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The aim of this study was to develop a comprehensive index system based on remote sensing (RS) and geographic information system (GIS) techniques to evaluate the status quo of ecological security in the farming–pastoral zone of northern China, for the purpose of facilitating sustainable development in ecotone regions. Taking a typical transitional piedmont region with farming–pastoral production mode as a case study area, the region's present ecological security situation was evaluated by constructing an index system with 3 types of indicators. These indicators were: 1) vegetation growth, measured by the decadal difference in the normalized difference vegetation index (NDVI); 2) change in landscape patterns, measured by the deviation of present from potential landscapes; and 3) severity of soil erosion, measured by organic matter content in topsoil. Data for the indicators, derived from RS images, historical maps, field surveys, and archival materials, were all mapped with the aid of a digital elevation model (DEM), according to their conjugation relationships. The results were obtained by classifying different combinations of elements in an index matrix of 3 indicators by means of mapping. The final results show that nearly the entire study area was in a condition ranging from somewhat insecure (SIN) to insecure (INS), with an average score of 3.46 in a 5-grade range, indicating declining ecological security. The situation was better in the farming–pastoral district. The whole region needs to adjust its production modes to learn from practices in the farming–pastoral district, in order to alleviate deterioration and improve ecological security in the region.

Keywords: *Ecological security; land use/cover change; landscape degradation; NDVI; remote sensing; GIS; Inner Mongolia; China.*

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Introduction

Zhalute Banner (county), Inner Mongolian Autonomous Region, is located in a vast ecotone or transitional zone between the farming and pastoral regions in northern China. In recent decades the land use/cover in the region has changed greatly due to overgrazing and/or reclamation of grasslands, rapid population growth, common property grazing, and settlement of nomadic herders—the results of ecologically unfriendly policies and regulations. These changes have caused serious local ecological damage (Wang et al 1996; Wang et al 1999; Shi and Kang 2000; Kang et al 2002). Degradation of vegetation, pasture deterioration, land desertification, accelerated soil erosion, and saline alkalinization are among the adverse impacts threatening the ecological security of the Banner (Kang et al 2000).

To reverse the trend of ecological damage and promote sustainable development in the region, priority must be given to measures such as cessation of unsustainable grassland reclamation, containing of the stocking rate within the carrying capacity on pastures, and restoring of steppe vegetation. To achieve the goal of ecological restoration, an evaluation of Zhalute Banner's current ecological security situation must be carried out as a first step. This requires construction of an effective and comprehensive evaluation system as an operational guide. The present article explores the current condition of ecological security in Zhalute Banner as a case study. We expect the study to contribute to the theory and methodology of ecological security.

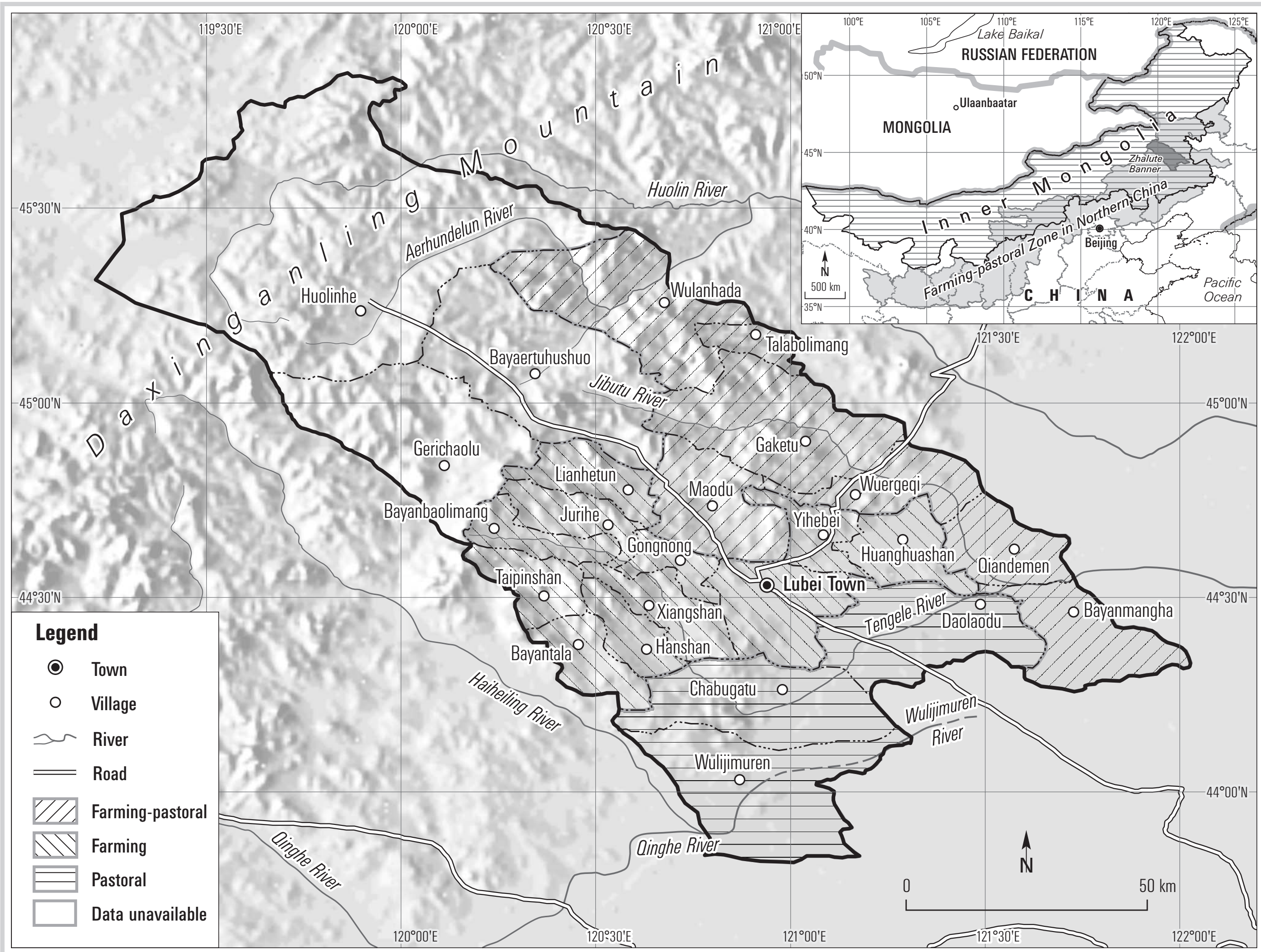
Research hypothesis

Ecological security is defined as a goal of stakeholders to create conditions such that the physical surroundings of a community provide for the needs of its inhabitants without diminishing its natural stock (Rogers 1997). In other words, ecological security refers to the undamaged or unthreatened conditions of a living space that constitutes an environment for regional development (Qu 2002). "The insecure environment represented by degraded environmental quality and depleted natural resources—very often caused by human overexploitation of nature—will weaken or even damage the sustainable socioeconomic development of a region" (Qu 2002). Hence the key to maintaining good ecological security conditions in a region lies in harmonious human coexistence with nature and few adverse impacts on the environment resulting from human activities. Thus evaluation of ecological security in a region should emphasize the stability of ecological conditions and the appropriateness of human activities in that particular region. If the natural environment is in good condition and natural resources are not overexploited as a result of human activities, then the region is ecologically secure; otherwise it is insecure.

In accordance with the above hypothesis, several indices were selected for evaluation of ecological security in Zhalute Banner. The evaluation index system was constructed on the basis of the following points:

- A region is most ecologically secure when the environment is maintained in its natural state. For example, land covered with original vegetation, even in a very severe environment, is regarded as ecologically

FIGURE 1 Map of the study area: Zhalute Banner, Inner Mongolian Autonomous Region, China. (Map by Andreas Brodbeck)



secure as long as it is not affected by human activities.

- Appropriate forms of land use, such as crop farming with adequate water and favorable soil conditions, or animal stocking within the limits of livestock carrying capacity, have little adverse impact on a region's ecological security.
- Ecological security can be measured by such indicators as the degree of soil erosion, the condition of vegetation growth, and the deviation of existing landscape patterns from original patterns. The key indicators for deviation are retrogressive vegetation succession and land use/cover change.

Methodology

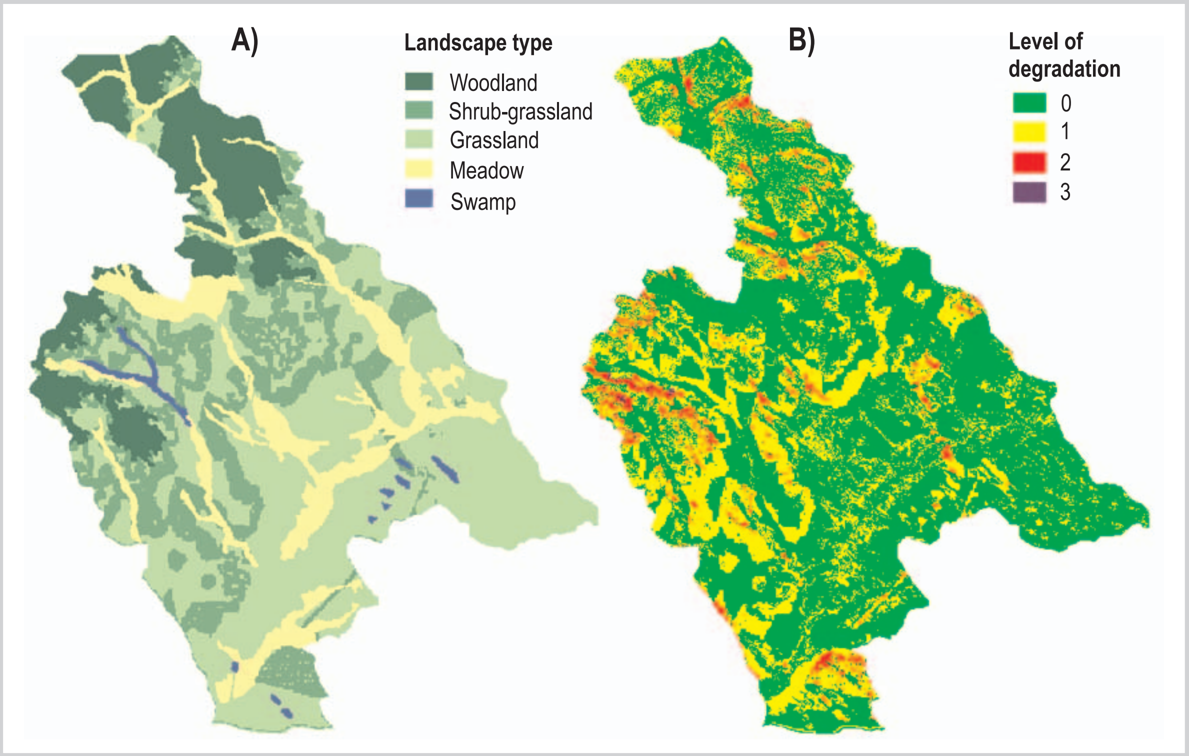
Sampling area

Zhalute Banner is located in the transitional piedmont zone, between the Inner Mongolian Plateau and Songliao Plain. Limited by the framework of remote sensing (RS) data, the sampling area for this case study was concentrated mainly in the middle to southern parts of the Banner, covering an area of 11,783.97 km^2. The elevation ranges from 1444.2 m in the northwest to 179.3 m in the southeast (Figure 1). Annual precipitation varies from 421.5 mm to 387.6 mm, and annual mean temperatures from 0.1°C to 5.8°C, along the gradient of elevation. Vegetation and soil also show a gradient with elevation. The land in the northern part is covered with open forests (woodland) and shrub–grassland, growing on dark Chernozem. In the middle to southern parts, grassland prevails, growing on Castanozem (OSSTZB 1987). Depending on the mode of production—crop farming or animal husbandry—and local tradition and customs, the sampling area was divided into 3 "districts:" a farming district, located mainly in the middle and western parts; a farming–pastoral district, mainly in the middle and eastern parts; and a pastoral district, mainly on the southern plain (Figure 1).

Sampling method

To verify the precision of RS image interpretation, field investigations were conducted in July and August of 2000 in the sampling area. The quadrat method was

FIGURES 2A AND B 2A: Potential landscape pattern in the study area.
2B: Landscape degradation in the study area, showing the level of degradation and spatial pattern of present landscape type in contrast to potential pattern. (Maps by authors)



applied to survey grassland and shrubland communities for identification of the community type, with quadrats of 1 m × 1 m and 4 m × 4 m, respectively. Ninety-one quadrats were recorded with 4 to 7 times on average for each community type. GPS instruments were used to determine the position of each quadrat on the spot.

In the meantime, the surface soil under each investigated community was also sampled from a layer 5–20 cm below ground. Two or 3 soil samples were collected for each community type, for a total of 53 samples. The organic matter content was analyzed in the laboratory to determine the overall nutrient condition of the soil.

The NDVI index as a representation of vegetation growth

The NDVI (Normalized Difference Vegetation Index) data for the study area, derived from the NOAA/AVHRR images resolved at 1 km^2 in July 1999 and July 1988, were used to indicate temporal and spatial changes in vegetation growth. The NDVI is based on the difference between the maximum absorption of radiation in the red (due to chlorophyll pigments) vs the maximum reflection of radiation in the near infrared or NIR (due to leaf cellular structure), and the fact that soil spectra, lacking these mechanisms, typically do not show such a dramatic spectral difference (Jensen 1996). The NDVI values ranged from –1 to +1: typically bare soils, 0.08 – 0.1; desert vegetation, 0.1 – 0.3; flourishing vegetation, 0.4 – 0.7; water and barren lands, about –0.3 (Goward et al 1985; Konecny 2003).

July is the peak growing season for most plants in the study area, and both 1999 and 1988 were years with normal weather conditions in terms of climatic fluctuation (Kang et al 2002). Thus the NDVIs for these 2 years, one recent and the other a decade earlier, are a good representation of conditions for vegetation growth (Goward et al 1991; Eastwood et al 1997; Xu et al 2002). Changes in the vegetation are revealed by a comparison of NDVI for the 2 years (Qi et al 2000; Leprieur et al 2000).

To simplify the comparison, a new NDVI image was generated from the NDVI value for 1999, minus the value for 1988, by overlaying the images of 1999 and 1988. Thus an NDVI value of zero was defined as the threshold. A value around zero for a pixel of the new image indicates no change in the vegetation. A value significantly greater than zero (defined here as >0.05) indicates improved vegetation. Similarly, if the value is significantly less than zero (defined as <–0.05), then the vegetation shown on the pixel is regarded as degraded or even destroyed.

Assessment of deviation of present land use/cover from the original

This process was divided into three steps:

Step 1: Mapping of present land use/cover distribution
The Landsat–TM image (track 121/29, pixel resolution 30 m × 30 m) for July 1997 was used to map the present land use/cover, interpreted by ERDAS IMAGINE GIS software (Version 8.5; Kerr and Cihlar 2003). Different land use/cover types were interpreted and their spatial distribution was delineated according to the national land use/cover classification system for China (Kang et

al 2002). Interpretation of the remote sensing image was geo-referenced and verified with the field survey data described above.

Step 2: Restoration of original landscape and potential vegetation
The old topographic maps (scale 1:100,000), drawn by the MSCBPLA (1950) from aerial photographs taken by Japanese troops in the early 1940s, were applied to restore the original landscape with the aid of a digital elevation model (DEM; scale 1:100,000) for the case study area, according to the general conjugate relationship between vegetation and topography (elevation, slope, and aspect) and river system (Wu 1980; Hoersch et al 2002). The restored potential landscape pattern is shown in Figure 2A.

Step 3: Gradation of deviation of present land use/cover from the original landscape
The digitalized map, showing the deviation of present land use/cover from the original landscape, was obtained by overlaying the present land use/cover map drawn from Step 1 with the restored potential landscape map from Step 2.

Landscape degeneration in Zhalute Banner, caused mainly by overgrazing and over-reclamation of crops on pastures or deep slopes, followed the retrogressive vegetation succession (Wang et al 1996):

Open forest or woodland ⇒ brushwood or shrub grassland ⇒ grassland ⇒ desert

By comparing the present natural land cover with the restored potential landscape through map overlaying, deviation from the original condition was classified into 4 categories that parallel the retrogressive vegetation succession:

0: no change between the present and the original;
1: land cover degraded to the next stage of degeneration;
2: further degradation to the next stage; and
3: the final stage of retrogressive succession (Figure 2B).

For example, woodland that had degraded to shrub–grassland was ranked 1, as was shrub–grassland that had degraded to grassland, or grassland that had degraded to desert. By contrast, woodland that had degraded to grassland, or shrub–grassland that had degraded to desert was ranked 2. Rank 3, the highest deviation, occurred where woodland had changed to desert.

The change from previous natural landscape to present farmland is complicated, as this type of change cannot simply be regarded as doing harm to regional ecological security. Human agricultural activity, as long as it is moderate and appropriate, may even benefit regional sustainable development and ecological security. For example, farmland with an adequate water supply (annual rainfall >400 mm and drainage slope degree <5°) can be regarded as ecologically secure. In this case it was ranked 0. Cultivation on slopes >5° or with rainfall <400 mm, however, not only accelerates soil erosion but also causes water shortage that affects sustained yields in subsequent years. Reclamation under such conditions should be considered ecologically insecure. This case was ranked 1, because it can be restored to a comparatively secure state by halting agricultural activity for about 10 years (Wang et al 1996).

Evaluation of soil erosion classified by organic matter content in surface soil

Degradation of the landscape not only impedes vegetation growth; it also diminishes soil fertility. In other words, where vegetation degrades, soil undergoes heavier erosion, with a consequently greater loss of soil organic matter. This means that the content of organic matter in soil can be used as an indirect indicator of soil erosion and an indicator of regional ecological security.

Accordingly, the isogram showing spatial distribution of organic matter in surface soil was mapped (Figure 3), using the Kriging method integrated into GIS software (Surfer 7.0 and MapInfo 6.0; Cressie 1990, 1991; Deutsch and Journel 1992). Three grades of soil erosion were classified on the basis of average organic matter content in surface soil (OSSTZB 1987), namely:

Light, if >3.5%;
Moderate, if between 2.0% and 3.5%;
Heavy, if <2.0%.

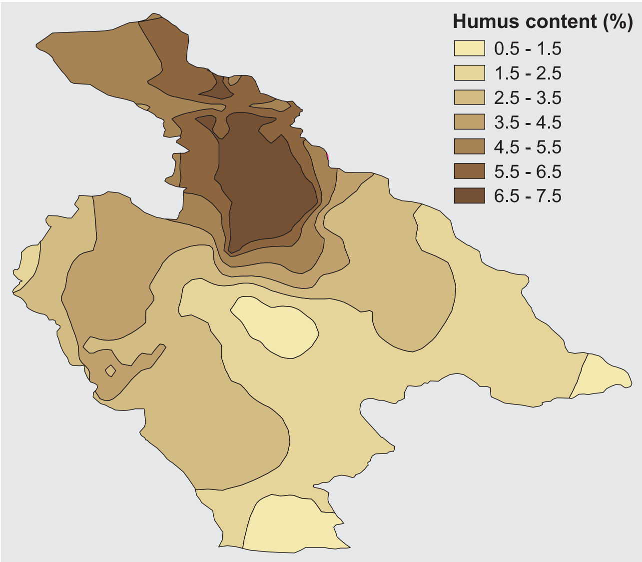


FIGURE 3 Spatial distribution of surface soil organic matter content in the area of the case study. (Map by authors)

Index matrix of ecological security

By combining the above results, a general matrix of indices was constructed to evaluate the status of ecological security for the area of the case study. This was done in a process that involved image overlaying, using the digital maps drawn above:

Step 1: Establishing matrices of landscape deviation, vegetation growth, and soil erosion respectively, ie:

Matrix of landscape deviation:

$$\mathbf{X} = \begin{bmatrix} X_1 & X_2 & X_3 & X_4 \end{bmatrix}^T;$$

Matrix of condition of vegetation growth:

$$\mathbf{Y} = \begin{bmatrix} Y_1 & Y_2 & Y_3 \end{bmatrix}^T;$$

Matrix of status of soil erosion:

$$\mathbf{Z} = \begin{bmatrix} Z_1 & Z_2 & Z_3 \end{bmatrix}^T.$$

Step 2: Combining the above three matrices into a Combination Matrix:

$$\mathbf{XYZ} = \begin{bmatrix} X_1Y_1Z_1 & X_1Y_1Z_2 & X_1Y_1Z_3 & X_1Y_2Z_1 & X_1Y_2Z_2 & X_1Y_2Z_3 & X_1Y_3Z_1 & X_1Y_3Z_2 & X_1Y_3Z_3 \\ X_2Y_1Z_1 & X_2Y_1Z_2 & X_2Y_1Z_3 & X_2Y_2Z_1 & X_2Y_2Z_2 & X_2Y_2Z_3 & X_2Y_3Z_1 & X_2Y_3Z_2 & X_2Y_3Z_3 \\ X_3Y_1Z_1 & X_3Y_1Z_2 & X_3Y_1Z_3 & X_3Y_2Z_1 & X_3Y_2Z_2 & X_3Y_2Z_3 & X_3Y_3Z_1 & X_3Y_3Z_2 & X_3Y_3Z_3 \\ X_4Y_1Z_1 & X_4Y_1Z_2 & X_4Y_1Z_3 & X_4Y_2Z_1 & X_4Y_2Z_2 & X_4Y_2Z_3 & X_4Y_3Z_1 & X_4Y_3Z_2 & X_4Y_3Z_3 \end{bmatrix}.$$

Step 3: Establishing a 5-rank evaluation system: Rank 1, ecologically secure (SEC); Rank 2, relatively secure (RSE); Rank 3, relatively insecure (RIN); Rank 4, insecure (INS); and Rank 5, extremely insecure (EIN; see elaboration in Table 1). In addition, the status of ecological security in the case study area was evaluated with matrix data, pixel by pixel.

Results and discussion

General evaluation of case study area

Integrated evaluation of ecological security in the case study area is shown in Figure 4. Statistically, about 0.96% of the land was ranked SEC, sparsely scattered in the northern mountainous or hillside region; 2.37% was ranked RSE, mainly occurring around the first rank areas; 46.77% was ranked RIN, mostly distributed in the northern to middle regions; and nearly half (49.89% of the land in the area) was ranked INS, situated in the southern area. Only a small area (0.06%) was ranked EIN, and is difficult to see on the map. Generally speaking, the further north the location, the better the situation.

Assigning 1, 2, 3, 4 and 5 to grade ranks SEC, RSE, RIN, INS and EIN respectively, and weighting each grade by its areal percentage using the formula

$$S = \sum_{i=1}^{5} G_i \cdot A_i \,,$$

where S represents the general score of ecological security for the area, G_i the score of grade i and A_i the areal percentage, the general level of ecological security for the entire study area was INS, with an average of 3.46. This means that restoration of the ecological environment in the case study area was an urgent and already necessary task; more attention should be paid to protection of the natural landscape.

Evaluation of different districts

As for the evaluation of the 3 major land use districts, the results showed that the pastoral, farming–pastoral and farming districts were almost at the same level, though they varied from district to district, averaging 3.55, 3.29 and 3.51 respectively (Table 2). Further examination of the relative percentages, however, revealed little difference among the districts. For example, more than half of the pixels (58.3%) in the pastoral district fell into the INS category, while this category was relatively smaller in the farming–pastoral district (37.4%). With reference to the relative percentages in the other 2 categories, SEC and RSE, it can be concluded that the situation in the farming–pastoral district was the best, though still rather unsatisfactory. Another phenomenon is that in each district there were a few pixels that fell into the SEC category, though the percentage was small (Table 2). It can be inferred from this that the case study area, Zhalute Banner, is indeed a transitional zone that is well suited for combining farming with pastoral production. As long as human activity is within the ecological carrying capacity, any district can maintain its ecological status. It must be mentioned that a few pixels (about 0.2% in the farming district) already fall into the EIN category, indicating a very serious problem, perhaps because the agricultural district was often densely populated.

Ecological security is closely related to the mode of production in the case study area. Traditional and/or intensive production methods not only cause environmental deterioration, thus reducing ecological security, but also hinder regional socioeconomic development as a result. To reverse the serious situation in the area, transformation of production modes should become the priority for regional development. In the farming district, highly productive farmland with terraces and irrigation systems should be developed to raise production per unit, while reducing soil erosion and water loss. In the pastoral district, overgrazing on pastures should be halted and the population that exceeds carrying capacity, along with their surplus animals, should be relocated to other districts to alleviate the ecological

TABLE 1 Integrated gradation of ecological security for the case study area.

Level of degradation[a)]	Degree of ecological security[b)]	Level of degradation and description of landscape characteristics
I (dark green)	SEC (secure)	All three indices in the highest category; no deviation from former landscape pattern; high vegetation cover and only slight soil erosion.
II (light green)	RSE (relatively secure)	Two indices in the highest category and the third in any except the lowest, including two subgroups: one with no landscape deviation but relatively low vegetation cover or relatively serious soil erosion; the other with some landscape deviation but vegetation cover still high or only slight soil erosion; both showing only slight landscape degradation. Without further human activity, this area can be restored to its original state over a short period.
III (yellow)	RIN (relatively insecure)	Two indices in the highest but the other in the lowest category, or only one index in the highest and the other two either in the middle or only one in the lowest; or all three indices in the middle categories. Half of the combinations belonged to this largest group. Ecological security was unsatisfactory but balance could still be maintained in the area for a while. Warning: regional ecological security will ultimately be affected if human activities are inappropriate; land use intensity in the region should be reduced.
IV (orange)	INS (insecure)	Two indices in the lowest and the third in any category; or one in the lowest but the other two in any category except the highest. Typical state for high alert for regional ecological crisis, caused by highly inappropriate human activities. Local ecosystem has been severely degraded and should be restored or reconstructed urgently with human effort.
V (red)	EIN (extremely insecure)	All three indices in the lowest categories. Area has undergone ecological disruption, and landscape cannot be restored to original state, even over a rather long period of time. Currently uninhabitable for human beings.

[a)] Color scale: compare with Figure 4.
[b)] Mapping of degrees: compare with Figure 4.

burden in the district. Moreover, in the farming–pastoral district, attention must be given to the promotion of fodder raising and shed raising of livestock on farmland formerly used for grain production, under comparatively better ecological conditions but with lower crop productivity. Small bank loans guaranteed by the local government might be needed to make a good start on this transformation.

Ecological security relating to retrogressive vegetation succession

Along with retrogressive succession of natural vegetation and landscape degeneration, the possibility of ecological insecurity threatening the area is also rapidly increasing. This is because vegetation is closely related to its habitat, and vegetation degradation will surely result in unfavorable environmental change related to the vegetation itself, such as soil erosion and water loss. The greater the deviation from the original landscape through retrogressive vegetation succession, the more ecologically insecure the area becomes. Thus the conditions of ecological security in an area can be calculated through the following steps: surveying the present vegetation and landscape in the area; virtually restoring the potential vegetation or original landscape; making a comparison between the present and the original; and drawing a conclusion of "ecologically secure" if current

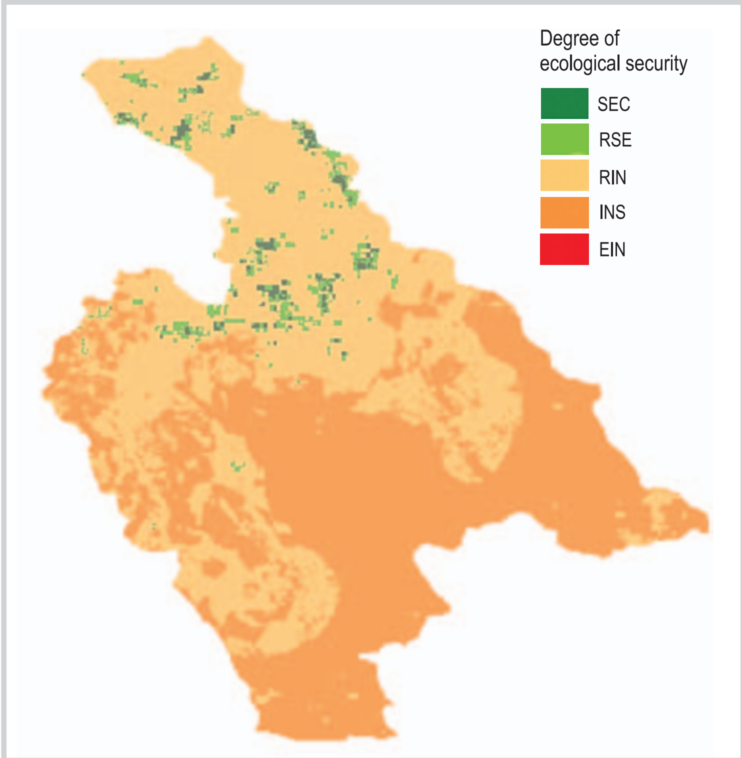


FIGURE 4 Spatial distribution of degrees of ecological security in the study area. SEC: secure; RSE: relatively secure; RIN: relatively insecure; INS: Insecure; and EIN: extremely insecure. (Map by authors)

TABLE 2 Comparative assessment of ecological security in different agricultural areas, based on integrated gradation.

District	Area (%)					Score
	I Secure (SEC)	II Relatively secure (RSE)	III Relatively insecure (RIN)	IV Insecure (INS)	V Extremely insecure (EIN)	
Pastoral	0.34	0.61	14.30	21.36	0.00	3.55
Farming–pastoral	0.57	1.37	17.27	11.46	0.00	3.29
Farming	0.06	0.39	15.21	17.07	0.06	3.51
Total	**0.96**	**2.37**	**46.77**	**49.89**	**0.06**	**3.46**

conditions are similar to, remain unchanged, or are better than the original. Otherwise, "ecologically insecure" is the proper ranking if current conditions are much worse than original conditions.

Application of the evaluation index system

Based on 3 main indicators that describe ecological security conditions in a region, the evaluation index system was constructed by means of a set of digital images. The indices were quantified and synthetically corrected according to the conjugate relationship between landform and vegetation distribution, using the DEM model for the region, pixel by pixel (Hoersch et al 2002; Shen 2002). Judging from the representativeness of indices and the quantification process, this evaluation index system could be applied with confidence and promise to other areas in the farming–pastoral zone, or even to regions beyond this zone, if a few revisions in indices were made in accordance with local ecological conditions.

Integrating combinations of indices

Ranking the ecological security level, or rationalizing the gradation of combinations of indices, is a somewhat subjective and arbitrary process. Very often it is rather difficult to figure out which rank a particular combination of indices should be in, especially when there is a contrast in the index scores within the combination, eg where one is the highest and the other is the lowest.

In this study, if a combination had one index score in the lowest category, then it was ranked no higher than RIN, the third rank. And if a combination had 2 scores in the lowest category, then it was ranked lower than the third rank, ie INS, the fourth rank. We can imagine that if in a pixel representing place the vegetation was poorly damaged, or soil erosion was serious, or landscape was degraded to the worst stage, the ecological security condition would not be good, although other indices might be quite good or even very good. Similarly, if 2 indices had the lowest scores, meaning 2 aspects of ecological security were degraded to the most severe degree, that particular place must be undergoing an ecological crisis.

It must be mentioned that we did not consider weighting among the 3 indices concerned, as this is still an arbitrary process that could lead to complicated evaluation results. The first consideration of this case study was to develop an approach for comprehensive evaluation of regional ecological security. In this sense our purpose has been largely fulfilled.

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