubei and the coastal areas from Guangdong to Zhejiang, which show high GDP per capita, there are only a small number of grass-roofed dwellings sporadically distributed. From the bar graph in Figure 14b, the number of grass-roofed dwellings decreases sharply when the GDP gradually increases.

However, some grass-roofed dwelling settlements in economically developed areas have been able to survive due to tourism development. For example, in Rongcheng, Shandong Province, more than 50 seagrass-roofed dwellings with a history of 200 years are preserved to attract tourists, which not only protects the cultural heritage but also facilitates local economic development.



(**a**)

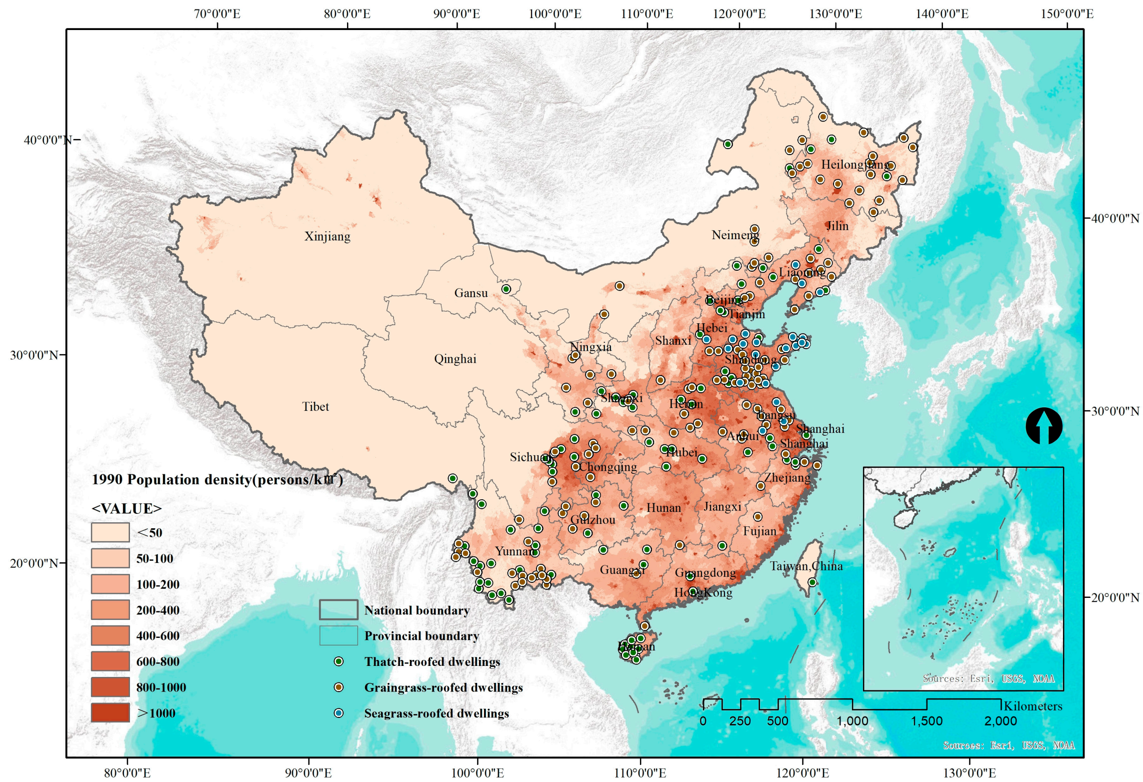


(**b**)

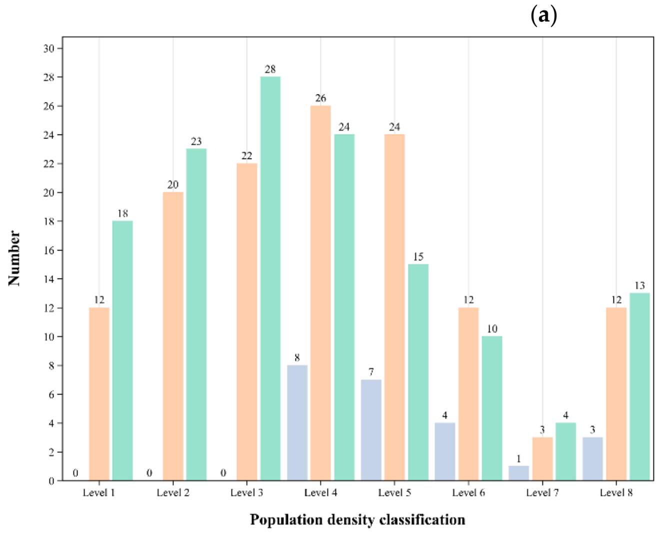
Figure 14. (**a**) Spatial distribution relationship between grass-roofed dwellings and per capita GDP value[4]. (**b**) Quantitative statistics of grass-roofed dwellings in areas with different levels of per capita GDP. * Data for Taiwan Province of China are not included in the 1995 per capita GDP data due to limitations in data availability.

(2) Population Density

Figure 15 depicts the relationship between the spatial distributions of China's population density and the grass-roofed dwellings. The bar graph reveals that the total number of traditional grass-roofed dwellings initially increases and then decreases as population density rises, with the peak in the low-density level ranging from 100 to 500 people/km^2. There is generally a positive correlation between population density and economic development. Regions with lower population densities often imply slower economic growth and lower regional attractiveness. In these regions, grass-roofed dwellings tend to congregate and cluster within small areas. The lack of sustained interactions with larger populations over time has contributed to the preservation of grass-roofed dwellings in such areas. The grass-roofed dwelling clusters with higher kernel density indexes are all located along the provincial boundaries, far away from the administrative centers, which also indicates that the marginal areas have better preservation of grass-roofed dwellings. It should be noted that, in areas with the sparsest population density, which covers most of the northwest nomadic ethnic areas or extreme climatic zones, there are inherently fewer human settlements, making it reasonable that the number of grass-roofed dwellings in these areas is less than that in areas with medium population density.



(**a**)



No.	Class	Index range (persons/km²)
1	Level 1	less than 50
2	Level 2	50-100
3	Level 3	100-200
4	Level 4	200-400
5	Level 5	400-600
6	Level 6	600-800
7	Level 7	800-1000
8	Level 8	more than 1000

*China's population density spatial distribution data is based on population data the type of land use, night-time light brightness and density of settlements.

(**b**)

Figure 15. (**a**) Spatial distribution relationship between grass-roofed dwellings and population density[5]. (**b**) Quantitative statistics of grass-roofed dwellings in areas with different levels of population density. * Data for Taiwan Province of China are not included in the 1990 China's population data due to limitations in data availability.

(3) Road network density

Figure 16 shows that the largest number of grass-roofed dwellings are distributed in regions with medium and medium-to-high road density areas, such as Shandong, Hebei, Henan, Jiangsu, Sichuan, Chongqing, etc., where convenient traffic could bring a broader market for the utilization of traditional dwellings. A considerable portion are distributed in areas of low-to-medium density, such as Yunnan, Hainan, and Heilongjiang. These areas, due to their remote locations, experience limited connectivity with the outside world, thereby reducing the impact of rapid environmental transformation and protecting the traditional grass-roofed dwellings from developmental damage. In areas with the lowest road density, mostly in the western regions, the poor accessibility due to natural factors such as topography and geomorphology would limit the frequency of human activities; therefore, the quantity of grass-roofed dwellings shows a significant decrease. Finally, the relatively small portion of areas with a high-density road network within the country explains the sharp decline in the number of grass-roofed dwellings in these areas.

(4) The overall impact of socio-environmental factors

Compared to the natural factors, the socio-environmental factors such as economic, population, and urbanization constructions are highly correlated, jointly presenting a pattern of social development. Therefore, based on the relevant statistics of the above three factors, we can understand the survival of the grass-roofed dwellings in the context of a general socio-economic development process.

Firstly, some of the grass-roofed dwellings are concentrated in the central and western regions with lower levels of modernization, such as Yunnan, Guizhou, Heilongjiang, etc. These regions have less population mobility and lower land expansion, reducing the influence of external factors on the preservation of the traditional grass-roofed dwellings.

Secondly, in areas with rapid urbanization, the distribution of the number of grass-roofed dwellings is relatively small. In these areas, with high development intensity and rapid urban turnover, the process of replacement construction has often been carried out in a disorderly manner without a clear understanding of the heritage value of the traditional dwellings. In this process, some of the traditional grass-roofed houses have had their grass roofs replaced by tin or tile material or replaced as a whole by modern, newer buildings.

Last but not least, there is not a complete negative correlation between the level of social development and the survival of traditional grass-roofed dwellings [45]. On the one hand, the modernization development has brought about the improvement of people's spiritual and cultural pursuit, thus creating demands for protecting the built heritages. On the other hand, the level of urban construction directly affects the scope of cultural exchange and the speed of cultural dissemination. In general, relying on the isolation from external influences is not a long-lasting conservation strategy. It is essential to improve the recognition of the value of cultural heritage and the support of infrastructure to attract external forces to discover, participate in, and jointly protect the unique architectural heritage of the grass-roofed dwellings.

In the light of the above analysis, this study concludes that the improvement of the level of social development will have a double-sided impact on the preservation and survival of the grass-roofed dwellings and that the degree of economic construction, population mobility, and external contacts not only affect the differences in the physical preservation conditions of the grass-roofed dwellings but also influence the transformation of the social concepts and consciousness, thus forming the characteristics of a diversified and heterogeneous geographic distribution.

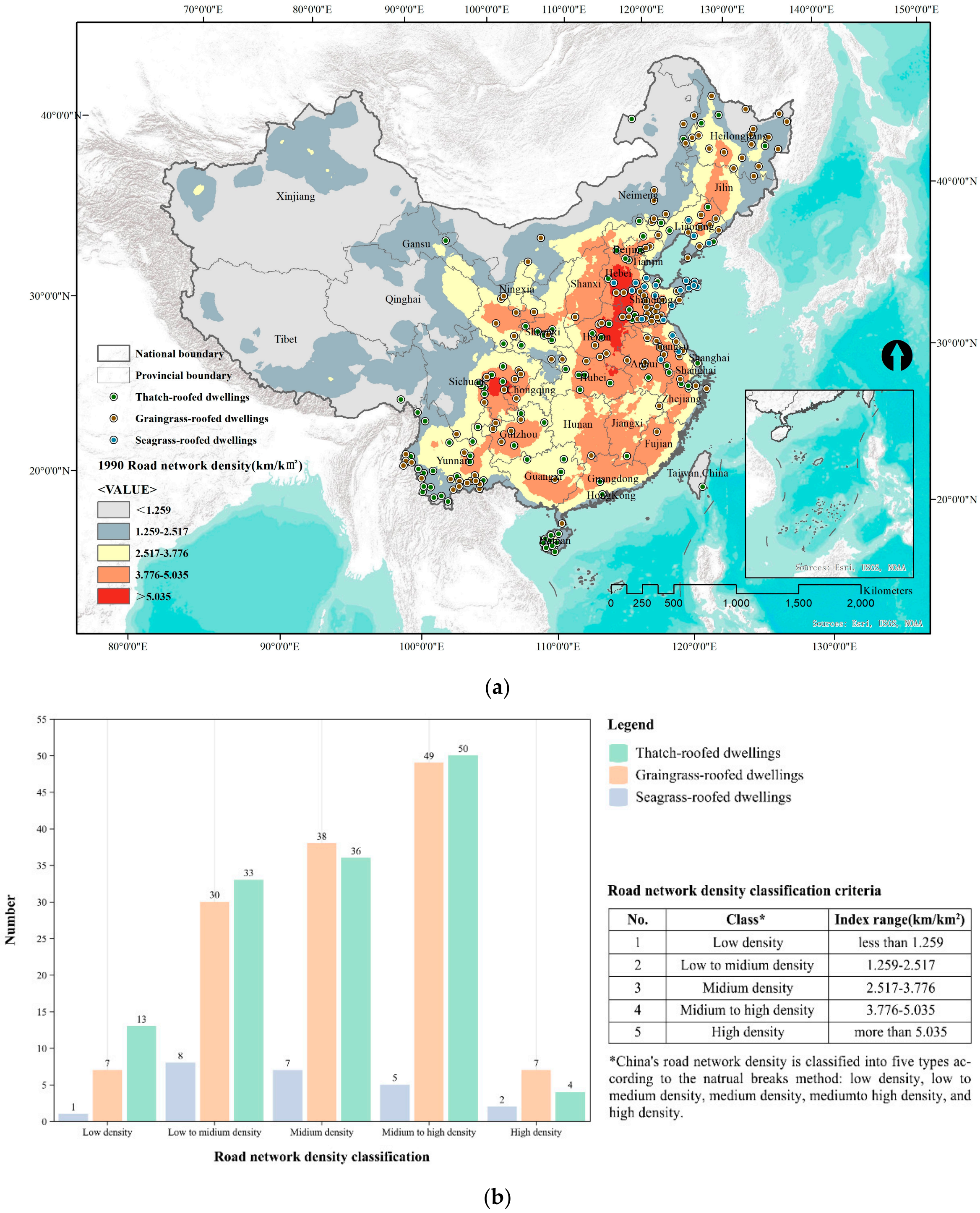


Figure 16. (**a**) Spatial distribution relationship between grass-roofed dwellings and road network density[6]. (**b**) Quantitative statistics of grass-roofed dwellings in areas with different levels of road network density.

4. Conclusions

Grass-roofed dwellings represent a distinctive category of traditional vernacular architecture, with physical remnants found across various regions worldwide, including extensive distribution throughout China. In this paper, we construct a classified dataset comprising three types of traditional grass-roofed dwellings in China and develop a recognition model through deep learning methods. Utilizing image data with geospatial semantic information sourced from the internet, we conduct image recognition, classification, and spatial positioning of the three types of grass-roofed dwellings. The Geographic Information System is applied to create thematic maps and conduct visualized analyses. This study provides fundamental information and effective methods references for further research on these endangered traditional dwellings. We draw the following conclusions:

(1) Traditional grass-roofed dwellings in China have a significant clustered distribution pattern primarily concentrated southeast of the Hu Line and in the fringe areas of China's mainland. Among them, thatch-roofed dwellings are most widely distributed, with high intensity distribution cores in North, South, and Southwest China; grain-grass-roofed dwellings exhibit a predominant distribution in the northeastern regions, as well as in Shandong and its surrounding area; and a smaller number of seagrass-roofed dwellings are mainly distributed in the regions surrounding the Bohai Sea.
(2) The natural environment has an essential influence on the original construction and distribution of traditional grass-roofed dwellings. Factors such as vegetation type, precipitation, temperature, humidity, elevation, etc., directly or indirectly impact the supply of suitable grass materials for roofing by influencing the growth pattern of grass. The environmental adaptability of grass material will also restrict the construction and distribution of grass-roofed dwellings. In general, the existing grass-roofed dwellings are mainly distributed in areas with higher rainfall, higher moisture index, milder temperatures, and lower elevations, and less distributed in areas that are rainless, arid, and have severe cold or extreme heat. As an ecological construction method closely related to natural resources, grass-roofed dwellings reflect the close interaction between humans and nature—that is, to make full and effective use of local materials while at the same time ensuring the buildings constructed by these materials adapt to local natural conditions. In this regard, traditional grass-roofed dwellings provided us with some inspiration.
(3) Socio-environmental factors, including economic development levels, population distribution, and road network density, along with the process of regional modernization development, exert influence on the retention of the existing traditional grass-roofed dwellings through the substitution of new buildings for traditional dwellings. It was found that with the growth of economy, population, and modernization, the protection of traditional grass-roofed dwellings has been subjected to more impacts, but when the socio-economic development reaches a certain level, the emphasis on and effective use of traditional architectural culture will promote the retention of grass-roofed dwellings. This further highlights the importance and urgency of enhancing the awareness of the cultural values of traditional architecture. In addition, the modern adaptation of traditional grass-roofed dwellings and the application of traditional eco-wisdom in contemporary contexts are issues of significant relevance and merit further exploration.

5. Discussion

In terms of research content, this study pays attention to the relationship between the natural and social environments and the spatial distribution of samples of traditional grass-roofed dwellings. Nowadays, the local constraints of grass-roofed dwellings are gradually weakening, and how to make traditional grass-roofed dwellings adaptable to modernization through scientific means is an issue worth further deepening, and also an important means of fine-tuning protection, for which the studies of many international scholars have provided good ideas. Some scholars are concerned about the safety and protection of traditional grass-roofed dwellings. Tensei Mizukami compared fire prevention methods in grass-roofed dwellings across the UK, Denmark, the Netherlands, and Japan. He evaluated fireproofing materials, fire protection distances, and firefighting techniques, emphasizing the importance of addressing potential fire hazards in unnoticed flammable structures such as the eaves and interior windows [46]. Some scholars also advocate learning the ecological wisdom in the construction of traditional grass-roofed houses to make the buildings more sustainable. For example, through the detailed explanation of the performance of reed materials, Hayley Bouza et al. proposed that its strong sound insulation, heat preservation, light weight, and other characteristics are worthy of being promoted as a material for the construction of residential houses [47]; they also proved experimentally that grass-roofed houses constructed using coconut leaves have the natural characteristics of cooling down, which saves energy better [48].

From a methodological perspective, there are also issues worth discussing. Firstly, in many regions, grass-roofed dwellings historically existed but have since disappeared. Secondly, traditional grass-roofed dwellings still persist in some areas but have not yet been detected. Theoretically, both cases could be addressed using the same method—that is, interpreting specific features from remote sensing images. A number of international studies have used remote sensing images as data for identification models to quickly extract vegetation information, building preservation, and ecological spatial evolution in target areas [49–51]. These studies are mainly at the scale of building complexes and villages, focusing on a single type of sample. Therefore, there are limitations compared to the methods used in this paper that use images taken from the ground. Firstly, historical remote sensing images with full-area coverage are difficult to obtain, resulting in the incompletion of the spatiotemporal structure of the interpreted samples. Secondly, due to the small volume of grass-roofed dwellings, their recognition requires extremely high-precision remote sensing images. This will result in a massive dataset for coverage of the whole domain, which poses significant demands in terms of computing power and increases the technical complexity. Nevertheless, compared to the method using ground-shot image resources employed in this paper, recognition based on remote sensing images may offer more precise results. Therefore, combining or comparing the outcomes of studies utilizing different methodologies could provide valuable insights.

Author Contributions: Conceptualization, J.T.; Methodology, J.T., Y.Z., and P.R.; Software, Y.Z.; Validation, J.T. and X.Z.; Formal Analysis, Y.Z. and X.Z.; Investigation, Y.Z., Z.W., and J.X.; Resources, J.T. and J.X.; Data Curation, Y.Z.; Writing—Original Draft Preparation, Y.Z. and X.Z.; Writing—Review and Editing, J.T. and X.Z.; Visualization, Y.Z.; Supervision, J.T. and X.Z.; Project Administration, J.T.; Funding Acquisition, J.T. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by Ministry of Education of China [23YJA850004], National Natural Science Foundation of China [52378018], and Guangdong Provincial Basic and Applied Basic Research Fund Committee [2021B1515020013].

Data Availability Statement: The original contributions presented in the study are included in the article, further inguiries can be directed to the corresponding author.

Acknowledgments: The authors thank Ying Lin, Fudan Zheng, and Deli Tsai for discussions on the research methodology of this paper, especially for assistance in dataset production and feedback on the study.

Conflicts of Interest: The authors declare no conflicts of interest.

Notes

1. Data Source: Xu, X. (2017). Spatially interpolated dataset of mean conditions of meteorological elements in China. Resource and Environmental Science Data Registration and Publication System. (http://www.resdc.cn/doi, accessed on 18 March 2024). https://doi.org/10.12078/2017121301.
2. Data Source: Xu, X., & Zhang, Y. (2017). Meteorological Background Dataset in China. Resource and Environmental Science Data Registration and Publication System. (http://www.resdc.cn/doi, accessed on 22 March 2024). https://doi.org/10.12078/2017121301.
3. Data Source: Xu, X. (2017). Spatially interpolated dataset of mean conditions of meteorological elements in China. Resource and Environmental Science Data Registration and Publication System. (http://www.resdc.cn/doi, accessed on 22 Feburary 2024). https://doi.org/10.12078/2017121301.
4. Date Source: Xu, X. (2017). Spatial distribution of kilometer grid GDP dataset in China. Resource and Environmental Science Data Registration and Publication System. (http://www.resdc.cn/doi, accessed on 22 March 2024). https://doi.org/10.12078/2017121102.

[5] Data Source: Xu, X. (2017). Spatial distribution of kilometer grid population dataset in China. Resource and Environmental Science Data Registration and Publication System. (http://www.resdc.cn/doi, accessed on 22 March 2024). https://doi.org/10.12078/2017121101.

[6] Data source: Grabbed from the Google map web.

References

1. Yang, J. Applied Research of Plant Materials in Ancient Chinese Architecture—Grass Bamboo Wood. Ph.D. Dissertation, Southeast University, Shenyang, China, 2018. Available online: https://kns.cnki.net/kcms2/article/abstract?v=KqXyGY4RJv1EYWHv7U77Sz2aoAMRkjON-q6carHjrW3aAkTL3Wz49X1Lp9oFMdzXktcnCDEqxMQMvsjvmGdu_E41tmTDHsCHa_L_sHVJweC3Q1FGKyhzkcywkCkiUYFtG7c0idTsinw-aAykWQ1LhCiLs-7CQRmFY1rDVIYyz1ZnRasWhDO-GQ==&uniplatform=NZKPT (accessed on 25 December 2023).
2. Wang, W.; Zhou, L. Natural Zoning of Traditional Chinese Dwelling Forms. *Archit. J.* **1992**, *38*, 12–16.
3. Wang, L. Cultural Regionalization Research on Construction Techniques of Han Traditional Dwellings in Northeast China. Master's Thesis, Harbin Institute of Technology, Harbin, China, 2019. [CrossRef]
4. Ji, S.Y.; Jun, H.J. Deep learning model for form recognition and structural member classification of east asian traditional buildings. *Sustainability* **2020**, *12*, 5292. [CrossRef]
5. Wang, N.; Zhao, X.; Zhao, P.; Zhang, Y.; Zou, Z.; Ou, J. Automatic damage detection of historic masonry buildings based on mobile deep learning. *Autom. Constr.* **2019**, *103*, 53–66. [CrossRef]
6. Siountri, K.; Anagnostopoulos, C.N. The classification of cultural heritage buildings in athens using deep learning techniques. *Heritage* **2023**, *6*, 3673–3705. [CrossRef]
7. Dimitrov, A.; Golparvar-Fard, M. Vision-based material recognition for automated monitoring of construction progress and generating building information modeling from unordered site image collections. *Adv. Eng. Inform.* **2014**, *28*, 37–49. [CrossRef]
8. Cheng, G. Research on Modern Architectural Space Construction Based on Straw Materials. Master's Thesis, Nanjing University of the Arts, Nanjing, China, 2014.
9. Oliver, P. *Encyclopedia of Vernacular Architecture of the World*; Cambridge University Press: New York, NY, USA, 1997; Available online: http://archive.org/details/encyclopediaofve0001unse_z0h2 (accessed on 28 February 2024).
10. Uy, N.; Shaw, R. Shaped by Wind and Typhoon: The Indigenous Knowledge of the Ivatans in the Batanes Islands, Philippines. In *Indigenous Knowledge for Disaster Risk Reduction: Good Practices and Lessons Learned from Experiences in the Asia-Pacific Region*; United Nations International Strategy for Disaster Reduction: Bangkok, Thailand, 2008; pp. 59–63. Available online: https://www.academia.edu/16343023/Shaped_by_Wind_and_Typhoon_The_Indigenous_Knowledge_of_the_Ivatans_in_the_Batanes_Islands_Philippines (accessed on 28 February 2024).
11. NHI, O.N.Y.; Hai, T.T.; Van Thuong, L. The Local Climate Adapting Characteristics of Traditional Buildings in Indochina-Sustainable Designs from Vernacular Architecture. *Res. Militaris.* **2022**, *12*, 1433–1441. Available online: https://resmilitaris.net/index.php/resmilitaris/article/view/1962 (accessed on 25 February 2024).
12. Zhang, J.; Qiao, X. An Exploration of the Intrinsic Value of Thatched Houses in Ancient Canal Heritage Villages: A Study Based on Thatched Houses in Xinglong Village, Taierzhuang Region, Lunan. *Huazhong Archit.* **2008**, *26*, 166–171.
13. Wang, J.; Li, X.; Yang, Q.; Wang, T. The ecological wisdom and craftsmanship of thatched roofs. *Tradit. Chin. Archit. Gard.* **2020**, *37*, 25–30.
14. Chen, R. A Study on the Conservation Design of Traditional Residences in Hainan Li Flood Village Based on Locality. Master's Thesis, Hainan Normal University, Haikou, China, 2023. [CrossRef]
15. Steger, C. A roof of one's own: Choice and access in global thatch sustainability. *World Dev. Sustain.* **2023**, *3*, 100088. [CrossRef]
16. Zámolyi, F.; Herbig, U. Reed as building material-renaissance of vernacular techniques. In *International Symposium on Advanced Methods of Monitoring Reed Habitats*; Csaplovics, E., Schmidt, J., Eds.; Rhombos: Berlin, Germany, 2011; p. 83. Available online: https://www.researchgate.net/profile/Ulrike-Herbig-2/publication/318349101_Reed_as_building_material_-_renaissance_of_vernacular_techniques/links/5964f8caa6fdcc41b1d3c63a/Reed-as-building-material-renaissance-of-vernacular-techniques.pdf (accessed on 25 February 2024).
17. Ministry of Housing and Urban-Rural Development of the People's Republic of China. *Tyological Collection of Traditional Chinese Dwellings*; China Architecture & Building Press: Beijing, China, 2014.
18. Dosdall, R.; Hahn, V.; Preuß, F.; Kreisel, H.; Miersch, J.; Schauer, F. Characterization of fungi of the genus Mycena isolated from houses thatched with Phragmites communis Trin. in Northern Germany: Enzyme pattern and reed decay. *Int. Biodeterior. Biodegrad.* **2014**, *96*, 174–180. [CrossRef]
19. Ultralytics. Ultralytics YOLOv8 Docs. Home—Ultralytics YOLOv8 Docs. 2023. Available online: https://docs.ultralytics.com/zh/#yol (accessed on 2 February 2024).
20. Qamar, S.; Baba, A.I.; Verger, S.; Andersson, M. Segmentation and Characterization of Macerated Fibers and Vessels Using Deep Learning. *arXiv* **2024**, arXiv:2401.16937. [CrossRef] [PubMed]
21. Su, H.; Wang, Y.; Zhang, Z.; Dong, W. Characteristics and influencing factors of traditional village distribution in China. *Land* **2022**, *11*, 1631. [CrossRef]
22. Liao, Y.; Cenci, J.; Zhang, J. Chinese Modern Architectural Heritage Resources: Perspectives of Spatial Distribution and Influencing Factors. *ISPRS Int. J. Geo-Inf.* **2023**, *12*, 358. [CrossRef]

23. Chen, M.; Gong, Y.; Li, Y.; Lu, D.; Zhang, H. Population distribution and urbanization on both sides of the Hu Huanyong Line: Answering the Premier's question. *J. Geogr. Sci.* **2016**, *26*, 1593–1610. [CrossRef]
24. Liu, M.; Zhou, Z. Application and construction process of thatched roofs. *Constr. Archit.* **2009**, *19*, 52–53.
25. Wu, J.; Shen, C.; Zhang, J.; Zhou, X.; Han, S. Spatial pattern and its changes of grain production using GIS. *IOP Conf. Ser. Earth Environ. Sci.* **2018**, *113*, 012044. [CrossRef]
26. Yin, X.; Lawrence, M.; Maskell, D.; Chang, W.-S. Construction and monitoring of experimental straw bale building in northeast China. *Constr. Build. Mater.* **2018**, *183*, 46–57. [CrossRef]
27. International Union for the Conservation of Nature [IUCN]. IUCN Red List of Threatened Species. Search by Species Name. 2010. Available online: https://www.iucnredlist.org/ (accessed on 18 March 2024).
28. Xu, S.; Zhang, Y.; Zhou, Y.; Xu, S.; Yue, S.; Liu, M.; Zhang, X. Warming northward shifting southern limits of the iconic temperate seagrass (Zostera marina). *iScience* **2022**, *25*, 104755. [CrossRef] [PubMed]
29. Wang, S.; Cui, Y.; Liu, J.; Xia, Z. Research progress on seagrass and seagrass ecosystems. *Acta Pratacult. Sin.* **2016**, *25*, 149–159. Available online: http://cyxb.lzu.edu.cn/EN/volumn/current.shtml (accessed on 1 April 2024).
30. Gong, T.; Li, C. Simple practical wisdom: A study on the construction techniques of the floor boat-shaped house of the Li ethnic group in Hainan. *ZHUANGSHI* **2022**, *10*, 88–93. [CrossRef]
31. Lu, Q. *Hainan HongKong Macau Ancient Architecture*; China Building Industry Press: Beijing, China, 2015.
32. Zhang, T. Study on Climate Adaptability of Typical Traditional Dwellings Envelope. Ph.D. Dissertation, Xi'an University of Architecture and Technology, Xi'an, China, 2014. Available online: https://kns.cnki.net/kcms2/article/abstract?v=KqXyGY4RJv3rr2QaJe2zog_I2VavgmT9R1WwiOsIwyNWIC9P3cp5uBVTc3ABO_i6oqmUVDjx137GHFiMLaLe7WPLiFJxVWfQWElYV61SGgB6FBx0gt-NE4IPBBmcIGBH61IeuKIveY6bpGO1b1tvF0pbKHIQS4UfGzlK0SgmxYE=&uniplatform=NZKPT (accessed on 1 April 2024).
33. Short, F.; Carruthers, T.; Dennison, W.; Waycott, M. Global seagrass distribution and diversity: A bioregional model. *J. Exp. Mar. Biol. Ecol.* **2007**, *350*, 3–20. [CrossRef]
34. Li, X.; Wang, K.; Zhang, S.; Feng, M. Distribution and flora of seaweed beds in the coastal waters of China. *Sustainability* **2021**, *13*, 3009. [CrossRef]
35. Shi, Y.; Fan, H.; Cui, X.; Pan, L.; Li, S.; Song, X. Overview on seagrasses and related research in China. *Chin. J. Oceanol. Limnol.* **2010**, *28*, 329–339. [CrossRef]
36. Davies, P.; Morvan, C.; Sire, O.; Baley, C. Structure and properties of fibres from sea-grass (*Zostera marina*). *J. Mater. Sci.* **2007**, *42*, 4850–4857. [CrossRef]
37. China Academy of Building Research (n.d.). *Thermal Design Code for Civil Building (GB50176-2016)*; China Architecture & Building Press: Beijing, China. Available online: https://www.mohurd.gov.cn/gongkai/zhengce/zhengcefilelib/201702/20170214_230579.html (accessed on 3 April 2024).
38. Yang, Q. The Environmental Suitability of Enclosure of Vernacular Dwellings in Northeast China from the Material Perspective. Qingdao University of Technology. Master's Thesis. 2020. Available online: https://link.cnki.net/doi/10.27263/d.cnki.gqudc.2020.000028 (accessed on 26 October 2023).
39. Yang, J. A Study on the Application of Grass Materials in Ancient Chinese Architecture. *Archit. J.* **2019**, *10*, 46–53.
40. Karyono, T.H.; Suwantara, I.K.; Nugrahaeni, R.; Suprijanto, I.; Vale, R. Temperature performance and thermal comfort study in vernacular houses in East Nusa Tenggara, Indonesia. In Proceedings of the 7th Windsor Conference: The Changing Context of Comfort in an Unpredictable World Cumberland Lodge, Windsor, UK, 12–15 April 2012; pp. 12–15.
41. Fullen, M.A. Agro-environmental sustainability of the Yuanyang rice terraces of Yunnan (China): Lessons for Europe. In *Protection of the Ecological and Productivity Functions in a Pan European Context: International Conference of ESSC, Průhonice, Czech Republic, 22–25 June 2009*; University of Wolverhampton: Wolverhampton, UK, 2009; pp. 12–18. Available online: http://hdl.handle.net/2436/108337 (accessed on 27 February 2024).
42. CMA Wind and Solar Center. *China Wind and Solar Energy Resources Bulletin*; CMA Wind and Solar Center: Beijing, China, 2024.
43. Ren, Y. The Real Situation, Value and Path of Traditional Village Protection. *Acad. Res.* **2023**, *12*, 47–53.
44. National Bureau of Statistics of the People's Republic of China. Statistical Bulletin on National Economic and Social Development in 1995. 2001. Available online: https://www.stats.gov.cn/sj/tjgb/ndtjgb/qgndtjgb/202302/t20230206_1901939.html (accessed on 1 April 2024).
45. Kang, J.; Zhang, J.; Hu, H.; Zhou, J.; Xiong, J. Analysis on the spatial distribution characteristics of Chinese traditional villages. *Prog. Geogr.* **2016**, *35*, 839–850.
46. Mizukami, T. A Comparative Study of Building Regulations and Fire Protection Methods on Thatched Rooves in the United Kingdom, Denmark, the Netherlands and Japan. *Fire Technol.* **2023**. [CrossRef]
47. Bouza, H.E.; Asut, S. Advancing reed-based architecture through circular digital fabrication. In Proceedings of the eCAADe 2020 (Online): 38th International Conference on Education and Research in Computer Aided Architectural Design in Europe, Berlin, Germany, 16–18 September 2020; pp. 117–126. Available online: http://papers.cumincad.org/cgi-bin/works/paper/ecaade2020_240 (accessed on 1 April 2024).
48. Vimalraj, A.; Jeyasubramanian, K.; Baskar, I. Sustainable building envelopes: Evaluating the thermal performance of thatched roofs fabricated using coconut leaves. *Sustain. Chem. Pharm.* **2024**, *42*, 101771. [CrossRef]

49. Wu, F.; Wang, C.; Zhang, B.; Zhang, H.; Gong, L. Discrimination of collapsed buildings from remote sensing imagery using deep neural networks. In Proceedings of the IGARSS 2019-2019 IEEE International Geoscience and Remote Sensing Symposium, Yokohama, Japan, 28 July–2 August 2019; pp. 2646–2649. [CrossRef]
50. Qiu, G.; Yin, H.; Xie, W.; He, L.; Ao, Z. Research on vegetation information extraction in the area of important buildings based on remote sensing image. *Mol. Vis.* **2011**, *18*, 1395–1401. [CrossRef]
51. Walker, R.S.; Hamilton, M.J.; Groth, A.A. Remote sensing and conservation of isolated indigenous villages in Amazonia. *R. Soc. Open Sci.* **2014**, *1*, 140246. [CrossRef] [PubMed]