



The evolution of settlement system and the paths of rural revitalization in alpine pastoral areas of the Qinghai-Tibet Plateau: A case study of Nagqu County

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ABSTRACT

The Qinghai-Tibet Plateau (QTP) is an area with highly distinctive natural and socio-cultural characteristics. In recent years, the pastoral areas of northern Tibet have undergone a phase transition from nomadic to settled grazing, and the settlement system is in a stage of formation and evolution. Against the backdrop of China's new strategy of rural revitalization, conducting associated research on the evolution of the settlement system and the prospect of rural revitalization is of great significance for improving the living and working conditions of herdsmen in alpine pastoral areas and promoting sustainable development on the QTP. Using settlement patch data obtained by visual interpretation of high-definition remote sensing images, combined with field investigations, this paper explores the temporal and spatial evolution characteristics of the settlement system in Nagqu County, northern Tibet, summarizing its development status and existing problems from the perspective of factor-structure-function, and details the paths for rural revitalization on this basis. The results show the following: (1) Since 2005, the settlement system of Nagqu County has undergone a phase transition from concentrated settlement to functional expansion, with the continuous enrichment of development elements and the enhancement of functions. The density distribution of settlements shows strong adaptability to the natural geographical environment. The pattern of settlement has gradually changed from resource-dependent to facility-dependent. Transportation and public service facilities play an important role in guiding the speed and direction of settlement evolution. (2) There are still various problems in the settlement system of Nagqu County, including a weak industrial foundation; some occupation of important ecological spaces and ecologically fragile areas by settlements; insufficient attention to the cultural aspect of the Tibetan settlement system; a scattered settlement layout, which makes grassroots governance difficult; a large talent gap; and weak spatial support system of settlements. (3) From the perspective of enriching and integrating the development factors of rural settlements, reorganizing the diversified structure of rural settlements, and improving and expanding the functions of rural settlements, this paper explains the correlation mechanism between optimization of the rural settlement system and rural revitalization, and puts forward the implementation paths for rural revitalization in alpine pastoral areas of the QTP. The study expands our understanding of the characteristics of settlements in sparsely populated alpine pastoral areas, and provides valuable, up-to-date policy guidance for the promotion of rural revitalization in alpine pastoral areas on the QTP.

1. Introduction

By 2020, China had achieved complete poverty alleviation, lifting

more than 1.4 billion people out of poverty. China's achievement in solving the historical problem of poverty has attracted worldwide attention. However, China features a vast territory, uneven regional

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development, especially rural decay, which has become a key issue that needs to be addressed urgently (Liu and Li, 2017). In this context, the Chinese government began to implement rural revitalization strategy in 2017 by issuing the “Opinions of the Central Committee of the Communist Party of China and the State Council on the Implementation of the Rural Revitalization Strategy” and its “Rural Revitalization Strategic Plan (2018–2022)” in 2018 to announce the direction of rural revitalization (Li et al., 2021). A rural settlement is a site of rural production and habitation, where the interaction of various elements promotes the formation and evolution of its functions. It carries the effective operation of the economic, social, cultural, and ecological subsystems of the rural system (Roche, 2002; Looney, 2015) and is the basic spatial unit within which to promote rural revitalization (Zhou et al., 2020). Current studies on rural revitalization tend to focus on rural economic and social development (Mitchell, 2013; Fang et al., 2014; Huang et al., 2020), largely ignoring the fundamental and decisive role of the rural settlement as a spatial carrier of rural revitalization. Research on the exploration of rural revitalization paths based on the evolution of rural settlements is still relatively limited.

The elements and functions of rural settlements are the key factors that affect rural revitalization, and they have obvious geographical differences (Boudet et al., 2020). Globally, in a comprehensive review of the characteristics of rural development in large macro-regions such as Africa, South America, Central Asia and South Asia (Linard et al., 2012; Conrad et al., 2015; Barbier and Hochard, 2018; Zalles et al., 2021), and in small micro-regions such as rural inland Australia, villages near protected areas in developing countries, villages on the edge of wetlands in southern Bangladesh, and villages and towns in southern Italy (Oldfield, 2005; McManus et al., 2012; Naidoo et al., 2019; Huq et al., 2020), the study found that the elements and functional characteristics of rural settlements vary across geographical characteristics, natural background, locational conditions, spatial layout and scale (Koopmans et al., 2018), there are also significant differences in the paths that drive them to achieve rural revitalization (Ma et al., 2018; Zhou et al., 2020). Compared with rural settlements in plain or hilly areas, mountainous settlements are restricted by natural geographical conditions, scattered spatial layout, limited access to transportation, and limited opportunities for communication with each other, such that it is difficult for the central settlement to play a leading role in the social and economic radiation of surrounding settlements (Marconcini et al., 2020; Liang and Li, 2020; Peng and Wang, 2020). Under such conditions, there are many shortcomings in rural revitalization, and it is more difficult. Compared with large-scale rural settlements, since small settlements have a weak industrial foundation and often experience population loss; the small size of the population also makes it difficult to reach the population size threshold for the deployment of infrastructure, which leads to incomplete or poor infrastructure and public services, affecting the function of such settlements (Linard et al., 2012). In these areas, the bottleneck of rural revitalization is prominent. Compared with rural settlements in developed areas, settlements in remote and underdeveloped areas lag behind, with few development factors, imperfect functions, small industrial scale, outdated ideology, and lack of the radiating and leading role of cities and towns (Zhou et al., 2013; Heck et al., 2018; Jiang et al., 2021). Thus, the starting point for rural revitalization in such areas is low and the required investment is large. Therefore, the regional characteristics of rural settlements and the differential spatial pattern of development conditions dictate different rural revitalization paths.

China's terrain is akin to a three-level ladder, rising from east to west. The average altitude of the Qinghai-Tibet Plateau (QTP)—the highest rung of the ladder—is above 4000 m. The climatic conditions here are mainly cold and arid, the human living environment is harsh, and the level of socio-economic development lags significantly behind that of low-altitude inland areas (Li et al., 2019; Qi et al., 2020). Historically, there were no human settlements in northern Tibet; the local Tibetan herdsmen lived a nomadic life based on traditional animal husbandry (Farrington and Tsering, 2019; Zhang et al., 2020). Due to

democratic reforms in Tibet and the implementation of China's policies on poverty alleviation and resettlement of nomadic peoples, the herdsmen of the Changtang Plateau (CTP) ended their nomadic lifestyle, which they had maintained for generations, and gradually took up settled life (Xu et al., 2017). Meanwhile, with the opening of the Qinghai-Tibet Railway in 2006 and the advancement of the modernization process, the pastoral areas of northern Tibet entered a new stage. The herdsmen's ideology is gradually opening up, marketization awareness is developing, and the economic level is gradually improving. The human settlements in some areas have grown from scratch, from small to large, and the settlement system is in the stage of formation and evolution (Tian et al., 2021; Zhang et al., 2022). Strong constraints imposed by the natural environment and the significantly changing socioeconomic environment, determine the typicality, complexity, and particularity of the settlement system in alpine pastoral areas of northern Tibet. Compared with low-altitude inland areas, on the QTP the unique of paths are required to promote rural revitalization.

However, due to the small scale and scattered distribution of human settlements in the pastoral areas of northern Tibet (Li et al., 2018), previous research methods based on land use types, machine interpretation of remote sensing images, big data, and the night-light index to explore the space of human activities have a relatively high scale threshold for the identification of settlement spaces. Although these methods can effectively describe the spatial change of human settlements in densely populated areas (Sun et al., 2017; Yi et al., 2019), they cannot identify the spatial pattern of human settlement systems in sparsely populated areas from a micro perspective (Zhang et al., 2023). Such limitations of technical methods restrict the development of research to a certain extent; thus, existing research on settlement systems has rarely addressed such areas, and it is difficult to provide theoretical support for rural revitalization in alpine pastoral areas of northern Tibet.

In addition to addressing these gaps in the literature, this paper emphasizes the important relationship between the choice of rural revitalization paths and the evolution characteristics of rural settlements. We selected Nagqu County in alpine pastoral areas of the QTP as an example to explore the paths of rural revitalization on the basis of evolutionary characteristics of the settlement system using settlement plaque data obtained via visual interpretation of high-definition remote sensing images, as well as information obtained from field investigations. The underlying assumptions of the study are as follows: (1) under the harsh natural environment and the dynamic process of industrialization, urbanization and modernization, the human settlements in the alpine pastoral areas of the QTP are significantly different from the inland plains in terms of their characteristics and formation and evolution process; (2) based on the special development history of settlements, rural revitalization in alpine pastoral areas on the QTP has special connotations and the uniqueness of development paths. While verifying and analyzing the above questions, this study proposes the implementation paths for promoting rural revitalization in alpine pastoral areas of the QTP. The results can provide a reference for optimizing the human settlement system and for promoting rural revitalization development in alpine pastoral areas of the QTP.

2. Materials and methods

2.1. Study area

The QTP is an area with highly distinctive natural and social cultural characteristics, and is known as the “third pole” of the earth (Wu et al., 2016; Sun et al., 2020). CTP in northern Tibet has extremely harsh natural conditions and is known as one of the top ten uninhabited areas in the world (Allan et al., 2017). It is the area with the most difficult natural conditions and the lowest level of economic and social development in China (Harris, 2010; Xu et al., 2020), and also one of the areas with the greatest difficulty in promoting rural revitalization in the new

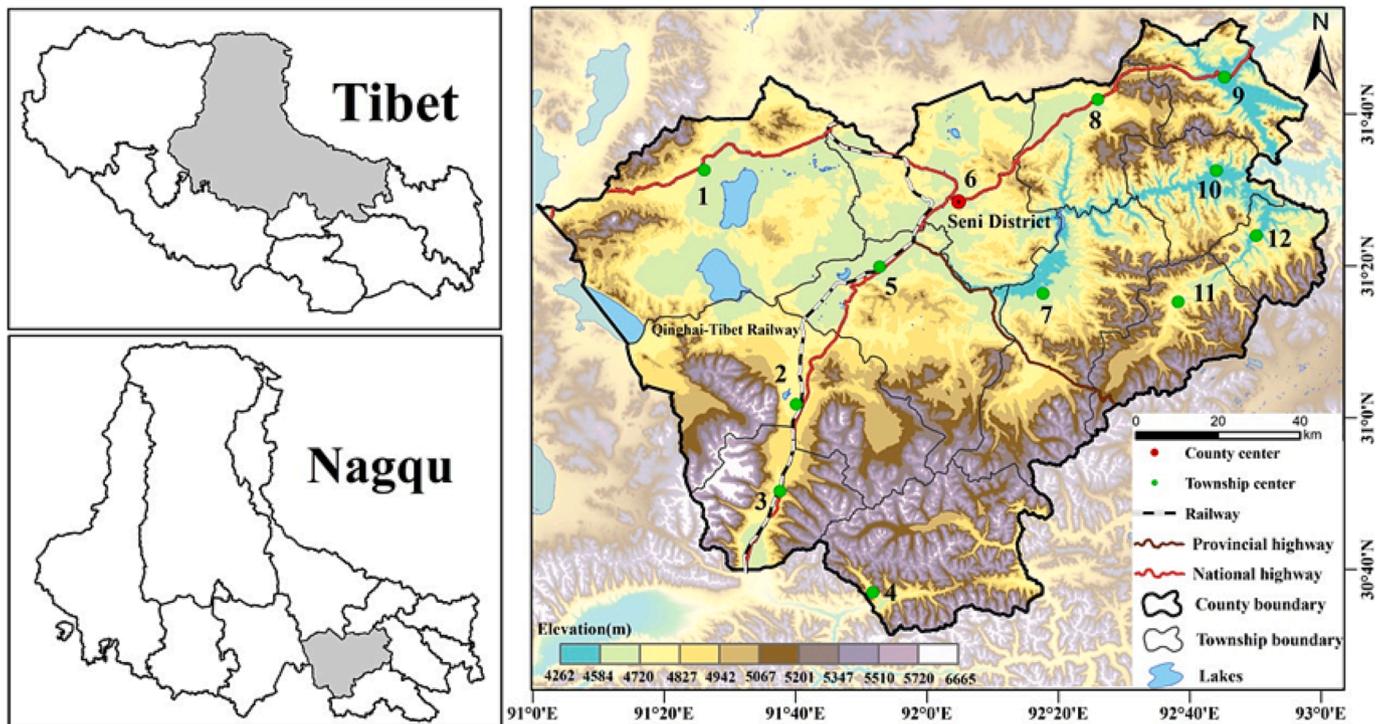


Fig. 1. Location and elevation map of Nagqu County, Tibet. (1. Namaqie Township; 2. Xiangmao Township; 3. Gulu Township; 4. Youqia Township; 5. Luoma Township; 6. Nagqu Township; 7. Dasa Township; 8. Kongma Township; 9. Daqian Township; 10. Nima Township; 11. Luomai Township; 12. Sexiong Township).

era. Nagqu County is located in the CTP, in the hinterland of the QTP, between $91^{\circ}02' - 93^{\circ}05'E$ and $30^{\circ}31' - 31^{\circ}55'N$ (Fig. 1). The county's average elevation is over 4500 m and the highest altitude is 6665 m. Natural disasters caused by wind, snow, and freezing temperatures occur frequently here, and living conditions are harsh. Nagqu County is the administrative center of Nagqu City, covering an area of 16,200 km², with jurisdiction over 3 towns, 9 townships, 141 administrative villages and 1,108 natural villages. By 2020, the population of the county had reached 112,900, with a population density of 6.97 inhabitants/km²-far lower than the average population density of 145 inhabitants/km² in China. Although Nagqu County was renamed Seni District in 2017, we continue to refer to it by its former name because the settlement research featured in this paper has been carried out since 2005, and the historical name of this area of northern Tibet is better known.

The following characteristics make Nagqu County a good example of pastoral areas in northern Tibet: (1) Located in the CTP, Nagqu County is a purely pastoral county and a typical representative of alpine pastoral areas of the QTP. (2) Nagqu County is an area where settlements appeared earlier in the history of pastoral areas of northern Tibet. The current settlement system has not only inherited the location characteristics of the original settlement, but is also driven by modern social and economic development. The settlement system has significant roots in terms of the social and cultural environment. (3) The county is a gateway to the opening-up and development of northern Tibet because the Qinghai-Tibet Railway and the Qinghai-Tibet Highway pass through it. It is a typical county in pastoral areas of northern Tibet to promote rural revitalization, and has a leading and demonstrative effect on the development of other regions. (4) The urbanization rate of Nagqu County was only 25.80% in 2020, nearly 40 percentage points lower than the average level in China. Its development stage is significantly lagging behind low-altitude inland areas, and its regional environment and development characteristics are typical.

2.2. Data sources

The basic data analyzed in this article include settlement patch data,

geographic element data, and field survey interview materials. (1) Settlement patch data. During the field investigation, we found that the settlements in the pastoral areas of northern Tibet usually consist of living rooms, kitchens, warm sheds, hay sheds, and livestock pens that form enclosed courtyards. The borders of the courtyards are clearly visible in high-definition images, so we used high-resolution remote-sensing images of Nagqu County from Google Earth professional in 2005 and 2010 and multi-spectral high-resolution remote-sensing images from Resources Satellite Three satellite 02 in 2017 with a spatial resolution of 2.5 m. The study area was divided into longitude and latitude grids with equal spacing in five intervals, and a total of 190 square grids with equal area were obtained. Through the visual interpretation and verification of each grid, a high-precision sub-village-yard-scale settlement patch data set for the 3 years (2005, 2010, and 2017) was obtained. (2) Geographic feature data. DEM data with a resolution of 30 m were obtained from the geospatial data cloud (<http://www.gscloud.cn/>), and data on roads, lakes, administrative boundaries, as well as the scope of nature reserves, were obtained from the Resource and Environment Data Center of the Chinese Academy of Sciences (<https://www.resdc.cn/>). Statistical data were obtained from the "Tibet Statistical Yearbook," "Nagqu Regional Yearbook," and "Nagqu Yearbook." (3) In July 2018 and August 2020, we carried out field investigations in northern Tibet. Through discussions with local government officials, interviews with herdsmen, and field visits, we obtained a wealth of research materials on the development of settlements in Nagqu County.

2.3. Methods

2.3.1. Landscape pattern index

The landscape pattern index can directly reflect the characteristics of a settlement pattern. We selected the total patch area (TPA), the number of patches (N), the mean patch area (MPS), the patch density (PD), the maximum patch area (MAX), and the minimum patch area (MIN) to characterize the evolution of settlement patterns in Nagqu County, and the Average Nearest Neighbor Index (ANN) to characterize the spatial

agglomeration of the settlement. The ANN is the ratio of the average distance between the center of a settlement and the center of its nearest neighbor to the expected value of the distance between adjacent settlements under the assumption of a random distribution (Sun et al., 2017). The formula is as follows:

$$ANN = \frac{D_0}{\bar{D}_e} = \frac{\sum_i d_i/n}{\sqrt{nA/2}} = \frac{2\sqrt{\gamma}}{n} \sum_i d_i \quad (1)$$

In the formula, D_0 is the average distance between the two nearest settlements, \bar{D}_e is the average distance between the two settlements under the assumption of random distribution, n is the total number of settlements, d is the distance between settlements, and A is the surface area of the study area. If $D_0 = \bar{D}_e$, the settlement pattern is random; if $D_0 > \bar{D}_e$, the settlement pattern is discrete; if $D_0 < \bar{D}_e$, the settlement pattern is an agglomeration pattern.

2.3.2. Rank-size rule

Sonis and Grossman's study of rural settlements found that the distribution of rural settlement size classes obeyed negative exponential characteristics (Sonis and Grossman, 1984). We choose the "rank-scale" rule to explore the characteristics of the scale hierarchy of alpine pastoral settlements on the Tibetan Plateau. This paper uses the area of the settlement patch to characterize the settlement scale. The rank-size rule of settlements is based on the change rate of scale (Formula (2)), and the logarithm of both sides is taken to obtain Formula (3). Through the analysis of Formula (3), it is found that the logarithm of the size of a one-digit settlement has a linear relationship with its rank-size. Therefore, either Eq.(4) or Eq.(5) can effectively express the rank-size characteristics of rural settlements.

$$L_i = L_1 \delta^{i-1} \quad (2)$$

$$\ln L_i = \ln L_1 + (i - 1) \ln \delta \quad (3)$$

$$\ln L_i = -aR_i + b \quad (4)$$

$$y = -ax + b \quad (5)$$

In the formulas, L_1 is the scale of the first rural settlement, L_i is the scale of a rural settlement with rank i , $\delta = L_{i+1}/L_i$ is the change rate of the scale of the adjacent settlements, R_i and x are the rank of the i th settlement, a and b are the slope and intercept, respectively, of the fitting line, y is the logarithm of L_i , and the goodness of fit R^2 is used to indicate the degree to which the rank-size characteristics of rural settlements conform to a negative exponential distribution. The smaller the slope a , the more balanced the settlement scale distribution; the smaller the intercept b , the smaller the first settlement scale.

2.3.3. Kernel density estimation

Kernel density estimation (KDE) is an effective method to reveal the spatial aggregation of settlements. It uses a smooth peak function to fit the observed data points and simulates the true probability distribution curve. The formula is as follows:

$$f(x, y) = \frac{1}{nh^2} \sum_{i=1}^n K\left(\frac{d_i}{h}\right) \quad (6)$$

In the formula, $f(x,y)$ is the kernel density value at the position (x,y) , n is the number of rural settlement patches, h is the bandwidth, i is the kernel function, and d_i is the distance from the i -th observation point at (x,y) . The higher the kernel density value, the greater the distribution density of rural settlements, and vice versa.

3. Characteristics of settlement system evolution

3.1. Time evolution

3.1.1. Settlement development stage

The settlement system in Nagqu County is developing continuously, transforming from a number-increasing expansion to a large-scale expansion (Table 1). The elements of settlement development are constantly enriched, and the functions of the settlement are improved. The period from 2005 to 2010 was the key advancement period for the herdsmen's settlement project in Nagqu County. Some herdsmen who had no permanent homes in the county began to build houses, barns, and fences, and entered the stage of settled grazing (Xu et al., 2017). The end of nomadic life has improved the development of the original mixed living with humans and animals. Settlements in some areas have emerged from scratch, and a large number of new settlements have appeared. In Nagqu County, 2456 households settled down between 2005 and 2010. At this stage, the settlement area had increased by 1436.07 hm^2 , accounting for 40.22% of the overall increase from 2005 to 2017, and the number of settlements had increased by 214, accounting for 76.98% of the total increase. The settlement system presents an expansion pattern with an increasing number of patches. The settlements are dominated by residential functions, with insufficient production and service functions. The settlement development elements are limited and the functions are relatively single.

With the normalization and stabilization of settled life, the increase in production and living needs of herdsmen has promoted the enrichment of settlement elements and the expansion of settlement functions from 2010 to 2017. During this period, the administrative villages constructed infrastructure such as standardized clinics, farmhouses, poverty alleviation shops, greenhouses, and dual-use heating sheds for planting crops and raising livestock. Meanwhile, modern, market-oriented physical projects have begun to emerge, such as animal husbandry cooperation bases and trading markets. A new rural construction policy in Nagqu County aiming to create "well-off new villages" has been steadily implemented, promoting the dynamic development of some settlements. During 2010 to 2017, the settlement area had increased by 2134.47 hm^2 , accounting for 59.78% of the total increase, and the number of settlements increased by 64, accounting for only 23.02% of the total increase. The settlement system presents the original expansion pattern of increasing settlement scale, with increasing factors for settlement development, increasing production, consumption, cultural and entertainment functions, and improvement of the quality of the settlement's living environment.

From 2005 to 2017, the population of Nagqu County increased from 89,700 to 110,200, an increase of 20,500 in 12 years. While population growth promotes the expansion of the settlement area, the density of settlements is also increasing, from 0.16 per square kilometer in 2005 to 0.18 in 2017. The average patch area continued to increase, from 1.52 hm^2 to 2.60 hm^2 in 12 years. The seat of Nagqu County government is the largest settlement patch, far exceeding other settlements in the county. With the development opportunities brought by the opening of the Qinghai-Tibet Railway, the agglomeration level of administrative, economic, and social factors in Nagqu County has significantly improved, and its area has been expanding continuously, rising from 800.52 hm^2 in 2005 to 1330.32 hm^2 in 2017. The smallest settlement in

Table 1
Settlement landscape pattern index of Nagqu County (2005–2017).

Year	TPA/ hm^2	N	PD/ (1/ km^2)	MPS/ hm^2	MAX/ hm^2	MIN/ m^2	ANN
2005	4,023.48	2,647	0.16	1.52	800.52	117.28	0.3709
2010	5,459.55	2,861	0.17	1.91	940.53	174.19	0.3754
2017	7,594.02	2,925	0.18	2.60	1,330.32	241.94	0.3797

Nagqu County is a single-family-scale settlement patch which is independently distributed on the broken landform of the valley, keeping a certain distance from the surrounding settlements. With the improvement of production and living conditions in the pastoral areas, the development elements of these settlements continue to increase and the area is also expanding. The settlement system in Nagqu County presents a significant state of spatial agglomeration, and with the evolution of time, the degree of settlement agglomeration has continued to increase. The ANN index increased from 0.3709 in 2005 to 0.3797 in 2017. The geographical pattern of “large dispersion and small concentration” has become increasingly prominent.

3.1.2. Scale structure of settlement system

From the fitting curves (Fig. 2), most of the settlement patches in Nagqu County fall on the rank-scale rule curves, and the goodness of fit is above 0.9692, indicating a high degree of fit. The rank-size structure of the settlement system in Nagqu County shows the coexistence of “warping” and “cutting off.” The actual value of most settlements is only slightly different than the theoretical value, differing significantly from the theoretical value only in the head and tail. The head settlements are those in the township center, low-lying area, and along the traffic line. Natural geographical conditions here are relatively suitable for settlement; indeed, the scale of settlement is larger than in other areas, and these settlements constitute the basic framework of the settlement system in Nagqu County. The settlements in the tail are small, mostly distributed in Luoma Township and Sexiong Township in the southwest of the county. Due to the location of Nyenqing Tanggula Mountain, the settlements here are distributed in small bands in broken valleys. From the perspective of time evolution (Fig. 2d), the slope of the fitting curve

of the rank-scale rule of the settlement system in Nagqu County is generally decreasing, indicating that the scale structure of the settlements is developing in a relatively balanced direction.

3.2. Spatial evolution

3.2.1. Density distribution characteristics

In this paper, the patch area of settlement was taken as the observed value to explore the spatial density distribution characteristics of the settlement system (Fig. 3). The density of settlements in Nagqu County reflects a strong adaptability to the natural geographical environment. Over time, the density of settlements in environmentally favorable areas has increased significantly. The settlement density forms multiple density cores centered around the township government, showing regional distribution characteristics of being dense in flat land and river valleys, sparse in hills, absent in mountains, and dense in meadows, sparse in shrubs, and absent in deserts. The distribution pattern is mostly consistent with the geomorphic pattern of Nagqu County, which is low in the north and high in the south, with Nyenqing Tanggula Mountain range stretching from northeast to southwest. The settlement densities of the 12 government township locations in Nagqu County are all above 1.1 hm²/km². Over time, the settlement density has increased significantly, especially in the administrative center of Nagqu Town, Gulu Town, Roman Town, Namaqie Township, and Xiangmao Township. In 2017, the settlement density in these areas was as high as 3.63 hm²/km², making them the densest settlement areas in the county. Such areas are located on flat land in front of mountains and the platform of the river valley, with relatively low elevation, flat terrain and good water conditions. The surface vegetation is mainly *kobresia meadow*, with good

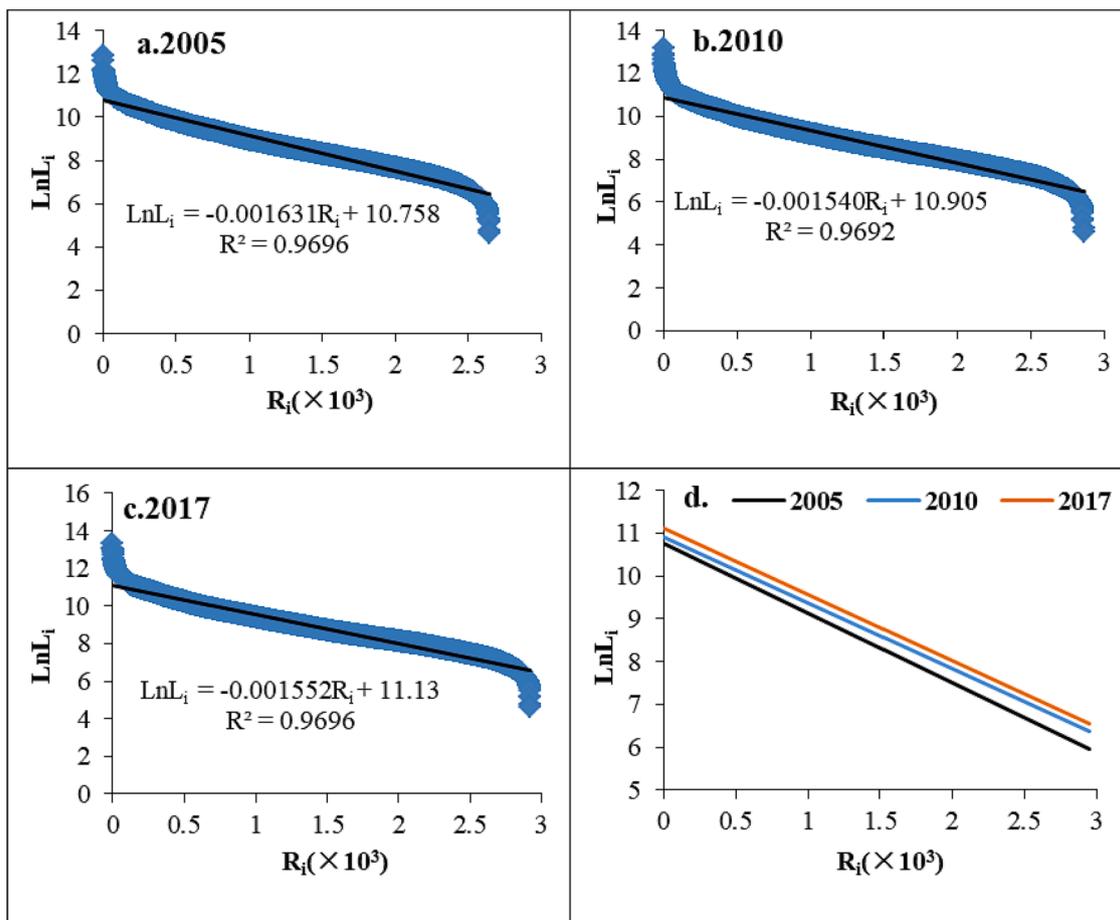


Fig. 2. Characteristics of settlement rank-size rule in Nagqu County (2005–2017). (Figures a, b, and c represent the rank-size rule characteristics in 2005, 2010, and 2017, respectively. Figure d represents the comparative results of the fitted curves of rank-size rule for the three years.)

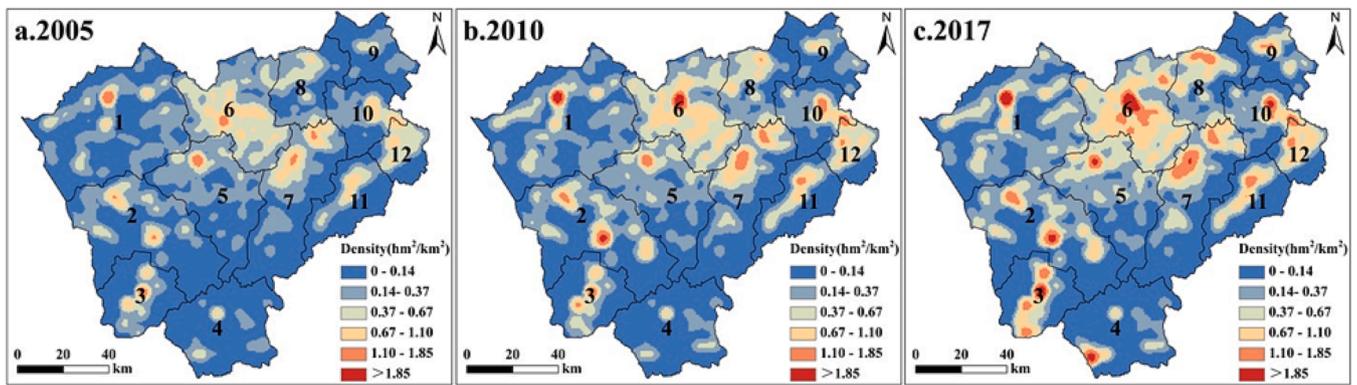


Fig. 3. Evolution of spatial density of the settlement system in Nagqu County (2005–2017). 1. Namaqie Township; 2.Xiangmao Township; 3.Gulu Township; 4.Youqia Township; 5.Luoma Township; 6.Nagqu Township; 7.Dasa Township; 8.Kongma Township; 9.Daqian Township; 10.Nima Township; 11.Luomai Township; 12.Sexiong Township). (Figures a, b, and c represent the spatial density distribution characteristics of the settlement system in 2005, 2010, and 2017, respectively.).

growth of herbage and strong carrying capacity for livestock. Meanwhile, traffic connections with the outside are relatively good. The above-mentioned regional environmental characteristics together thus provide favorable basic conditions for the development and expansion of settlements.

The northern part of Youqia Township and the southern parts of Dasa Township, Xiangmao Township, and Luomai Township are located at the northern foot of Nyenqing Tanggula Mountain, with high altitude, rugged terrain, cold climate, and a sparse river network. The vegetation on the ground here is mainly shrub, such as *prunus chinensis* and *juniper*

altarea. The grazing conditions are poor, the frequency of wind and snow disasters is high, and the natural geographical conditions are harsh. The settlement density is low, about 0.37 hm^2/km^2 , with no significant change over time. Gulu Town, Luomai Township, and Sexiong Township belong to the valley topography between mountains. Restricted by mountains on both sides, the settlement layout is hindered in space. However, the valley topography features good aquatic and grass resources and helps to avoid wind and snow disasters. The settlements here have evolved in strips with a density of about 1.5 hm^2/km^2 .

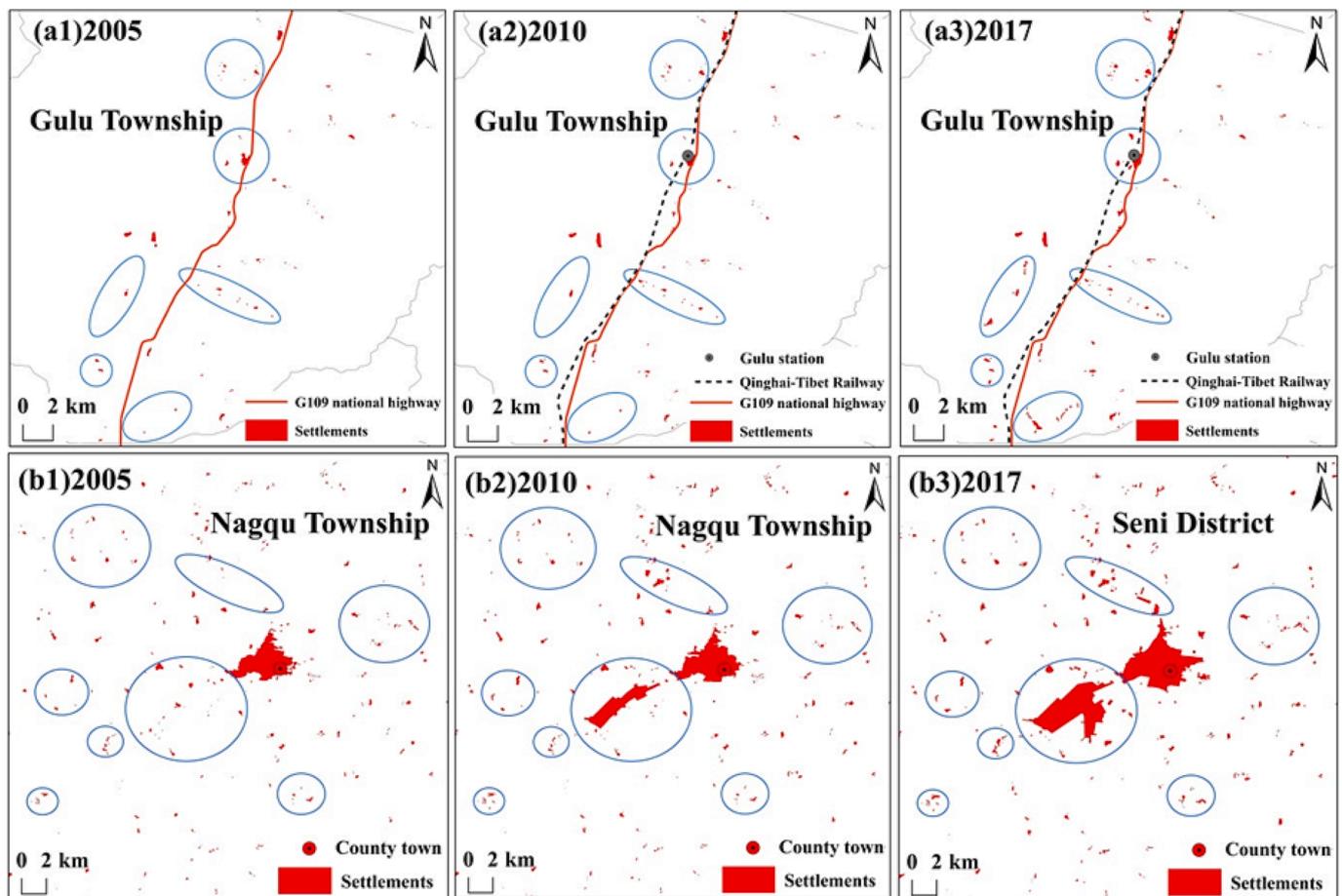


Fig. 4. Evolution of settlements near traffic lines and township centers in Nagqu County (2005–2017). (Figures a1, a2, and a3 represent the settlement evolution near the national road within Gulu township in 2005, 2010, and 2017, respectively. Figures b1, b2 and b3 represent the settlement evolution near Nagqu Township in 2005, 2010 and 2017, respectively.).

3.2.2. Settlement evolution near traffic routes and township centers

With the opening of the Qinghai-Tibet Railway and the steady progress of urbanization and modernization, pastoral areas of northern Tibet have entered a new stage of open development. Tourism activities, the powerful transportation function represented by the Qinghai-Tibet Railway, and the flow of people, logistics, capital and other new elements brought about by foreign investment promotion activities in aid to Tibet have injected vitality into the development of the northern Tibet Plateau. The herdsmen's awareness of modernization and marketization has been enhanced, their livelihoods have been diversified, their incomes have increased significantly, and the requirements for living conditions have gradually increased. Some herdsmen no longer rely only on the availability of water and grass when choosing where to settle; they also consider the proximity of transportation lines and township centers that can provide diversified public services. Thus, the selection of settlement location has gradually changed from resource-dependent to facility-dependent. We analyzed the settlement evolution around Gulu Town, a typical road-crossing town, and Nagqu Town, a regional development center, and found that the trend favoring settlement near traffic routes and township centers is very significant, as shown in Fig. 4. The blue ellipses demarcate areas with a significant increase in the number and scale of settlement patches. From 2005 to 2017, the number of settlement patches on the Gulu section of the Qinghai-Tibet Highway increased by 32, and the average patch area increased from 2.03 hm^2 to 3.90 hm^2 , which was significantly higher than the county average. The settlement area within 10 km of Nagqu County has increased by 205.5 hm^2 , but the number of settlement patches has decreased only by 19. The settlement expansion here presents a pattern of adjacent patch merging and fusion. In the past 12 years, the increase in settlement area within 3 km of Nagqu County's main transportation lines and within 5 km of township centers accounted for 94.91% of the county's total increase in settlement area. Therefore, traffic and public service facilities in Nagqu County play an important role in guiding the speed and direction of settlement evolution.

3.2.3. Settlement evolution in special geographical space

Nagqu County has a large ecological space and high ecological protection value. The northwestern part of the county is home to the *grus nigricollis* National Nature Reserve. The reserve covers an area of 2832.21 km^2 , accounting for 17.49% of the total area of Nagqu County. *Grus nigricollis* is the only crane that lives and reproduces on the plateau; its survival places extremely high demands on the ecological environment. Changes in the external environment, especially human activities, have a great impact on the survival of *grus nigricollis* (Xu et al., 2020). The reserve is a flat dam area close to plateau lakes. The aquatic and grass conditions are relatively good. Due to the lack of effective space guidance and environmental protection constraints during the

settlement of herdsmen, there are also a large number of human settlements in the core area of the reserve (Fig. 5a). Since 2005, the number of settlement patches in the core area of the reserve has increased from 48 to 64, and the settlement area has nearly doubled to 64.05 hm^2 . The increasing intensity of human activities brings greater ecological hazards to the survival and habitat protection of rare wild animals.

As herdsmen settled in northern Tibet, pastures were divided into administrative villages and even households, and herdsmen could only graze on their own pastures. Coupled with the allocation of pasture resources, the division into administrative villages has had a fixed effect on the location selection of pastoral settlements. This has led to undesirable consequences, such as the uneven distribution of grassland resources and regions with bad natural conditions being divided into multiple administrative villages, leading to the irregular evolution of settlements. There are 141 administrative villages and 1,108 natural villages in Nagqu County. The overly-dense administrative village division ignores the balance of aquatic and grass resources and the suitability of the living environment for settlement. The administrative villages circled with red lines in Fig. 5b are in high-altitude mountain areas. These areas have sparse vegetation, frequent disasters, and poor environmental conditions that are not conducive to human survival. However, under the overlapping effect of administrative management system and pasture contracting policy, some herders are attached to the pastureland that is divided in this area and live in the environment with poor natural conditions. From 2005 to 2017, the proportion of settlement areas in Nagqu County that are above an altitude of 4800 m decreased slightly, but the high-altitude settlement area nevertheless increased by 96.67 hm^2 . The extremely hypoxic environment puts humans at risk of various diseases, such as rheumatoid arthritis, cardiovascular and cerebrovascular disease, so there is an urgent need for these settlements to be withdrawn.

4. Evaluation of settlement system and paths of rural revitalization

4.1. Evaluation of settlement system

Based on the above research, we summarized the evolution characteristics of the settlement system in Nagqu County from the perspective of element-structure-function (Table 2). Modern scientific and technological methods have begun to be applied to optimize traditional production factors and improve the utilization efficiency of resources in pastoral areas. The development factors of settlements have increased, and public service facilities in some settlements have become more abundant. The herdsmen's ideology has gradually opened up, changing from "reluctant to kill and sell" to "effective animal husbandry." The scale of settlements has increased, the choice of settlement location has

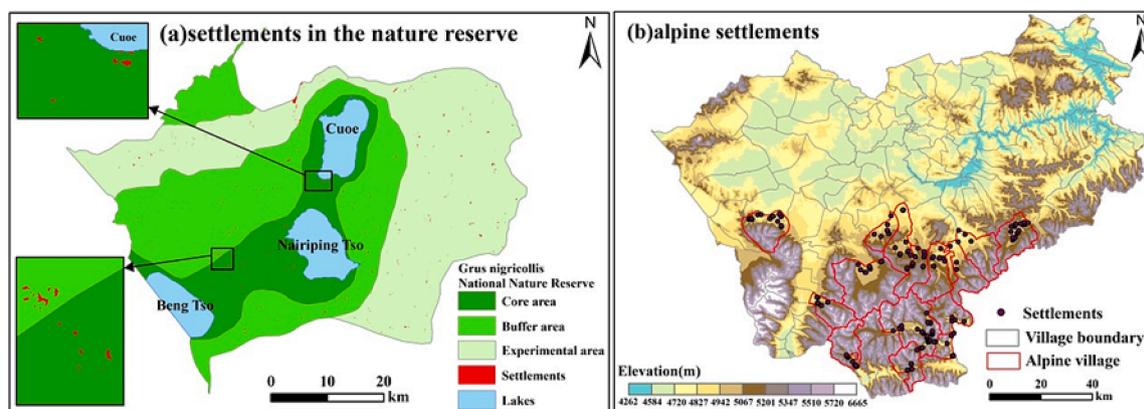


Fig. 5. Distribution of settlements in ecological and high-altitude spaces in Nagqu County. (Figure a characterizes the settlements in the nature reserve, figure b characterizes the settlements in the high-altitude region).

Table 2
Evolution characteristics of the settlement system in Nagqu County.

Stage of development	Elements			Structure		Function			
	Animal husbandry conditions	Infrastructure	Regional culture	Scale and system	Geographic conditions	Support network	Economy	Society	Ecology
Concentrated settlement (2005–2010)	Extensive, depending on the nature of livestock	Limited, poor, mainly religious facilities	Conservative, self-enclosed, and emphasizing traditional religious concepts	Small, scattered, relatively independent	Comply with natural conditions and rely mainly on animal husbandry resources	Few traffic lines and poor infrastructure interconnection	Traditional animal husbandry, weak industrial and commercial foundations	Establish connections with blood and geography as the link, poor mobility among herdsmen and little communication	Encroachment in ecological space, low awareness of ecological value utilization
Functional expansion (2010–2017)	Artificial grass planting and other scientific and technological means gradually extended	Public service facilities such as health clinics and shops are becoming more abundant	Awareness of modernization and marketization has increased	Scale expansion, decentralization, and partial concentration	Transportation and public service facilities are mainly attached	Transportation facilities have improved	Industry is diversified, and the proportion of herdsmen's non-agricultural employment has increased	Business relationships have gradually increased, as well as exchanges within and between villages	Gradual utilization of ecological landscape resources and development of tourism
Overall evaluation	The factors of settlement development have increased, but the utilization degree needs to be improved, human resources are lacking, and the ability of factor integration and optimization needs to be enhanced			The spatial pattern of scattered in large scale and concentrated in small areas has been formed. The nodes need to be strengthened, and the spatial support system needs to be improved.		Settlement functions have developed from single to multiple directions, and development benefits need to be improved. It is necessary to combine development conditions and pay attention to differentiated paths selection			

changed from resource-dependent to facility-dependent, and the support conditions of the transportation network of the settlement system have improved. The functions of settlements have been expanded, from the traditional residence-grazing combination to the diversified combination of residential, animal husbandry, industry, commerce, leisure, and other functions.

Considering the rural revitalization strategy implemented by China in the new era, we found that there are still several development problems in the settlement system of Nagqu County and the social and economic activities it supports. First, the industrial foundation is weak. Nagqu County is located in northern Tibet, which is endowed with good animal husbandry resources. The production activity here is mainly animal husbandry, with low product yields and long cycles. Animal husbandry operations are many and scattered, and the diversified development ability of the industry is weak. Second, the rationality of the settlement space layout needs to be improved. The study found that there are a large number of human settlements in the core area of *grus nigricollis* National Nature Reserve, which poses a threat to the security of ecological space. Some settlements located in extremely high mountain areas. These phenomena lead to a poor quality of life for the herdsmen, and human activities in these areas can easily cause irreversible damage to the fragile surface ecosystem. Third, insufficient attention has been paid to the cultural value of the settlement system in Tibetan areas. During the discussion with the management department of Nagqu County, it was found that grassroots social organizations and management have not paid enough attention to the role of regional culture and religious beliefs in shaping and leading the transformation of herdsmen's values and the cultivation of endogenous power. Fourth, the scope of grassroots governance is wide, difficult, and there is a large talent gap. Nagqu County has a large number of settlements, scattered distribution, and high administrative costs. However, due to the particularity of social governance tasks in this area, the capability of grassroots management needs to be improved. In addition, talented workers are the key to rural revitalization and settlement development. However, due to Nagqu's remote location and poor development, the difficulty of introducing talent and the outflow of local talent exist simultaneously, limiting the healthy development of the rural settlement system. Fifth, the spatial support system for settlements needs to be improved. Road construction in Nagqu County is still lagging behind. As of 2020, the road access rate of the 141 administrative villages in the county was only 77.3%, and only six rural passenger transport lines have been opened. Limited transport connections affect the level of production and the quality of life of the residents.

4.2. Optimization of the rural settlement system and rural revitalization paths

Rural settlements are spaces for rural production and living, as well as the basic spatial unit of rural revitalization. The realization of rural revitalization is closely related to the optimization of the rural settlement system. The essence of promoting rural revitalization in the new era is to enrich and integrate the development elements of rural settlements, reorganize the diversified structure of rural settlements, enhance and expand their functions, and optimize the rural settlement system to achieve the strategic goals of "prosperous industry, livable ecology, civilized rural customs, effective governance, and prosperous life" (Fig. 6).

4.2.1. Adjust the settlement space layout and optimize the settlement organization structure

First, it is necessary to focus on ecological migration in the core areas of the *grus nigricollis* National Nature Reserve, as well as high-altitude mountain areas. It is necessary to increase financial support for resettlement, issue resettlement funds to cover grass and livestock expenses, select transportation routes or township centers and other areas with strong resource and environmental carrying capacity for resettlement.

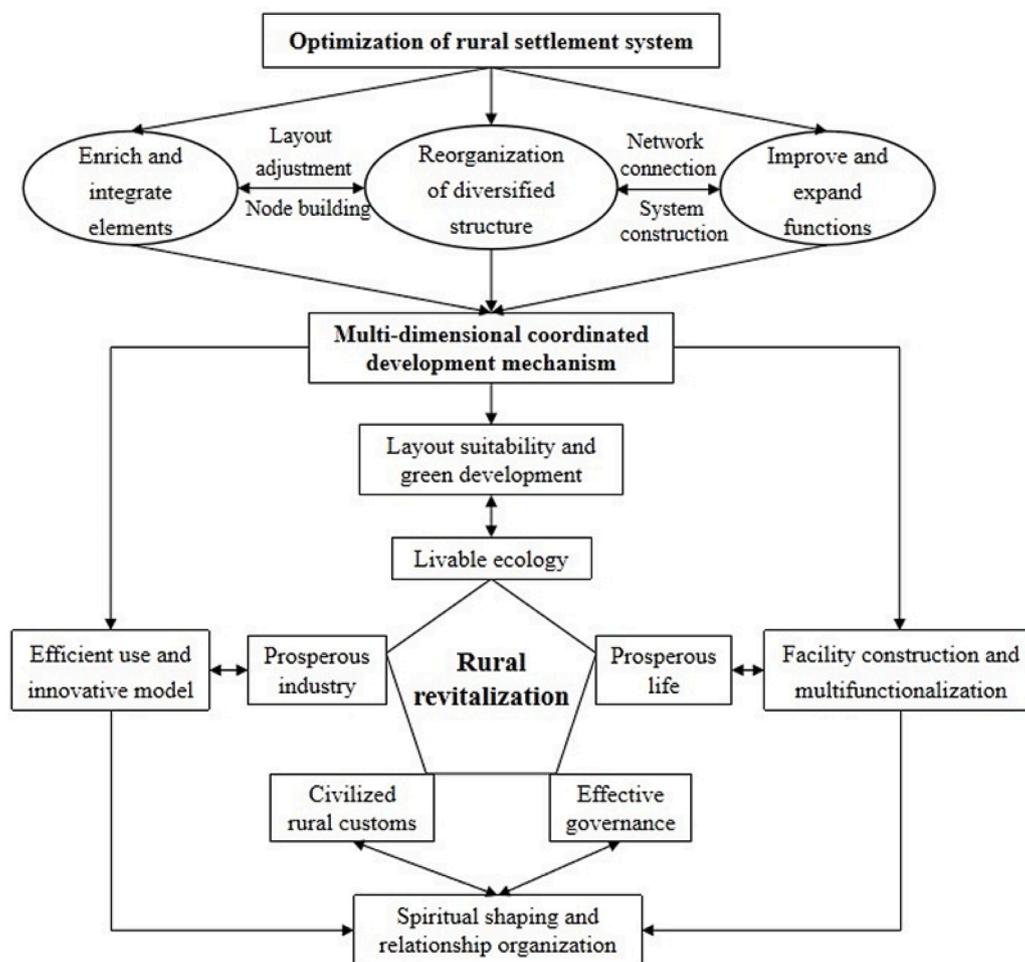


Fig. 6. Correlation mechanism between optimization of rural settlement system and rural revitalization in alpine pastoral areas of the Qinghai-Tibet Plateau.

Second, it is necessary to reduce the establishment of basic-level administrative villages and promote the delineation and protection of grasslands. The boundaries of grassroots administrative villages should be redrawn according to the distribution of animal husbandry resources. Third, the appropriate “villagization” of settlements should be promoted by building a central village system and optimizing the organization of settlements. Settlements should be selected with a large scale and superior location as an artificial grass-planting base. Planners should promote moderate concentration of settlements and develop them into central villages, and strengthen their connections and industrial links with key township centers such as Luoma Town, Xiangmao Township, and Gulu Town, gradually forming a top-down multi-level settlement hierarchy in Nagqu County—which includes 11 township centers—with multiple central villages.

4.2.2. Strengthen infrastructure configuration and improve settlement service functions

On the one hand, in combination with the top-down settlement hierarchy in Nagqu County, it is necessary to improve connections between central settlements of various levels and the two main traffic corridors: the Qinghai-Tibet Highway and the G317 National Highway. To build a “point-axis” system of spatial connection, element transmission and functional support with central villages and towns as nodes and the road network as the skeleton, form the “hard support” of settlement spatial structure. On the other hand, it is necessary to focus on promoting the Tibet aid funds and projects of Zhejiang and Liaoning provinces and the five major state-owned enterprises of the central government to tilt towards the field of public service facilities. Give

priority to the construction of basic public service facilities such as electricity, water, and communications in basic-level settlements. Combining the effective service radius, focus on promoting the distribution of public service facilities such as education, medical care, elderly care, public health, and social culture in central villages where conditions permit. Build green energy infrastructure such as biomass energy and solar energy according to local conditions to meet the needs of house heating, cooking, domestic hot water, and improve the clean energy utilization level in pastoral areas. Continuously improve the construction level of public service facilities in different levels of settlements in Nagqu County, and build the settlements into a space carrier for herdsmen to enjoy a prosperous and beautiful life.

4.2.3. Give full play to the advantages of resource elements and build a characteristic industry system in pastoral areas

The first task is to focus on the unique climate and ecology types of pastoral areas in northern Tibet, based on the advantages of resource elements, to improve compatibility between the development of animal husbandry and the resource environment, and focus on promoting the development of the yak, Tibetan sheep, and forage industries based on the resource and environmental carrying capacity. The second is to implement the “grazing and supplementary feeding” animal husbandry development model, accelerate the adjustment of the herd structure, actively carry out the green development of animal husbandry demonstration counties and modern demonstration pastures, and accelerate the transformation of animal husbandry from traditional livestock to industry prosperous animal husbandry. The third is to vigorously promote new agricultural and animal husbandry business entities such as

large breeding households, specialized farmer and herdsmen cooperatives, and agricultural and animal husbandry enterprises; and build a new type of animal husbandry management system that combines intensification, specialization, organization, and socialization. The fourth project is to start by expanding functions and satisfying needs to gradually establish a diversified industrial system for the development of medicinal materials characteristic of the plateau, such as *ophiocordyceps sinensis* and other unique biological resources available in mountain landscapes and ethnic communities.

4.2.4. Strengthen cultural heritage in Tibetan areas and expand social and cultural forms

It is necessary to promote the inheritance of excellent traditional culture, tapping into the profound nomadic cultural heritage of Nagqu. This can be done by extracting the “Nagqu spirit” from the story of Gesar, the mysterious ancient Xiangxiang civilization, paying attention to its cultural influence and ideological and moral-educational functions, and promoting creative transformation and innovative development that meet the requirements of the times. Moreover, it is necessary to cultivate positive, healthy, and colorful social and cultural forms. Tibetan herdsmen should be empowered to run their own cultural and artistic groups with ethnic characteristics and build a brand of mass cultural activities; this will increase positivity among the herdsmen, and enrich their spiritual lives. Xiangxian culture can also be promoted through grassroots cadres, moral models, and people who can provide demonstrations and guidance, and cultivate civilized rural customs.

4.2.5. Improve the degree of social organization in pastoral areas and attach importance to the role of talent

First, it is necessary to establish a united insurance unit under the top-down organizational structure of the settlement in light of the reality of the large and sparsely populated areas in alpine pastoral areas, and implement a joint household system among neighbors and a cooperative linkage system between villages, and improve the degree of socialization of herdsmen. Second, based on the special status of ethnic religions in Tibetan areas in the social organization system of herdsmen, it is necessary to give full play to the overall management capabilities of grassroots party organizations and herdsmen party members, and conduct extensive legal education and education on anti-separatism among monks, nuns, and religious believers in temples. Third, attention should be paid to the important role of talent in the organization and management of the settlement system by increasing the recruitment of cadres to aid Tibet, and improving the ability of management talent to deal with emergencies and maintain stability. At the same time, it would be useful to implement a modern agriculture and animal husbandry talent support plan; expand the recruitment of agriculture and animal husbandry science and technology talent; orient training of high-level talent in animal husbandry.

5. Discussion

5.1. Fully understand the peculiarities of settlement evolution in alpine pastoral areas of the QTP

Alpine pastoral areas of the QTP have a cold and arid climate, extremely high altitude, fragile ecosystems, great ecological value, and low suitability for human survival. The population is sparse, human beings rely on traditional animal husbandry as their main livelihood, socio-economic development is lagging, the level of urbanization is low. It is an ethnic area with distinctive regional cultural characteristics (Harris, 2010; Papworth et al., 2014; Farrington and Tsering, 2019). Its unique natural geographic environment and socio-economic characteristics have resulted in a settlement evolution that is significantly different from that of plains agricultural areas. There were no human settlements in the past in northern Tibet (Xu et al., 2017; Zhang et al., 2020). With the development opportunities brought about by the

implementation of the nomadic settlement policy and the opening of the Qinghai-Tibet Railway in recent years, the modernization of pastoral areas in northern Tibet has continued. Thus, settlements in some areas have emerged from scratch, from small to large, and are in a period of formation and evolution, and their development stage is significantly lagging behind that of rural settlements in plain agricultural areas (Fig. 7).

Comparing the relationship between the level of development of settlements in plain agricultural areas and alpine pastoral areas over time (Fig. 7), we can find that with the advancement of social development and urbanization, the development level of rural settlements in plains agricultural areas continues to increase (Long et al., 2019), and the agglomeration effect of cities is increasing. A large number of rural population and production factors continue to transfer to cities (Qu et al., 2020; Li et al., 2020; Liang et al., 2020). After entering the O1 moment of the mid-urbanization stage, the polarization effect of cities has intensified, the urban-rural gap has widened, the rural has declined (Liu, 2018), and the level of rural development has also begun to decline. In this context, the Chinese government proposed a rural revitalization strategy in 2017. Its purpose is to promote rural revitalization through the investment of policies and funds, and other factors, so as to achieve a benign development that further improves the level of rural development at the O2 moment (Long et al., 2019). However, during this process, alpine pastoral areas have undergone a transition from nomadic to settled life. The settlement system has grown from nothing, is in the stage of formation and evolution, and its development is very slow, and urbanization has been in the initial stage for a long time. With the promotion of the rural revitalization strategy in alpine pastoral areas, the settlement system will be optimized and the level of development will also be improved.

Comparing the development of settlements in plains agricultural areas and alpine pastoral areas, we found that the process of rural revitalization in plains agricultural areas entails optimizing the existing declining settlement system, and is currently moving from “existence” to “excellent” (Liu et al., 2016). However, alpine pastoral areas have experienced a process of constructing and optimizing a settlement system that has not yet matured. Thus, it is in the process of moving from “none” to “excellent,” meaning that the development starting point of the two types of areas differs. In addition, the level of urbanization in plains agricultural areas is high, with cities able to radiate and drive development in their surroundings. In the process of rural revitalization, the development of the plains agricultural areas can be strongly driven by a city, and the level of urban-rural integration is high (Li et al., 2019; Li et al., 2021). However, there are few cities in alpine pastoral areas, the level of urban development is low, and the distance between urban and

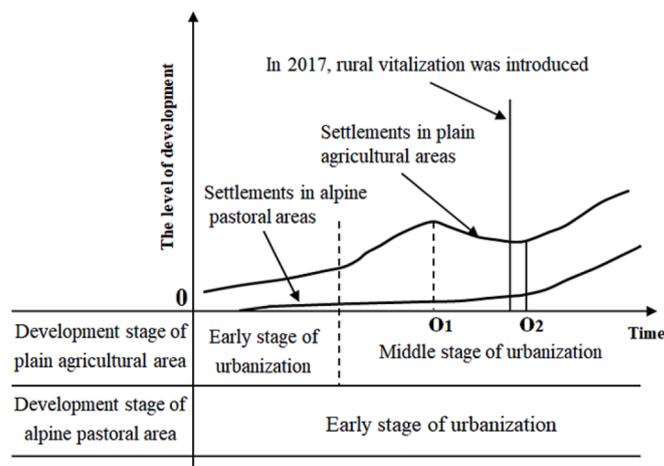


Fig. 7. Differences in the evolution of settlement systems in plateau pastoral areas and plains agricultural areas.

rural spaces is great (Fang and Li, 2015), so it is difficult for cities to play a radiating role in rural settlements. The development momentum of pastoral settlements is significantly weaker than that of plains agricultural areas. The keys to rural revitalization are to give full play to local resource elements and provide national policy support. Differences in geographical environment affect the development characteristics of rural settlements and selection of the paths to rural revitalization (Li et al., 2021). Therefore, in implementing rural revitalization in different regions of China, it is necessary to pay attention to the development status and existing problems of rural settlements as its spatial carrier, and to formulate rural revitalization paths that are suited to the characteristics of the region based on the actual situation therein.

5.2. The focus of rural revitalization in alpine pastoral areas of the QTP

Unlike low-altitude inland areas, the natural environment of the QTP places strong constraints on human survival, the ecosystem's anti-interference ability is weak, and restoration is difficult (Coggins and Hutchinson, 2006; Yang et al., 2021). The basis of human survival and development is to select suitable areas for settlement layout; therefore, the primary task of rural revitalization is to optimize the spatial layout of settlements and adjust areas where the layout is unreasonable. However, this problem does not exist in low-altitude inland areas more suitable for human survival. In addition, rural revitalization in alpine pastoral areas requires special attention to the role of people. All Tibetans are religious, Tibetan culture has shaped a unique regional identity, so religion and tribal culture have played an important role in shaping the ideology of herdsmen (Salick et al., 2012). The arduous natural environment and long-term closed state of development have made the herdsmen in alpine pastoral areas conservative and self-sufficiency in ideology. These conditions make it difficult for herdsmen to cultivate and accept new ideas and concepts. In addition, religious issues in Tibetan areas are often intertwined with political and ethnic issues. The issue of religion is a key concern for the development of Tibetan areas (Woodhouse et al., 2015). All these factors make the shaping of people's inner spiritual world and the construction of social and cultural features in the process of rural revitalization more complicated in alpine pastoral areas than in other areas.

In the process of promoting rural revitalization in alpine pastoral areas, the revitalization of people requires three steps. First, we must focus on eliminating the influence of negative religious factors, resolutely clean up possible channels of transmission. Herdsmen's minds must be emancipated through education and the cultivation of self-reliance and a modern consciousness; the religious system and ethnic regional culture can be used to shape a positive spiritual world for herders and create a civilized society in Tibetan areas. The second task is to strengthen local herdsmen's production skills and the capabilities of grassroots managers. To address the needs of animal husbandry production and grassroots management, categorized training should be implemented to cultivate capable leaders and management talent, to give play to the goose effect and stimulate local talent to support rural revitalization. Finally, advantage can be taken of the talent available in the provinces that aid Tibet; in this regard, high-level talent can be introduced to Tibet, and Tibetan university students and migrant workers can be encouraged to return to their hometowns to start businesses and to improve the knowledge level in animal husbandry and technology. Through implementation of the above measures, the efficient allocation of various elements of the settlement system by people will be realized, endogenous development motivation will be strengthened, and the multi-dimensional self-rejuvenation and long-term revitalization of the village will be realized.

5.3. Significance and limitations of the study

Taking Nagqu County, a sparsely populated alpine pastoral area on the QTP, as an example, this paper used settlement patch data obtained

from the visual interpretation of high-definition remote-sensing images and extensive field investigations to propose rural revitalization paths based on exploration of the evolution of the settlement system. It also compared the development of the settlement system in alpine pastoral areas of the QTP with that of plains agricultural areas, and analyzed the implementation of rural revitalization in alpine pastoral areas. In terms of research methods, visual interpretation, though laborious, has high identification accuracy, which can make up for the fact that computer remote-sensing interpretation or settlement research based on land use type cannot depict small-scale ground object information. This study also provided a research method to study human activities in sparsely populated areas from a microscopic perspective. In terms of research area selection, the special environment of the alpine pastoral areas determines the particularity of its settlement development stage. The typical area selection and research findings are conducive to enriching the current research on settlement systems. From the perspective of research, this study linked settlement evolution with rural revitalization, attaching importance to the basic role played by rural settlements as carriers of rural revitalization, and outlined some principles of rural revitalization based on the development characteristics and existing problems of the current settlements, which makes the paths selection of rural revitalization more pertinent and feasible.

While aware of the proposed construction of the "Third Pole National Park Group" on the QTP (Fan et al., 2019) and the establishment Selincuo National Park, this paper did not discuss the influence of the development of tourism activities and the integration of various new factors on the settlement system and the choice of rural revitalization paths in alpine pastoral areas. In addition, this paper took only Nagqu County—a small part of the vast QTP and with a relatively high level of economic and social development—as an example. Shuanghu and Nyima Counties, which border the uninhabited area of the QTP, are among the most backward areas in China and feature human settlements that are in a more closed state of development. Research on the characteristics of settlement evolution in such areas needs to be carried out in the future.

6. Conclusion

Since 2005, the settlement system in Nagqu County has undergone a phase transition from centralized settlement to functional expansion. Development elements have been continuously enriched, functions have been improved, and the overall settlement scale structure has been relatively balanced, in line with the rank-scale rule of rural settlements. The density of settlements in Nagqu County shows strong adaptability to the natural geographical environment. Over time, the density of settlements in relatively favorable areas has increased significantly, showing the regional distribution characteristics of "dense in flat land and river valleys, sparse in hills, and no settlements in mountains" and "dense in meadows, sparse in shrubs, and no settlements in deserts." The distribution pattern is consistent with the geomorphic pattern of Nagqu County, which is low in the north and high in the south, with Nyenqing Tanggula Mountain lying on a northeast-southwest axis. The evolution of settlements in Nagqu County has gradually changed from resource-dependent to facility-dependent. Transportation facilities and public service facilities have an important guiding role in the speed and direction of settlement evolution. Due to the lack of effective space guidance and environmental protection constraints in the process of herdsmen's settlement, and the unreasonable administrative village setting in the pastoral areas, there are still human settlements in the important ecological space and the harsh natural environment of Nagqu County. The results show that there are still some problems in Nagqu County's settlement system, such as a weak industrial foundation, low rationality of spatial distribution, insufficient attention to the cultural value of the Tibetan settlement system, a wide range of grassroots governance, a large talent gap, a weak spatial support system of settlements, and so on.

From the perspective of enriching and integrating the development

elements of rural settlements, reorganizing the diversified structure of rural settlements, and improving and expanding the functions of rural settlements, this paper explained the correlation mechanism between the optimization of the settlement system and rural revitalization in alpine pastoral areas of the QTP, and put forward the paths for rural revitalization in those areas. The paths involves adjusting the settlement space layout and optimizing its organization structure; strengthening infrastructure configurations and improving settlement service functions; taking advantage of resource elements and building a characteristic industry system; strengthening cultural heritage and expanding social and cultural forms; improving the degree of social organization in pastoral areas; and highlighting the importance role of talent.

Globally, the QTP is the third pole of the earth with typical geographical characteristics, and its unique natural conditions and social culture have shaped a special human production and lifestyle. Based on the context of rural revitalization in China, this study explored the mechanism of linking the evolution of alpine pastoral settlements and rural revitalization on the QTP. The exploration of human-land relations in special regions provides a meaningful reference for enriching the theoretical content of rural geography studies in other regions around the globe. The exploration of rural revitalization paths in high-altitude sparsely populated areas is an important practical reference for the study of sustainable rural development in high-altitude mountainous regions on a global scale.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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