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Spatial Differentiation Characteristics of Human Settlements and Their Responses to Natural and Socioeconomic Conditions in the Marginal Zone of an Uninhabited Area, Changtang Plateau, China

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Abstract: The Changtang Plateau (CTP) in Qinghai-Tibet Plateau of China is one of the top-10 uninhabited areas with the most important ecological value in the world. It is of great academic and practical significance to carry out research on human settlements in the marginal zones of the uninhabited areas to promote harmonious coexistence between humans and nature on the CTP. Using high-definition remote-sensing images to visually interpret and identify settlement-patch data, combined with field investigations, this study explores the spatial characteristics of human settlements in Shuanghu and Nyima counties and their responses to natural and socioeconomic conditions in the hinterland of the CTP. Findings reveal that the scale of human settlements on the CTP is extremely small, and density is very sparse. Settlements on the CTP primarily consist of several households, with some containing more than a dozen households, or are sub-village scale. Socioeconomic development is low and socioeconomic factors have a weak influence on the settlement layout on the CTP. Natural factors are the core elements affecting the layout of human settlements on the CTP. Settlements tend to occur on low mountains, gentle slopes, and areas with high average annual temperatures. Careful settlement site selection can help to mitigate the impact of natural disasters. To meet the needs of grazing, settlement layouts must typically have a high-quality grassland orientation. Riverbanks are key settlement areas, and settlement sites are often far away from alpine salt lakes. The characteristics of settlements on the CTP and their responses to environmental conditions significantly differ from those of human settlements in low-altitude inland areas.

Keywords: alpine pasture; settlement; spatial differentiation; influencing factors; Qinghai-Tibet Plateau; Changtang Plateau; China

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1 Introduction

Human settlements are areas in which humans live and perform various social activities, and are the spatial units where human activity interacts most strongly with the natural environment (Jones, 2010). The spatial layout and evolution of settlements are affected by both natural conditions and the socioeconomic factors of the areas in which they are located. The natural environment is relatively stable and constitutes the spatial base

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of human activity and the overall framework of human settlement evolution. Socioeconomic factors represent the direct embodiment of human initiatives to adapt to or transform natural conditions with the characteristic of dynamic change. These factors have become the important driving forces of change in the spatial pattern of settlements (Ali, 2007; Esch et al., 2014; Tian et al., 2018; Xiao et al., 2018; Chen et al., 2019; Song and Li, 2020). Due to the heterogeneity of surface space laid out by human settlements, the two elements play significantly different roles in the development process of settlements under different geographical conditions (Linard et al., 2010; Xi et al., 2018; Yu et al., 2018). In areas where natural conditions are relatively suitable for human survival, such as plains or low-altitude hilly areas, humans have a strong ability to transform nature or optimize environmental conditions. They can obtain flat land via engineering, improve accessibility through the construction of transportation infrastructure, and improve water availability through the construction of canal systems and water networks (Ma et al., 2018; Su et al., 2019; Li et al., 2020). Human activities in such areas have a strong ability to optimize the living environment, adjusting or changing socioeconomic factors; such factors have become the core driving force for the layout and evolution of settlements. In such areas, the population and socioeconomic density are relatively high, the area of a single settlement-patch is large, the spatial distribution of settlements is concentrated, and the dynamic evolution characteristics of settlements are obvious. Existing theoretical and empirical research on settlements has mostly focused on these areas (Clark et al., 2009; Shi et al., 2016; Yang et al., 2017; Xu et al., 2019; Lu et al., 2020).

China is a vast territory, and its terrain goes through three steps from east to west. Natural geographical conditions become increasingly complex with the uplift of the terrain, from plains and hills to mountains and plateaus. The main surface ecosystems responsible for human survival gradually transition from cultivated land and paddy fields to oases, pastures, and even alpine deserts (Harris, 2010; Zhu et al., 2018; Peng and Wang, 2020). The suitability of natural environmental conditions for human survival also varies incrementally from high to low. On the Qinghai-Tibet Plateau (QTP), fragile ecosystems, such as alpine meadows, alpine grasslands, and alpine deserts, have become the main spatial carriers for human survival and development under cold and arid climate conditions (Lamsal et al.,2017; Li et al., 2018c). In contrast to low-altitude inland areas with superior natural conditions, the QTP is high altitude, oxygen is scarce, and the terrain is steep. Therefore, the geographical environment represents a substantial obstacle to human survival. Here, humans can only passively adapt to the hypoxic environment and their ability to transform natural conditions is extremely limited (Schwalb et al., 2010; Yin et al., 2017; Sun et al., 2020; Xu et al., 2020; Yi et al., 2020). Strong constraints of natural conditions and weak socioeconomic activities determine the typicality, complexity, and uniqueness of the distribution pattern of settlements, rendering it important to research settlements on the QTP thoroughly (Zhang et al., 2019b).

The Changtang Plateau (CTP), part of the QTP in northern Tibet, has an extremely harsh natural environment, and is one of the top-10 uninhabited areas with the most important ecological value in the world (Allan et al., 2017). Most of the CTP is designated as a national nature reserve; it provides habitats for rare animals, such as the Tibetan antelope and wild yak, both of which are unique to the QTP. Its ecological and environmental value is, therefore, significant (Farrington and Tsering, 2019; Xu et al., 2020; Xia et al., 2021). There have been no human settlements in the history of the CTP—herders have lived nomadic lives, following water and grass. However, in recent years, due to population growth and the expansion of livestock herds, the boundary of human activity has encroached on previously uninhabited areas due to a drive to obtain production materials, introducing increasing ecological and environmental risks. Due to the small scale and scattered distribution of settlements on the CTP, it is difficult to describe the associated settlement patterns using previous research methods that have high thresholds for the identification of settlement scale based on land use type, spatial population density, and big data (Reeves et al., 2006; Song Wei et al., 2014; Liu et al., 2016; Song L et al., 2017; Li et al., 2018a). Therefore, few studies have been conducted on this area. It is also difficult to compare the differences in settlement distribution patterns between alpine pastoral areas and low-altitude agricultural areas. However, it is highly necessary to compare the distribution characteristics of different types of regions in order to enrich the settlement research system.

Specifically, identifying effective research methods to explore the settlement layout of the CTP and its adaptability to its particular natural environment will not only enrich the current settlement research system but also elucidate how people and nature can coexist on the CTP (Zhang et al., 2020a). Moreover, such research methods will facilitate maintenance of the ecological environment and sustainable development of the CTP and QTP.

Taking Nyima and Shuanghu counties on the CTP hinterland as example areas, and using settlement-patch data obtained through manual interpretation of high-definition remote-sensing images from the professional version of Google Earth, combined with field investigations, this study explores the distribution pattern of human settlements and their responses to natural and socioeconomic conditions on the marginal zones of the Changtang uninhabited areas, where the natural environment is extremely harsh. The research method of visual interpretation and decipherment is expected to provide an effective research tool for exploring the evolution of settlements in sparsely populated areas. In revealing the site selection characteristics of human settlements under harsh natural environmental conditions and comparing them with the layout characteristics of settlements in low-altitude inland areas and their causes, this research has important theoretical and practical significance for expanding the case study of settlements in typical regions and enriching the connotation of settlement research system.

2 Materials and Methods

2.1 Study area

Nyima County and Shuanghu County are adjacent to one another and belong to Nagqu City (Fig. 1). Both counties are located in the hinterland of the CTP in northern Tibet, with the Kunlun Mountains to the north, and the Tanggula Mountains to the south, between 30°20′N–36°29′N, 85°02′E–90°26′E. The study area covers 190 900 km^2, and is characterized by high alti-

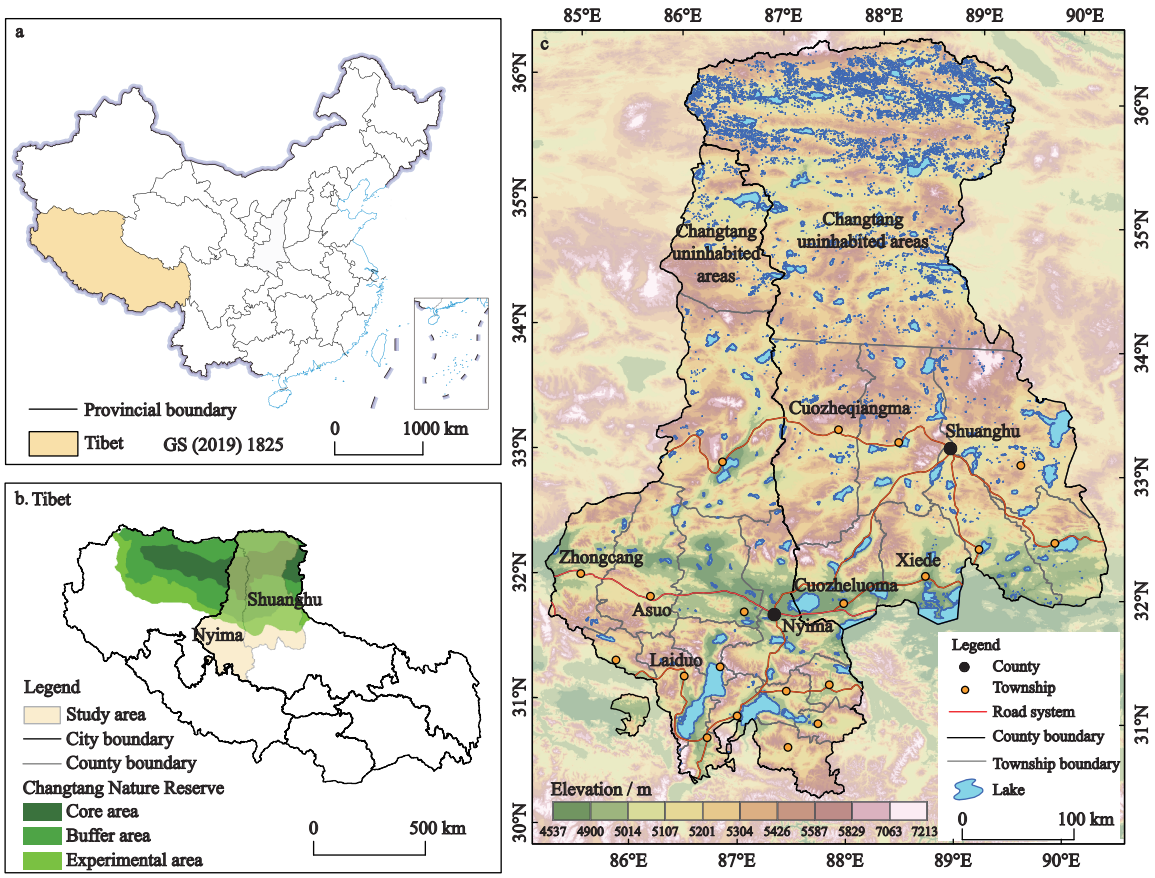

Fig. 1 Geographical location of Nyima and Shuanghu counties on the Changtang Plateau, China; a, the location of Tibet in China; b, the location of the study area in Tibet; c, the geographical environment conditions of the study area

tude (average of over 5000 m; maximum of 7044 m) and a dry, cold climate (annual precipitation of 150 mm; annual average temperature of –4 °C). It is within the semi-arid monsoon climate of the plateau sub-frigid zone and the arid climate of the plateau cold zone. The climate is cold and hypoxic, and the four seasons are unclear-the winter is long, there is no summer, and there is no completely frost-free period during the year. Wind and snow disasters are frequent here, and living conditions are extremely harsh.

As of 2019, the total population of the study area was 40 900, and the population density was 0.21 people/km^2. The population of Shuanghu County was only 9700, the population density was 0.08 people/km^2, and the gross national product of the two counties was 1.26 billion yuan RMB (Rural Social and Economic Investigation Department of National Bureau of Statistics, 2020). The per-capita income of herders was about 8000 yuan in the study area. Taking Nyima and Shuanghu counties as examples, we study the distribution pattern of human settlements on the CTP with the following characteristics. 1) Both are located in the hinterland of the CTP in the northern of Tibet and are pure pastoral counties. They are representative of the sparsely populated pastoral area of the QTP. 2) Both are distributed vertically from north to south. The northern parts of the counties are vast, uninhabited areas and there is a boundary between human activity and the purely natural environment. Both counties have similar distribution characteristics of human settlements. Carrying out research in this area is expected to reveal typical characteristics of human settlement patterns in interfacial areas. 3) The two counties in the study area belong to national key ecological function areas. The Changtang National Nature Reserve (CTNNR) accounts for 66.03% of the total study area. Thus, the requirements for ecological protection are high, as is the responsibility for ecological protection, because human activity and wild-animal living areas overlap significantly. Optimizing the spatial layouts of human settlements in such areas is of great significance to ecological protection of, and to constructing an ecological-safety-barrier within, the CTP and QTP.

2.2 Data source

The data in this study consist mainly of settlement-patch data, geographical-element data and materials obtained from the field survey. 1) Regarding settlement-patch data, field investigations established that settlements in the pastoral area of the CTP comprised courtyards made up of living rooms, kitchens, warm sheds, livestock pens, hay sheds, and lamb nurseries. Courtyard boundaries could be clearly identified in high-definition remote-sensing images (Ma and Xu, 2017; Zhang et al., 2019b). The professional version of Google Earth software integrates multi-temporal, multi-purpose, high-precision remote-sensing images, on which we can clearly identify the surface buildings. Using the professional version of Google Earth, the study area was divided into standard latitude and longitude grids. By means of visual interpretation and recognition of each grid, we obtained high-precision-sub-village-courtyard scale settlement-patches of the study area for 2017. Although the method of manual interpretation and recognition is time-consuming, it has high recognition accuracy and makes up for the shortcoming in computer remote-sensing image interpretation, which is unable to identify small-scale-feature information (Zhang et al., 2019b). Moreover, this method effectively solves the problem of obtaining fine-scale information, such as data on settlement-patches on the CTP. 2) For geographical feature data, a digital elevation map with a resolution of 30 m was obtained from the geospatial data cloud platform (http://www.gscloud.cn/). Data on temperature, precipitation, vegetation types, normalized differnce vegetation index (NDVI), lakes, water systems, scope of the CTNNR, administrative divisions, and roads were provided by the Data Center for Resources and Environmental Science, Chinese Academy of Sciences (http://www.resdc.cn/). 3) For the field surveys, the research team visited Nagqu City in 2018 and Shuanghu and Nyima counties in 2020 to conduct these surveys and obtain rich, first-hand materials on pastoral settlement and settled grazing through discussions with government departments, interviews with herders and field visits.

2.3 Methods

2.3.1 Landscape indexes

The landscape index is derived from landscape ecology, it can effectively condense landscape pattern information, and can be used to reflect the spatial pattern characteristics of the settlements in the study area. The total patch area (TPA), the number of patches (*N*), the mean patch area (MPS), the patch density (PD), the maxim-

um patch area (MAX) and the minimum patch area (MIN) are selected to reflect the size of settlements in the study area (Shi et al., 2016). The average nearest neighbor index (ANN) is selected to explore the spatial distribution of settlements (Equ. 1). The average nearest neighbor index is the ratio of the average distance between a settlement center point and the nearest settlement center point and its expected value of the settlement point in the study area under the assumption of a random distribution to judge the relationship between the settlement elements (Sun et al., 2017).

$$ANN = \frac{\overline{D_0}}{\overline{D_e}} = \frac{\sum_i d_i / n}{\sqrt{n/A}/2} = \frac{2\sqrt{\gamma}}{n}\sum_i d_i \quad (1)$$

where $\overline{D_0}$ is the average distance between the two closest settlements; $\overline{D_e}$ is the average distance between the two settlements under the assumption of random distribution; i is the numbering order of the settlements; n is the total number of settlements; d is the distance between settlements; A is the area of the study area. If $\overline{D_0} = \overline{D_e}$, the settlement pattern is random; if $\overline{D_0} > \overline{D_e}$, the settlement pattern is discrete; if $\overline{D_0} < \overline{D_e}$, the settlement pattern is an agglomeration.

2.3.2 Spatial 'hot spot' analysis

The Getis-Ord G_i^* index (Equ. 2) is a local spatial correlation detection index based on a distance weight matrix, which can be used to test whether there is a statistically significant accumulation of high or low values of the settlement area in a local area (Zhang et al., 2019a). This study uses it to explore the spatial correlation characteristics of the settlement scale.

$$G^*(d) = \sum_{j=1}^{n} w_{ij}(d)\, x_j / \sum_{j=1}^{n} x_i \quad (2)$$

where d is the distance between settlements, $w_{ij}(d)$ is the spatial weight defined by the distance rule, x_i and x_j are the observation areas in settlement i and j. To facilitate comparison, $G^*(d)$ is standardized to get $Z(G_i^*) = (G_i^* - E(G_i^*)) / \sqrt{\gamma ar(G_i^*)}$, $E(G_i^*)$ and $\gamma ar(G_i^*)$ are the mathematical expectation and variance of $G^*(d)$ respectively. Under the premise of statistical significance; if $Z(Gi^*)$ is positive, it is a hot spot where high values gather, if $Z(Gi^*)$ is negative, then it is a cold spot where low values gather.

3 Results

3.1 Settlement distribution characteristics

3.1.1 Landscape index characteristics

Settlements in the study area tend to be small, with a total area of only 1310.12 ha. In total, there are 2877 patches and the average patch area is only 0.46 ha (Table 1). The settlement scales of Nyima and Shuanghu counties are different: the scale of a single settlement in Shuanghu is larger compared to those in Nyima. The density of settlements in the study area is extremely sparse, with only one human settlement per 42.94 km^2 on average. The density of settlements fully reflects the sparsely populated characteristic of the CTP. The seats of Nyima County Government and Shuanghu County Government are the two largest settlement-patches in the study area, at 104 ha and 54.3 ha, respectively. This shows that against the special development background of maintaining stability in Tibet, the county seat with administrative management as its main function has fulfilled the function of population agglomeration to a certain extent. The smallest settlement patch is an independent courtyard with an area of only 144 m^2. From the perspective of spatial agglomeration status, the ANN index of the settlement patches in the study area is 0.32, indicating that the average distance between adjacent settlements is significantly smaller than the average distance under random distribution, and overall, the settlements have a clustered distribution.

3.1.2 Scale-level characteristics

Using the Jenks best natural break point method, the settlement scale of the study area was divided into six

Table 1 Characteristics of landscape indexes of settlements on the Changtang Plateau, China

Region	TPA / ha	*N*	MPS / ha	PD / (1/km^2)	MAX / ha	MIN / m^2	ANN	Style
Nyima	928.58	2320	0.40	27.12	104.00	150	0.34	Clustered
Shuanghu	381.54	557	0.68	108.86	54.30	144	0.39	Clustered
Study area	1310.12	2877	0.46	42.94	104.00	144	0.32	Clustered

Notes: TPA, the total patch area ; N, the number of patches; MPS, the mean patch area; PD, the patch density; MAX, the maximum patch area; MIN, the minimum patch area; ANN, the average nearest neighbor index

levels, and the number of patches in each level counted separately. A scale-level distribution map is shown in Fig. 2. The settlement scale in the study area has a typical pyramidal structure. As the settlement scale increases, the number of patches decreases. There are only 19 patches with a settlement area greater than 7.0 ha, most of which belong to the seats of township government. Patches with a settlement area of less than 1.0 ha account for 93.91% of all patches, and patches smaller than 0.2 ha account for 54.43% of all patches. Small settlements at the family and sub-village scale are the main settlement types in the study area. This shows that under special environmental conditions, such as high altitude, cold, and drought, the carrying capacity of livestock per unit area of grassland in the pastoral area is low. To obtain a sufficient area of grassland and avoid conflicts between grass and livestock caused by concentrated settlement, the alpine pasture area forms a typical small-scale settlement pattern.

3.1.3 Spatial distribution characteristics

From the perspective of local spatial correlation characteristics at the settlement scale in the study area, there are significant large-scale clusters of 'hot spots' and small-scale clusters of 'cold spots' (Fig. 3). 'Hot spot' areas include the flat area in front of the mountain where the Cuozheqiangma Township Government is located in the north of Shuanghu County; the river terrace between Najiangcu and Bengzecuo near the seat of Xiede Township Government; the broad valley of the mountain plains near the seat of Cuozheluoma Township Government; and the river valley near the seat of Laiduo Township Government in Nyima County. Such areas are low-lying and adjacent to rivers, with good water and grass conditions, and so are convenient for grazing, making them ideal areas for herders to settle in. Moreover, the spatial selection of township government

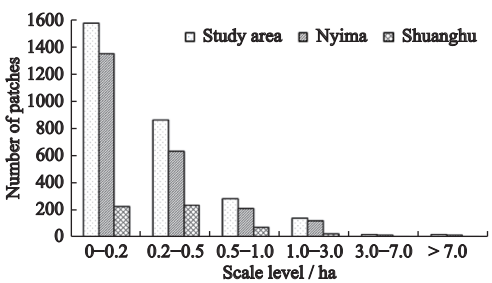

Fig. 2 Distribution characteristics of settlement scale on the Changtang Plateau, China

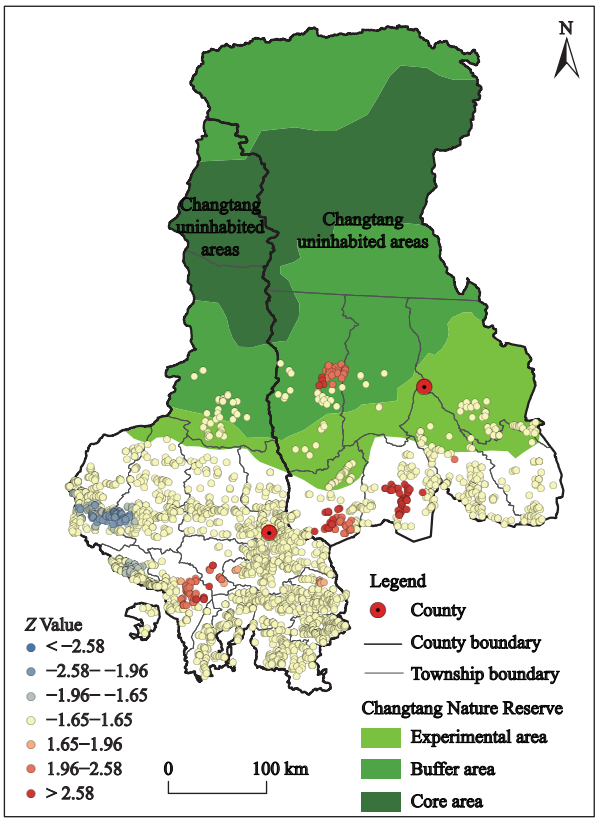

Fig. 3 Hot spots map of settlement scale in the Changtang Plateau, China

seats also tends toward superior geographical conditions that are more suitable for human survival. The convenient public services and relatively developed socioeconomic conditions of township government seats induce a certain amount of population growth and agglomeration. A 'cold spot' area is located in the southern intersection area of Zhongcang township and Asuo township in Nyima County. This comprises a mountain valley with two rivers, Chongchang Zangbo and Biri Zangbo. Although this area is suitable for grass growth, the terrain is separated, and scattered human settlements are confined to the mountain gullies, forming small agglomeration areas.

3.2 Analysis of influencing factors

Human settlements on the CTP are a product of the interaction between 'humans' and 'natural environment' subsystems within the special geographical environments such as extremely high altitude, cold and arid climatic conditions, fragile ecological environment, pastoral areas, and the need to rely on the natural environment to raise livestock. The level of socioeconomic de-

velopment in these areas is low. Limited transportation routes and service functions of highland towns established by administrative are socioeconomic factors that may impact the layout of settlements. Therefore, constrained by the strong natural environment and weak socioeconomic activity of the research area, this study explores the response characteristics of human settlements to various factors, including geomorphology, climate, vegetation, hydrology, traffic conditions, and the proximity of administrative centers.

3.2.1 Geomorphic factors

Geomorphology is the core element in natural conditions, and not only directly affects the spatial distribution of the population but also indirectly dominates human production activity by affecting the distribution and combination of resources-such as water, soil, air, light, and heat-in a region. In this study, elevation and slope were selected to explore the influence of geomorphic conditions on the spatial distribution of settlements.

The higher the altitude, the lower the partial pressure of oxygen in the air. In a high-altitude environment, the human body is deprived of oxygen, therefore, the suitability of human survival at high altitude is low. When the altitude is greater than 5500 m, human body functions are weakened, making it difficult for humans to survive for long. Areas above 5000 m form restricted areas for human settlements (Xi et al., 2018). The study area in the present case is extremely high, with areas above 5000 m accounting for 46.12% of the total (Fig. 4a). The altitude interval of the settlement distribution is 4400−5100 m. Settlements tend to be located in lower elevation areas. Areas with an altitude of 4500−4900 m account for only 36.02% of the total area of study area, but 79.34% of the total settlement area is distributed on above areas. The zone of altitude between 4700−4800 m has the largest settlement area; about 24.18% of the settlements area is in this zone. Less than 5% of settlements are located in areas above 5000 m.

Slope is an indicator that directly reflects the degree of steepness of the ground surface and influences settlement layout by affecting the convenience of human production and life. In line with the standards set by the 'Second National Land Survey Technical Regulations' issued by the Ministry of Land and Resources of China in 2007, this study divides the slope of the study area into five grades, as shown in Fig. 4b. The overall terrain of the study area is relatively low, and dominated by gentle slopes. Area with a slope less than 15° accounts for 77.63% of the total study area, while only 8.29% of the total study area has a slope greater than 25°. The slope characteristics of the settlement layout are consistent with the overall characteristics of the slope distribution in the study area; that is, typically gentle. The proportion of settlements in areas with a slope of less than 15° is as high as 90.11% of the total settlement area, among which settlements with a slope grade of 2° to 6° account for the largest proportion, reaching 33.52% of the total settlement area. Only a few settlements are distributed on steep slopes of 25° or more.

3.2.2 Climatic factors

Climatic conditions have a key impact on regional agricultural and animal husbandry, especially in the hinterland of the CTP. Extreme weather conditions can cause natural disasters, such as wind disasters, snow disasters, and freezing disasters, which pose threats to human life and livestock safety. Temperature and precipitation are the most representative indicators that quantitatively reflect the climatic conditions of a specific area. This study, therefore, selects temperature and precipitation as climatic factors that affect settlement layout (Figs. 5a, 5b).

Temperature refers to the surface temperature of a specific area, and significantly affects various physical, chemical, and biological processes on the soil surface. Temperature determines not only the growth and development of vegetation in pastoral areas but also whether

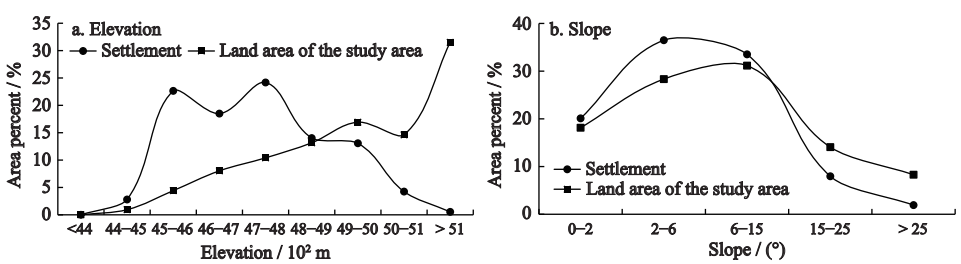

Fig. 4 Relationship between settlement layouts and geomorphic elements on the Changtang Plateau, China

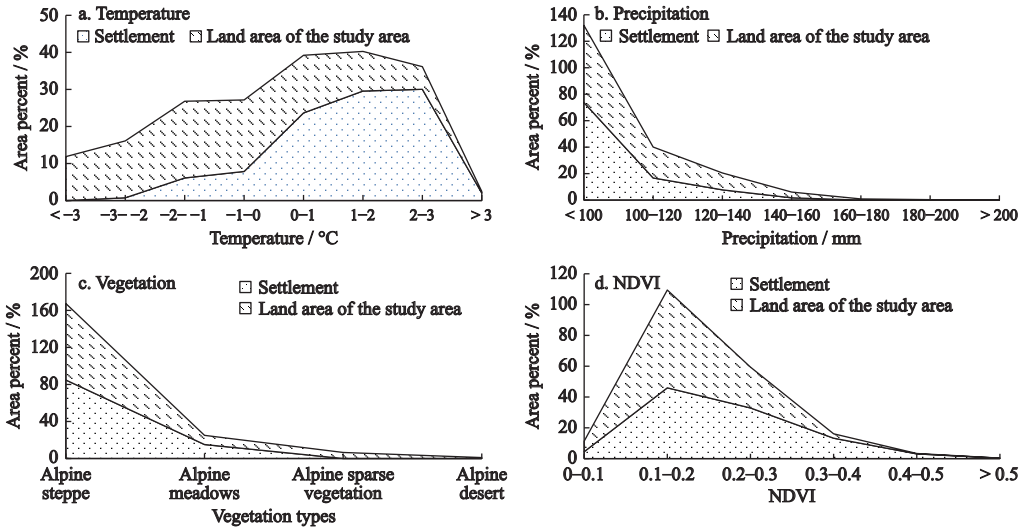

Fig. 5 Relationship between settlement layouts and climate and vegetation elements on the Changtang Plateau, China. NDVI, normalized differnce vegetation index

the surface environment is suitable for human survival. The average annual surface temperature of the study area spans an interval of –2.8–3.6 °C. Areas with an average annual temperature below 0 °C account for up to 67.22% of the total study area, mainly in extremely cold areas. The settlement layout shows a significant tendency towards higher average annual temperatures; 32.78% of the study area experiences an average annual temperature above 0 °C, and 85.29% of settlements are distributed in this area. Areas with an average annual temperature of 2.0–3.0 °C make up the largest proportion of the settlement area, 30.04%. Although the area with an average annual surface temperature below 0 °C is large, the proportion of the settlement area distributed therein is very small. The main reasons for this pattern are the good light and heat conditions for vegetation growth in areas with high average annual surface temperatures, high annual accumulated temperature, and rich pasture resources that are conducive to grazing. Moreover, in an alpine environment, areas with higher temperatures are less likely to endure freezing compared with areas with lower temperatures. Therefore, these areas are preferred suitable for human survival and development of animal husbandry.

Precipitation is an important condition affecting animal husbandry, especially in the CTP, which is located in arid and semi-arid areas. Water resources are essential for vegetation growth. The average annual precipitation in the study area spans 59−216 mm, and the area with precipitation less than 100 mm accounts for 58.27% of the total study area. The climate in the area is extremely dry; however, the proportion of settlement areas in zones with higher precipitation is not large. The average annual precipitation span of the settlement layout area is 59–158; the proportion of settlements distributed in the area with precipitation less than 100 mm is as high as 73.79% of the total settlement area. This proportion is significantly higher than the proportion of this area account for the total area of the study area. In areas with relatively high precipitation, for example, there is no settlement distribution in areas where the average annual rainfall is more than 160 mm. The reason for this is that areas of high precipitation are relatively small; moreover, on the extremely cold CTP, precipitation usually takes the form of hail or snow, and areas with heavy precipitation are often located in harsh environments, such as mountain tops, so there is little human activity. Water resources for the growth of forage grass and cultivation of human life come mainly from rivers and lakes formed by melting snow and ice in the mountains, and the distribution of settlements is not, therefore, strongly dependent on natural precipitation.

3.2.3 Vegetation factors

Animal husbandry is the basic industry for human survival in the pastoral areas of northern Tibet, and pastures are the basis for the development of animal husbandry. Animal husbandry production on the CTP is strongly dependent on grassland and vegetation conditions. Therefore, grassland quality and carrying capacity are important factors affecting the layout of human

settlements. This study chooses the two indicators vegetation type and NDVI to explore the influence of vegetation conditions on the layout of human settlements (Figs. 5c, 5d).

The study area includes four vegetation types: alpine *Carex moorcroftii* steppe, alpine *Kobresia* meadow, sparse alpine vegetation, and alpine desert grassland. The first two are the predominate types, accounting for 92.51% of the total study area. The distribution of settlements follows the direction of high-quality pastures, mainly in alpine *Carex moorcroftii* steppe and alpine *Kobresia* meadow. The former dominates, accounting for 84.82% of the total settlement area. However, there are few settlements in sparse alpine vegetation and alpine desert grassland. The grass species of alpine *Carex moorcroftii* steppe mainly consists of *Stipa purpurea*, which has a high grass yield and is enjoyed by livestock. *Stipa purpurea* has strong grazing resistance and can be mown as forage storage; therefore, it is an important grass species in animal husbandry production in northern Tibet. *Kebresia parva* is the main type of grass species in alpine *Kobresia* meadow, with a high heat value, soft grass quality, and good palatability for livestock, therefore proving an ideal grazing grassland. This kind of grassland forms only 9.92% of the total study area, but 15.11% of human settlements are located in this area.

NDVI is an index used to characterize the growth status and coverage of vegetation and can accurately examine the growth quality and carrying capacity of grassland. The NDVI index span of the study area is 0–0.58, and the overall vegetation coverage is low. The area with an NDVI lower than 0.2 accounts for as much as 70.32% of the total study area, and the area with NDVI higher than 0.3 comprises only 3.17% of the total study area. The tendency of settlements to be distributed in areas with higher vegetation coverage is very strong. Areas with an NDVI greater than 0.2 account for only 29.67% of the total study area, but the settlement proportion is close to 50%. In areas with a higher the NDVI, the grassland has better forage growth, higher grass production per unit area, and stronger livestock carrying capacity for a given set of conditions. This makes it the preferred area for herders to settle in and graze cattle.

3.2.4 Hydrological factors

Water resources represent a key factor for the development of animal husbandry and human survival in the pastoral areas of northern Tibet (Zhang et al., 2019b). Living by water shapes the spatial layout of settlements. There are many rivers and lakes on the CTP, forming a famous high-altitude lake group. Both animal husbandry and the lives of herders rely on rivers and freshwater lakes. In this study, rivers and lakes are distinguished, and multi-level buffer zones are established at 300 m intervals to consider settlement distributions under different hydrological conditions (Fig. 6). The distribution of settlements is predominately concentrated on riverbanks. As the distance from a river increases, the proportion of settlements continues to decrease. The area up to 900 m away from the river is the main distribution zone of settlements, with 91.22% of the total settlement area located here. The proportion of settlements within 300 m of a river is the largest, accounting for 58.55% of the total settlement area. The layout characteristic of settlements to lakes is not significant. Areas closer to the lake do not account for a large proportion of the settlements. In contrast, areas at a certain distance from lakes become a key distribution area of the settlements. Settlements within 300 m of lakes account for the smallest proportion, only 12.71% of the total settlement area, while within 600–900 m from lakes, 31.24% of the total settlement area exists, ranking this the highest among all classes. The reason for the smaller proportion of the settlement area closer to lakes is that lakes on the CTP are mostly saline. Thus, closer to lakes the soil becomes salinized, vegetation growth is difficult, and the ground is barren making this area unsuitable for human settlement or grazing cattle. There is also often surface runoff flowing into lakes. Such areas are rich in water and grass, and vegetation grows vigorously there, becoming a key area for herders to settle in. In addition, Tibetan herders' worship—'sacred mountains and holy lakes' (Ma et al., 2017; Zhang et al.,

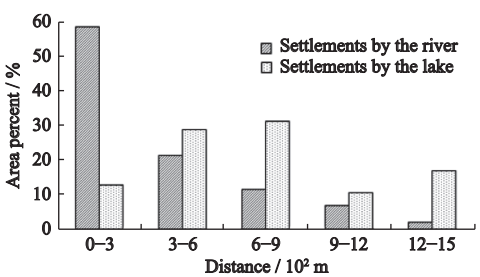

Fig. 6 Relationship between settlement layouts and hydrological conditions on the Changtang Plateau, China

2019b) and tend to avoid sacred natural landscapes, such as highland lakes, when choosing settlements.

3.2.5 Socioeconomic factors

Traffic conditions and the distance from the administrative center affect the exchange of material, energy, and information between rural settlements and the outside world, directly affecting production efficiency and quality of life for residents. This study analyzes the buffer zone of township roads and highways at 2 km intervals and township centers at 3 km intervals, and calculates the areas of settlements within different distances (Table 2). The proportion of settlement areas within 2 km of roads comprises 56.26% of the total settlement area, and as this distance increases the proportion gradually decreases. In addition, 9.84% of the total settlement area is distributed in the area 14 km away from roads. With socioeconomic improvements, human activity on the CTP has gradually broken away from the traditional lifestyle of 'self-sufficiency' and has increased the demand for external connections. This means that the layout of human settlements shows an obvious traffic-location orientation. However, because animal husbandry still uses the method of 'raising animals by nature', grazing activity is highly dependent on natural pastures, so a certain proportion of human settlements are still located in areas far away from major transportation routes but with relatively good water and grass conditions. With respect to distance from an administrative center, the settlement area within 3 km of a center accounts for only 34.94% of the total, with 48.24% of the total settlement area located more than 15 km from a town center. With the environmental conditions, vast area, and sparse population on the CTP, the functions of highland townships are relatively simple—mainly comprising administrative management, with limited economic functions. Human production activity on the CTP consists mainly of animal husbandry, and the level of non-agriculture activity is low. The effects of economic radiation from administrative centers to surrounding settlements are unclear, and the agglomeration of settlements in township centers is not yet pronounced on the CTP, where economic development is relatively poor.

4 Discussion

4.1 Typical characteristics and formation mechanism of settlements on the CTP

The characteristics of settlements in different regions have significant regional roots that are affected by differences in natural environmental conditions and production methods. In contrast to low-altitude areas where natural conditions represent fewer obstacles to human activity and the layout and evolution of settlements are mainly affected by socioeconomic factors (Song et al., 2020; Zhou et al., 2020), the natural environment of the CTP is extremely harsh, its suitability for human life is poor, and it is difficult to make significant improvement through socioeconomic construction activities. The level of economic development on the CTP is also very low, and humans are passively adapting to nature. Therefore, natural conditions have become decisive factors in the layout of human settlements there, with few and weak socioeconomic factors. Extremely high altitude, cold climate, aridity, pastoral areas, and other special geographical conditions determine the typicality and particularity of the scale and layout of human settlements on the CTP.

4.1.1 Small, scattered settlements

The average settlement-patch area in the eastern and central plain of China is about 0.2 km^2 (Li et al., 2018b).

Table 2 Relationship between settlement layouts and socioeconomic factors on the Changtang Plateau, China

Buffer distance of road / km	Settlement area / ha	Proportion / %	Buffer distance of township center / km	Settlement area / ha	Proportion / %
0–2	737.04	56.26	0–3	457.76	34.94
2–4	118.41	9.04	3–6	56.54	4.32
4–6	97.20	7.42	6–9	44.15	3.37
6–8	78.44	5.99	9–12	57.06	4.36
8–10	71.09	5.43	12–15	62.63	4.78
10–12	47.29	3.61	15–18	94.14	7.19
12–14	31.74	2.42	18–21	75.24	5.74
＞14	128.92	9.84	＞21	462.60	35.31

In contrast to the relatively large settlement scale of plain agricultural areas, the average settlement-patch area in the alpine pastoral area of the CTP is only about 0.5 ha, nearly 100 times smaller than that of agricultural plain areas (Yang et al., 2017). In contrast to the density characteristics of several settlement-patches per km^2 in low-altitude hilly areas and southwest mountainous areas in China (Guo et al., 2013; Song et al., 2017), there is only one settlement per 42 km^2 in the alpine pastoral area of the CTP, and the population and settlement density are extremely sparse. Moreover, in contrast to the high quality pasture of low-altitude regions with high coverage, high yield, and high livestock carrying capacity, the alpine pasture of the CTP is characterized by harsh climatic conditions, shallow soil layers, a low humus content, and sparse vegetation. The NDVI index of the study area is 0.1–0.4, which is significantly lower than that of a farming-pastoral transition zone, which has been found to be 0.4–0.6 (Peng and Wang, 2020). The vegetation coverage rate of the study area is low, the grassland carrying capacity is very limited, and the grassland area required to feed a unit of livestock is large.

This study found that settlements tend to be small and decentralized. The characteristics of this small and decentralized settlement pattern are very different from settlement layouts in the mountainous areas of southwest China in terms of density and settlement scale. Indeed, the number of settlements smaller than 1 ha accounted for 93.91% of the total number of settlements in the study area. Analysis establishes that using nature to raise livestock and settled grazing livestock, animal husbandry mainly relies on natural pastures within a certain distance around settlements. To ensure that herders in the settlements have sufficient pastures, the pastoral area of the CTP has formed sub-village-courtyard-scale settlements consisting of several households or more than a dozen households. A certain distance is maintained between settlements to avoid conflicts involving grass and livestock that would otherwise be caused by concentrated settlements.

4.1.2 High altitude adaptability and strong temperature sensitivity of the settlement layout

The high-altitude geographical environment means that although altitude has a strong influence on the spatial distribution of human settlements in low-altitude mountainous areas (Xi et al., 2018), it does not have a very significant spatial differentiation effect on the settlement layout of the CTP. In contrast to the inland population, Tibetan people living on the QTP possess a mutation of the EPAS1 gene conducive to surviving in the hypoxic environment (Yi et al., 2010). The pastoral settlements on the CTP in northern Tibet are scattered at an extremely high altitude of 4400–5100 m, largely precluding people without the necessary physiological adaptations to survive.

There are no significant differences in the proportions of settlements in different low-altitude regions with an average annual temperature difference of 3.0–5.0 °C (Zhou et al., 2020). However, in the cold climate of the CTP, there is a huge gap in the spatial distribution of settlements within the small temperature difference zones, where the average annual temperature is close to 0 °C. The difference in proportions of settlement areas between zones with temperatures of 0–3.6 °C and –2.8–0 °C is as high as 70 percentage points, and the distribution of settlements towards the higher temperature areas is clear. Extremely low-temperature conditions enhance the impact of temperature differences on the layout of human settlements.

4.1.3 The layout of settlements avoid areas with high precipitation

In low-altitude areas, precipitation differentiation — affecting agricultural and animal husbandry production, and therefore settlement layout—usually means that the climate of areas with high precipitation is relatively humid (Zhou et al., 2020). The favorable agricultural and animal husbandry production conditions mean that people are more likely to settle in these areas (Xu et al., 2014). However, in the cold and drought-prone environment of the CTP, an opposite distribution pattern is present. In areas with greater precipitation, the proportion of human settlements is smaller, and settlements are mainly distributed in areas with low precipitation. The reason for this heterogeneity is that, on the CTP, precipitation usually takes the form of hail and blizzards (He et al., 2020). Areas with high precipitation are often located in dangerous environmental zones, such as mountain tops, making it difficult for humans to survive. The source of water for animal husbandry and human life in these types of areas mainly consists of rivers and lakes formed by melting high mountain ice and snow. Therefore, settlement layouts are weakly dependent on areas with large amounts of natural rainfall, and have a differ-

ent distribution pattern from that of areas with low-altitudes.

4.1.4 The orientation of settlement layout close to roads and administrative centers is not strong

The attractiveness of roads and administrative centers in the context of settlement layouts on the CTP is significantly weaker than that of low-altitude inland areas. To obtain good transportation conditions and benefit from being close to economic centers, the layout of human settlements in low-altitude inland areas shows a typical characteristic of tending toward roads and township centers, with settlements concentrated within 5 km from the roads and 10 km from the township centers (Yang et al., 2017; Zhou et al., 2020). Compared with the low-altitude inland areas, the socioeconomic development of the CTP lags significantly, and is still being dominated by agriculture and animal husbandry, so has a strong dependence on natural grassland. Due to the need to communicate with the outside, there are some settlements located near roads. However, the lagging infrastructure construction on the plateau and the production demand of using natural grassland mean that a large proportion of settlements are considerably distant from traffic lines. In addition, the plateau towns set up by administrative management have weak economic functions (Fan and Wang, 2005; Zhou et al., 2013). Development of the non-agricultural economy on the CTP is limited, and the agglomeration effect of township centers on population and settlement layout is not pronounced.

4.2 Policy implications

Living in extreme environmental conditions (e.g., cold and hypoxic) for long periods will give rise to various stress characteristics in the human body, including enlarged hearts and lungs, and an accelerated heart rate. This can lead to a number of diseases, such as rheumatoid arthritis, cardiovascular and cerebrovascular diseases. The average life expectancy on the CTP is only 58 yr, 12 yr lower than the average level in Tibet (Xu et al., 2018; Zhang et al., 2020b). As human activity continues northward into the uninhabited area, some settlements have crossed the CTNNR experimental area and entered the buffer zone. Because of the extremely fragile ecological environment and the very limited grassland carrying capacity, human activity on the CTP is likely to cause ecological damage, such as livestock and wild animals competing for pasture, and humans and wild animals competing for space. Frequent natural disasters and wild-animal accidents pose a significant threat to the safety of herders and their property (Farrington and Tsering, 2019； Xu et al., 2020). In addition, due to the extremely small population density of the CTP, the construction of infrastructure, involving transportation, power, and communications is costly and difficult to construction and maintain (Yang et al., 2019). Settled herders have a low-quality of life, especially with regard to the lack of electricity, water, and communication signals, and difficulty in traveling.

Based on the above analysis, to protect the ecological environment of the CTP and improve the quality of life of herders, optimization of human activity on the CTP should concentrate on the following: 1) The government should facilitate ecological migration and relocation in areas with important ecological value or low suitability for living. For settlements posing a threat to wildlife protection in areas with high levels of natural protection,including those deep inside the CTNNR and human settlements with low level of suitability for human activity, including those located at altitudes above 5000 m, a gradual-withdrawal strategy should be formulated. This strategy could be coordinated and deployed by two levels of government in the Tibet Autonomous Region and in Nagqu City. The population could be relocated to other areas with a strong population-carrying capacity in southern Nagqu or southern Tibet. 2) In order to maintain the ecological balance of pastoral areas, the government needs to introduce policies to control the amount of livestock. The government needs to reasonably assess the regional grassland carrying capacity, determine the upper limit of livestock stock, use poverty alleviation funds to improve the effectiveness of the implementation mechanism of returning pasture to grass, and offer grassland ecological compensation to ensure the regional balance of grass and livestock and the healthy development of grassland ecosystems. 3) The government should encourage herders to settle in moderate concentrations and explore the development of modern pastoralism. For the relatively low-altitude, low-terrain, and lush pastures in the southern part of Nyima County, the government can promote the moderate concentration of settlements, improve infrastructure, and enhance the function of settlements. It is also possible to cultivate high-quality grass, establish artificial grass-growing bases, adopt a combined stock-raising method,

explore ways to develop modern animal husbandry in high-altitude areas, and improve the carrying capacity of grassland for livestock. 4) The government should optimize the allocation of pasture resources and reasonably adjust village administrative divisions. As the grassland resources in northern Tibet are divided into administrative villages, the historical delineation of village-level boundaries does not fully consider the rational spatial allocation of grassland resources. Problems exist, such as large gaps in the area of administrative villages, uneven distribution of resources, and guiding herders to settle in nature reserves and areas with harsh environments. Therefore, a reasonable assessment of the agricultural and pastoral resources within the administrative area of each county should be conducted. The boundaries of villages in areas with high ecological protection levels, such as nature reserves, should be removed, merged, and adjusted based on the spatial distribution of humans and animals to realize the coordinated development of resource allocation and ecological protection.

5 Conclusions

Under the special natural and geographical conditions of high altitude, cold climate, drought and pastoral areas, the scale of human settlements on the CTP is extremely small, and the density is sparse. The settlements present a spatial pattern of 'large-scale dispersion and partial concentration'. These settlements consist primarily of several households, with some having more than a dozen households, or are sub-village scale settlements. The scale and density of settlements here significantly differ from those in low-altitude inland areas. In areas with relatively superior natural and geographical conditions, such as piedmont flatlands, river terraces, and river valleys, settlements appear to be concentrated, while in the vertical and horizontal valleys, settlements are scattered because of the fragmentation of topography. This is due to the extremely harsh natural geographical environment, and the limited ability of humans to transform and optimize their living environment. The CTP has a low degree of socioeconomic development, which weakly influences the settlement layout. Natural factors are the core elements that affect the layout of human settlements on the CTP.

Although the manual visual interpretation method using high-definition remote-sensing images is labor-intensive and time-consuming, it is advantageous in terms of accuracy. For the CTP and QTP, where data are very scarce and difficult to obtain, the method provides an important way to conduct research from a micro-perspective. This study found that the influence of altitude, temperature, precipitation, roads, and administrative centers, on the settlement layouts of the CTP is significantly different from that of settlement layouts in low-altitude areas identified in past research. The typical case selection and differentiated research results enrich the connotation of the current settlement research system to a certain extent.This study only identified one period of settlement data, as it was limited by data availability. It also did not involve in-depth discussions on the dynamic characteristics of settlements over time. Due to the extremely dispersed population of the CTP, few investigations involving herders have been carried out. Combining the availability of data and the feasibility of the method, this article selected the geostatistical method to carry out research on factors affecting the settlement layout. Future research could focus on the influence of the complex and unique regional cultures of clan relations within the Tibetan social group, and the impact of symbiosis of tribes-temples-villages on their settlements.

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