Shape Classification and Formation of Decentralized Rural Settlements Based on the Alpha Shape Algorithm: A Case Study of Long Town, Mizhi County (Postprint)

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Abstract

To quantitatively classify the shape types of dispersed rural settlements and explore their formation mechanisms, this study employs Long Town, Mizhi County, in the Loess Hilly-Gully Region of Northern Shaanxi as a case study. The Alpha Shape algorithm is utilized to extract settlement outlines, the Boyce-Clark index is applied to classify settlement shape types, and multiple linear regression and regression tree methods are integrated to investigate the factors influencing settlement morphology. The results demonstrate that under a rolling radius of 100 m, the Alpha Shape algorithm can extract precise contours for 76.1% of settlements. The rural settlement shape types in the study area can be categorized into five classifications: block rectangle and its variants, elongated shape, dumbbell and bead-string shapes, belt rectangle and its combinations, and linear shape, with the Boyce-Clark index increasing sequentially. Elevation exhibits a significant positive correlation with the Boyce-Clark index, water resource accessibility shows a negative correlation with the Boyce-Clark index in high-altitude areas, and settlement area demonstrates a correlation that shifts from negative to positive with the Boyce-Clark index. These findings can provide references for delineating living space boundaries of dispersed settlements and enhance understanding of dispersed settlement morphology in the loess hilly-gully region.

Full Text

Abstract

To quantitatively classify the morphological types of dispersed rural settlements and explore their formation mechanisms, this study takes Long Town in Mizhi County, located in the loess hilly-gully region of northern Shaanxi, as a case study. The Alpha Shape algorithm was employed to extract settlement boundaries, the Boyce-Clark index was calculated to classify settlement shapes, and multiple linear regression combined with regression tree analysis was used to investigate the influencing factors. The results show that: with a rolling radius of 100 m, the Alpha Shape algorithm can extract accurate contours for 76.1% of settlements. Rural settlements in the study area can be classified into five types: block rectangle and its variants, extension shape, dumbbell and bead shape, ribbon rectangle and its combinations, and linear shape, with corresponding Boyce-Clark index ranges. Elevation shows a significant positive correlation with the Boyce-Clark index, while water resource availability shows a negative correlation with the index in high-altitude areas. Settlement area first shows a negative correlation then a positive correlation with the Boyce-Clark index. These findings provide a reference for delineating the living space boundaries of dispersed settlements and enhance understanding of dispersed settlement morphology in loess hilly-gully regions.

Keywords: rural settlement; morphological type; Alpha Shape algorithm; Boyce-Clark index; loess hilly-gully region

1 Introduction

The loess hilly-gully region is a typical semi-arid area and a critical zone for ecological protection and high-quality development in the Yellow River Basin. This region is characterized by crisscrossing gullies, fragmented terrain, and numerous dispersed rural settlements. Identifying the morphological characteristics of rural settlements and their influencing factors is essential for understanding settlement formation, planning physical settlement space, and rationally allocating infrastructure and public service facilities. Research on centralized settlements is relatively mature due to their more complete morphology, while dispersed settlements have received less attention because their boundaries are difficult to identify.

Currently, two main approaches exist for identifying rural settlement morphology: manual identification and machine recognition. Manual identification relies on specific rules to manually extract settlement shapes or boundaries. For instance, Pu Xincheng generated connecting lines from building patch vertices to obtain settlement boundaries at different precision levels by setting a length threshold of 100 m, while Xie Dan and Du Jia applied this method to study rural morphology in northern Hainan and karst mountainous areas of Guizhou, respectively. However, this approach requires manual extraction of village boundaries from topographic maps and is not suitable for scattered settlements. Machine recognition involves setting artificial rules to extract settlement contours using computers, overcoming the labor-intensive nature of manual extraction. Dong Yifan extracted village outlines by calculating influence distances between buildings through Delaunay triangulation and superimposing building convex hulls, though this method requires high-precision data.

For classifying rural settlement morphological types and studying influencing factors, early research generally used qualitative methods for artificial classification, often involving non-morphological characteristics such as settlement environment and population size. Jin Qiming classified Jiangsu rural settlements into clustered and ribbon types based on scale, density, and farming radius. Quantitative studies typically integrated economic-environmental and spatial pattern indicators, using cluster analysis to classify settlement types. For example, Ma Xiaodong et al. used hierarchical clustering of settlement pattern indices to identify cluster, broadband, and ribbon morphological types. While these studies improved quantitative analysis, clustering results often made direct morphological judgment difficult. Regarding influencing factors, existing research indicates that natural environmental factors form the basis of settlement morphology, with elevation and slope having significant impacts, and water resources strongly constraining settlement forms in arid regions. Additionally, social factors such as feng shui, clan systems, policies, and economic levels also influence settlement morphology. Overall, studies on influencing factors primarily use linear regression to analyze correlations between terrain, transportation, and settlement morphological features, though the relationship between settlement morphology and influencing factors is not entirely linear, with limited exploration of non-linear relationships.

In summary, current methods for identifying dispersed settlement morphology are inadequate, with existing approaches suffering from high computational demands and data requirements. Moreover, morphological classification lacks quantitative rigor, and non-linear influencing factors have been insufficiently explored. Therefore, this study uses Long Town in Mizhi County as a case study to apply the Alpha Shape algorithm for extracting dispersed settlement boundaries, introduce the Boyce-Clark index from urban morphology research into rural studies to improve the scientific rigor of shape classification, and combine multiple linear regression with regression trees to explore linear and non-linear relationships between settlement shapes and influencing factors, aiming to supplement research on rural settlement morphology in this region.

1.1 Study Area Overview

This study focuses on Long Town, Mizhi County, Yulin City. Located 25 km northwest of Mizhi County seat, the area covers 136 km^2 and belongs to the typical loess hilly-gully region, with an average annual precipitation of 552 mm. The topography features "one river plain and two gullies" (Fig. 1): the Wuding River plain and two tributary gullies (Malongyu Gully, locally called Longlaigou, and Yangzheng Gully, locally called Heishiyao Gully). Transportation is relatively convenient, with the Yulin-Shangluo Expressway passing along the eastern edge of the town and an entrance/exit located within the town, while the Shenmu-Yan' an Railway traverses the eastern part of the town area. After large-scale village consolidation, the number of administrative villages has been reduced to 25. However, considering that consolidated administrative villages contain too many natural villages with overly large distribution ranges unsuitable for morphological analysis, this study uses pre-consolidation settlements as analysis objects, totaling 44 natural villages.

1.2 Data Sources

The study data includes spatial vector and raster data. Vector data comprises the administrative boundary of Long Town, Mizhi County and 2018 land use data for Long Town, provided by the Long Town government in the CGCS2000 coordinate system. Raster data includes 30-arc-second resolution digital elevation data obtained from the Geospatial Data Cloud (http://www.gscloud.cn/).

1.3 Methodology

1.3.1 Alpha Shape Algorithm The Alpha Shape algorithm is a method for calculating the contour of scattered points. Given a set S of points in space, the minimum convex hull of S forms a closed polygon containing all points. However, the minimum convex hull cannot adequately describe the contour of scattered points because concave areas are not represented. The Alpha Shape algorithm is based on circles of radius a. For any given radius a, circles passing through any two points are drawn. The algorithm stipulates that when a drawn circle contains no other points, these two points can be considered boundary points. Calculating all such points yields the scattered point boundary. When radius a is too large, the resulting contour is coarse and approximates the minimum convex hull; when a is sufficiently small, more contour details are captured, including holes within the point set.

The dark portion in Fig. 2 shows the scattered point contour obtained using the Alpha algorithm at a given radius a, which is significantly smaller than the minimum convex hull and better depicts concave areas. Since radius a is fixed, point pairs with excessively large distances are discarded. Without manual setting, the default value of a is half the minimum distance between all point pairs. In practice, a must be adjusted to ensure most residential land is covered by the contour.

Radius a can be viewed as the influence range of buildings, i.e., the scope of external space. Pu Xincheng divided distances into 100 m and 150 m based on interpersonal relationships and actual rural spatial conditions, where 100 m represents the upper limit of social visual fields. Additionally, the study compared extraction effects at 100 m and 150 m radii. While both showed little difference in the number of settlement contours, 150 m resulted in lower extraction precision. Therefore, this study adopts a 100 m radius.

The specific calculation steps involve creating a point matrix using the fishnet tool in ArcGIS to match building patches, exporting point coordinates as a numerical matrix, and calculating the contour using Matlab' s Alpha Shape function. After obtaining boundary facets, boundary point sets are generated. When multiple surfaces exist, manual connection of points is required in ArcGIS.

1.3.2 Boyce-Clark Index Among current methods for measuring boundary shapes, the Boyce-Clark index is considered effective. This index compares settlement boundary shapes with a standard circle generated at a specific radius. The standard circle' s center significantly affects calculation results; this study uses the surface centroid as the circle center. During calculation, radiation lines (radii) from the centroid may intersect boundaries multiple times. To ensure complete coverage of settlement areas, the farthest intersection point from the centroid is defined as the radius. The formula is:

$$BC = |ri - \bar{r}| / (n \times \bar{r}) \times 100$$

where BC is the Boyce-Clark index, n is the number of radiation lines from the centroid, and ri is the length of the ith radius from centroid to graphic edge. The index precision depends on n; larger n values indicate smaller angular intervals between radiation lines and more precise results. Following relevant studies, n is set to 32, with radiation line intervals of 11.25°. Calculations are completed in ArcGIS: first determining each settlement contour' s centroid, then generating radiation lines at intervals, calculating each line' s length, and computing the BC index.

For settlements with multiple contours, different processing methods are applied. When BC indices are similar across contours, area-weighted averaging is used. When differences are substantial, the settlement is defined as a composite shape, with each surface' s BC index analyzed separately. The area-weighted formula is:

$$BC\_\{weighted\} = (A1 \times BC1 + A2 \times BC2) / (A1 + A2)$$

where A1 and A2 are contour surface areas, BC1 and BC2 are corresponding Boyce-Clark indices, and A is total area.

Different settlement shapes correspond to different BC indices. According to relevant research, settlement morphology can be divided into five standard types. Circular spatial forms are most compact, with BC indices increasing progressively as shapes deviate from circular to linear forms.

2 Results

2.1 Settlement Boundary Extraction and Shape Classification

2.1.1 Settlement Boundary Extraction Results The Alpha Shape algorithm demonstrates good performance in extracting boundaries for settlements with relatively uniform and compact residential point distributions (average patch spacing <135 m). At a 100 m extraction radius, 76.1% of settlements show clear contours, with single-contour settlements accounting for 44.8% and double-contour settlements for 31.3% (Table 2).

The number of settlement contour surfaces is primarily influenced by the standard deviation of patch average spacing. Single-contour settlements have an average patch spacing standard deviation of 34 m, while double-contour settlements have 56 m, with only 6 m difference in average patch spacing. Therefore, when overall patch spacing is similar, contour surface quantity is mainly affected by spacing distribution—larger standard deviations indicate greater spacing fluctuations and more contour surfaces.

Additionally, due to the complex terrain of the loess hilly-gully region, some settlements have extremely scattered residential distributions. Using a 100 m radius makes it difficult to maintain single contours, resulting in multiple contour surfaces (three or more), which account for 23.9% of settlements. With numerous contour surfaces, shape analysis becomes challenging. Therefore, settlements with fewer contour surfaces (less than three) are selected for further analysis, totaling 34 natural villages. These villages' spatial distributions cover various terrain regions of Long Town, including northern river beach areas and central gully and ridge areas.

2.1.2 Settlement Shape Index Calculation and Classification Based on BC index calculations for each surface, settlements with single contours can be classified into several types (Fig. 4):

1) **Block rectangle or block variant (star shape)**, BC range 17.032-33.032. Characterized by outward expansion from block shapes, with extensions in one or multiple directions resembling star shapes. Due to limited expansion, BC indices remain relatively low. Representative settlements: Pitiaomao, Sujiagou, Fengzhuang, Mahuyu, Ligedui.
2) **Extension shape**, BC range 37.438-53.288. Generated from block variant shapes with higher expansion degrees and BC values. Representative settlements: Shanjianleng, Hejiapo, Fengfuyan, Shapan, Fanxingzhuang, Tazhan, Longmao, Xigaomiaoshan.
3) **Bead shape or dumbbell shape**, BC range 55.775-70.644. Characterized by combinations of two or more extension shapes, with sudden increases in settlement area at certain nodes of ribbon settlements. Two-part combinations form dumbbell shapes; three or more parts form bead shapes. Representative settlements: Madigou, Gaozhuang, Baozhuang, Zhaojiawa, Changxingzhuang, Laoyushan, Anzhai, Baiqu, Caoshan, Dujiapan, Mashan.
4) **Ribbon rectangle or ribbon extension shape**, BC range 78.256-99.868. Features single ribbon rectangles or intersections of multiple ribbon rectangles forming ribbon extension shapes. Compared to multi-point extension shapes, these have greater extension distances without large nodes. Representative settlements: Guojiabian, Aijiayan, Dongpingyan, Houzhangxingzhuang.
5) **Linear shape**, with only Heishiyao Village fitting this type. The shape is a single line.

For settlements with double contours, when BC indices are similar, they can be approximated as single shapes using area-weighted averaging. When differences are substantial, they are treated as composite shapes. Composite shapes can be classified as: block rectangle + dumbbell/bead combinations (Yuhuangge, Zhaishan, Yanyaogou, Xinyaogou, Huangjiawa); block rectangle + multi-point extension combinations (Zhangjiawan, Zhangxingzhuang, Qianzhongzhuang); multi-point extension + dumbbell/bead combinations (Zhaoxingzhuang, Laozhuang); and multi-point extension + ribbon rectangle combinations (Langhougou, Chenjiayan).

2.2 Analysis of Influencing Factors

2.2.1 Factor Selection and Calculation Settlement scale is a crucial morphological characteristic—shape changes accordingly as settlement spatial scale increases or decreases. Therefore, settlement area is first selected as an influencing factor. The study area belongs to the loess hilly-gully region and semi-arid zone, where terrain conditions and water resource availability may strongly influence settlement evolution. Additionally, transportation accessibility may affect settlement morphology during formation processes. Previous research indicates clan concepts can influence settlement morphology, and surname distribution varies significantly among villages in this region. Therefore, this study selects settlement scale, terrain factors, water resource availability, transportation accessibility, and clan concept as candidate influencing factors.

Specifically: settlement scale is represented by settlement area; terrain factors include elevation, slope, elevation variation coefficient, terrain relief, surface incision depth, surface roughness, and profile curvature; water resource availability is measured by cumulative cost distance from residential patches to water sources (larger cumulative distance indicates lower availability); transportation accessibility is represented by average mileage from residential patches to the nearest major road (excluding internal village roads, primarily township roads); clan concept is measured by the number of surnames in each village (fewer surnames indicate stronger clan concept).

Using BC index as the dependent variable, multiple linear regression first determines the importance of candidate factors, removing highly collinear factors (variance inflation factor VIF > 10). Regression tree analysis then verifies results, as this model better fits non-linear relationships and is unaffected by data collinearity, supplementing multiple linear regression findings. All influencing factors follow normal or near-normal unimodal distributions and pass homogeneity of variance tests.

2.2.2 Multiple Linear Regression Results The adjusted R^2 is 0.344, indicating that influencing factors collectively explain 34.4% of BC index variation, meeting research requirements (Table 3). From the factor analysis (Table 4), slope, elevation variation coefficient, terrain relief, and surface incision depth show VIF > 10 and are not significantly correlated with BC index ($P < 0.05$), thus being removed from subsequent regression tree verification.

Factors significantly correlated with BC index include elevation and water resource availability. Elevation shows significant positive correlation with BC index—higher elevation corresponds to higher BC index, meaning settlement shapes gradually transition from clustered blocks to linear forms as elevation increases. Water resource availability shows overall positive correlation with BC index, though the trend is not pronounced.

2.2.3 Regression Tree Results and Factor Mechanisms Based on multiple linear regression results, elevation, area, curvature, transportation accessibility, water resource availability, population, and clan concept were selected as influencing factors. The sample was divided into training (70%) and test (30%) sets. Comparing root mean square errors (RMSE), the regression tree was pruned in R (Fig. 5). The elliptical boxes show each influencing factor’ s importance for settlement BC index, with higher positions indicating greater influence. Elevation and water resource availability significantly affect BC index, consistent with multiple linear regression results.

Elevation strongly correlates with terrain, which directly influences settlement shape types. Higher elevations generally correspond to ridge tops with poor terrain conditions and lack of large open areas, forcing residential points to distribute along roads and resulting in higher BC indices. Lower elevation areas include northern river beaches and river plain regions. River beach areas have flat terrain and high water availability, tending toward clustered block shapes with low BC indices. Due to large irrigable farmland areas and higher per capita income, these become regions with the largest settlement scale expansion. River plain areas are where high-grade highways are distributed, with more linear road sections compared to circular rural roads near ridge tops, resulting in more compact residential distributions or large nodes that easily form ribbon rectangle or dumbbell shapes.

Compared with multiple linear regression, the regression tree reveals that water resource availability’ s impact on BC index is non-linear and not simply positive. When settlement elevation is below 883.57 m, water availability has minimal impact on BC index, primarily affecting high-altitude settlements. As water availability increases in high-altitude settlements, BC index decreases, indicating more compact shapes. The region’ s water resources are unevenly distributed—rivers are mainly in low-altitude areas with little availability difference among settlements, resulting in minimal shape impact. High-altitude areas primarily rely on reservoirs with uneven distribution, creating large availability differences. Thus, increased water availability in high-altitude areas tends to improve settlement shape compactness.

Settlement area also affects BC index non-linearly. When settlement area is small (<0.02 km^2), BC index values are small as small settlements generally appear as scattered points. As area increases, BC index initially decreases because expansion fills internal holes, transforming shapes from scattered to clustered blocks. When settlement area reaches 0.036 km^2, BC index increases again as shapes develop into ribbon forms. This reveals the region' s rural settlement expansion pattern: small settlements don' t expand uniformly in all directions but extend along one or multiple directions. After reaching a certain scale, internal holes are gradually filled and BC index decreases. However, due to the region's ridge-dominated terrain, this pattern cannot continue indefinitely, and BC index rises again as settlements expand outward.

3 Discussion

The Alpha Shape algorithm calculates planar contours of scattered points without considering elevation' s impact on settlement shape. In actual settlement distributions, special cases may exist where residential patches are close in planar distance but differ significantly in elevation. From an external space perspective, these residential points cannot be considered as a whole. Additionally, this study uses Long Town as the research object with a limited number of rural settlements, resulting in a relatively small sample size for multiple linear regression and regression tree analysis. Future research should use stratified sampling across the loess hilly-gully region of northern Shaanxi to increase sample size and representativeness.

For policy formulation, this study provides references for delineating settlement living space boundaries. Planning settlement living space requires first determining boundaries before planning residential spatial layout and area. Using 100 m as the radius considers both social connections between buildings and spatial distance requirements, effectively extracting settlement boundaries. For other regions, this distance may need adjustment—for example, in plain areas, the radius should be much larger than 100 m. For settlements with concentrated residential distributions, determined living space boundaries can serve as a basis for controlling building sprawl and guiding intensive settlement expansion. For scattered, poorly centralized settlements, delineating living space boundaries can identify development zones and guide development toward multi-cluster "bead-shaped" settlements. For completely dispersed settlements, multiple settlement contour areas can identify settlement centers, guiding distant residential points to relocate toward centers.

4 Conclusions

Using rural settlements in Long Town, Mizhi County as examples, this study employed the Alpha Shape algorithm to extract boundaries of dispersed rural settlements, used the Boyce-Clark index to classify shape types, and combined multiple linear regression with regression tree analysis to examine influencing factors. The conclusions are:

1) The Alpha Shape algorithm demonstrates good performance in extracting

settlement shapes with moderate distribution distances (patch average spacing <135 m), effectively summarizing the morphological characteristics of 76.1% of settlements in the study area. With a rolling radius of 100 m, 76.1% of settlements show clear contours, including 44.8% with single contours and 31.3% with double contours.

2) When overall settlement patch spacing is similar, the number of contour surfaces extracted by the Alpha Shape algorithm is primarily affected by the standard deviation of patch spacing. Larger standard deviations indicate greater spacing fluctuations and more contour surfaces.

3) Settlement shapes in the study area can be classified into five types: block rectangle and its variants, extension shape, bead and dumbbell shape, ribbon rectangle and its combinations, and linear shape, with BC index ranges of 17.032–33.032, 37.438–53.288, 55.775–70.644, 78.256–99.868, and >100, respectively. Double-contour settlements mainly represent combinations of these shapes.

4) Multiple linear regression and regression tree results show that elevation has the greatest influence on settlement shape, with a significant positive correlation with BC index—higher elevation corresponds to higher BC index and lower shape compactness. Water resource availability and settlement area show non-linear relationships with BC index. When elevation exceeds 883.57 m, water availability negatively correlates with BC index —higher water availability corresponds to lower BC index and more compact shapes. When settlement area is less than 0.02 km^2, area and BC index are negatively correlated; when area exceeds 0.036 km^2, they are positively correlated.

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Note: Figure translations are in progress. See original paper for figures.