Journal of Civil Engineering, Science and Technology
Volume 17, Issue 1, April 2026, 105-120

ANALYSIS OF THE SPATIAL-TEMPORAL STRUCTURE OF LAND USE AND LAND COVER IN SUNAN YUGU AUTONOMOUS COUNTY, GANSU

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Date received: 14/12/2025 Date accepted: 11/03/2026
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DOI: 10.33736/jcest.11753.2026

Abstract —The Qilian Mountains serve as a vital ecological security barrier in China, with Sunan Yugu Autonomous County playing a crucial role in glacier and water conservation. Land use and land cover changes in this region significantly impact water resources, biodiversity, and ecosystem stability, necessitating a comprehensive understanding of their spatio-temporal dynamics. Existing studies had primarily focused on short-term changes or individual environmental drivers, and thus there is a gap in long-term integrated analysis considering topographical and spatial-temporal influences. To address this gap, this study utilized Landsat TM imagery (1985–2015), Digital Elevation Model-derived slope data, and field surveys to examine the long-term dynamics in Sunan County. The findings established a relatively stable distribution of woodland and grassland, averaging 14.56% and 56.77% of the total area, respectively, but also indicated a continuous decline in grassland and an expansion of arable land due to grassland conversion. Forests were primarily found on slopes of 15–25°, while grasslands were concentrated along riverbanks on slopes of rivers below the sixth level. Grassland loss was most pronounced on gentle slopes of <15° from 1995 to 2005 and on steeper slopes of >25° after 2005, while arable land expanded along river systems, notably on both steep and gentle slopes, by 107.51 km². The study further revealed that the Beida River played a dominant role in land-use and land-cover changes due to its large watershed area, while other watersheds contributed moderately. These findings emphasized the need for slope-based ecological management and watershed conservation to mitigate land degradation, enhance resilience to climate change and promote sustainable land use and land cover.

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***Keywords*:** land use and land cover; spatial-temporal structure analysis; slope; watershed; Sunan County

1.0 INTRODUCTION

The spatiotemporal structure changes of land use and land cover (LULC) are key indicators of ecological and environmental transformations, significantly impacting natural resources, biodiversity, and land productivity [1, 2]. In 1995, the International Geosphere-Biosphere Programme and the International Human Dimensions Programme on Global Environmental Change flagged the characteristics, drivers of LULC changes, and the correlations between LULC and its change agents as their core focus [3, 4]. Mountainous regions, especially those with undulating terrain and delicate ecosystems, are particularly susceptible to both natural and anthropogenic influences [5, 6]. However, climate change and human activities have intensified land degradation and altered land use patterns, creating ecological imbalance [7, 8, 9, 10].
The Qilian Mountains constitute a critical component of the country's plateau ecological security barrier, regulating regional water cycles, sustaining biodiversity, and mitigating desertification [11, 12, 13]. Within this region, Gansu's Sunan Yugu Autonomous County belongs to the National Qilian Mountain Glacier and Water Conservation Ecological Functional Zone. The county plays a significant role in glacier and water conservation, influencing the stability of major watersheds such as the Heihe, Shiyang, and Shule Rivers [14]. Its ecological environment has undergone continuous deterioration over an extended period, attributed to both weather conditions and human activities [15].

Recent studies have highlighted that spatial-temporal changes in arid and mountainous regions were influenced by topographical landscape, structure and socio-economic factors [16, 17, 18]. Remote sensing and Geospatial

Information System-based approaches had been widely applied to quantify land-use changes, particularly in high-altitude environments where accessibility was limited [19]. Research indicated that vegetation degradation, cropland expansion, and urbanization were the primary drivers of land transformation in China's sensitive ecological zones [20, 21].

As research progresses, the study of spatial-temporal land changes has encompassed mechanisms of change, process evolution, sustainable use, simulation prediction, and other areas [22, 12]. Most importantly, the quantitative and spatial distribution characteristics of changes, along with structural prediction and optimization had garnered significant attention [23]. Several studies had emphasized that slope and watershed factors played a crucial role in determining the suitability of land resources. For instance, forests were typically found on moderate slopes (15–25°), whereas croplands expanded in lowland river basins [24, 25]. Moreover, studies on land resource use in northwestern China suggested that grassland degradation was closely linked to overgrazing, climate variability, and policy-driven land conversion [26].

The Grain for Green Project proved effective in restoring vegetation cover, though its long-term sustainability and impact on watershed dynamics continued to be of significant concern [27, 28]. While there was substantial research on policy-driven land-use spatial-temporal changes, relatively few studies had comprehensively analyzed the interactions between slope, watershed characteristics, and land-utility transformations in the Qilian Mountain region.

Despite extensive studies on spatial patterns, most research focused on short-term changes, overlooking the long-term interactions between land use and topography [29, 30]. Additionally, existing studies often emphasize policy interventions or climatic impacts but lack a spatially explicit assessment of terrain-driven land transformations [31]. In Sunan Yugu Autonomous County, where complex terrain governs land use patterns, there is a limited understanding of how slope and watershed factors regulate land utility changes over multiple decades. To address these limitations, a systematic spatial analysis is required, integrating slope, watershed characteristics, and long-term LULC trends.

To bridge these research gaps, the spatial-temporal dynamics of land utility in Sunan Yugu Autonomous County from 1985 to 2015 are initiated in this study, emphasizing the influences of spatial-temporal structure in the watersheds. This research aims to contribute to the scientific understanding of terrain-driven spatial-temporal changes, offering insights for land conservation strategies, sustainable watershed management, and climate-adaptive land use planning in ecologically fragile zones. The major objectives are to analyse the temporal and spatial evolution of LULC over a 30-year period and to assess the relationship between LULC distribution and topographical gradients (slope factors) in relation to land use transformations.

2.0 MATERIALS AND METHODS

2.1 Overview of the Study Area

Sunan County is located between N 37°28' and 39°04' and E 97°20' and 102°13', in the middle of the Hexi Corridor and north of Qilian Mountain. The county is 650 km long from east to west, approximately 120–200 km wide from north to south, and has an average elevation of 3,200 m above mean sea level. The topography is narrow and long, featuring obvious topographic changes and complex topography. There are 13 river basins in the territory with a total basin area of 21,500 km², 964 glaciers, and 33 rivers at different scales with an annual runoff of 4.3 billion m^3. Three inland rivers and their tributaries originate here, that is, the Heihe, Shiyang and Shule rivers, which are an important ecological security barrier in western China and an important water source runoff area in the Yellow River Basin, as well as a priority area for biodiversity conservation in the country [32]. The mountainous terrain, townships, and slopes in the area are shown in Figures 1 to 3, respectively.

Figure 1 Qilian mountains complex topography

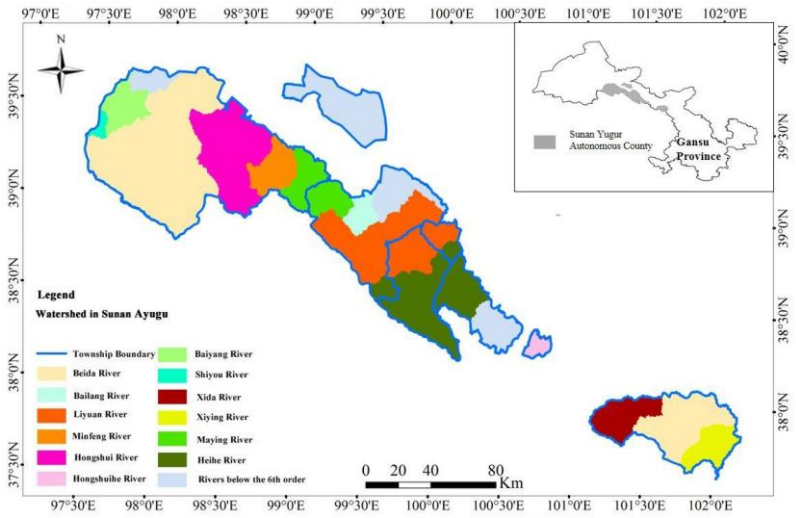

Figure 2 Major townships in Sunan County

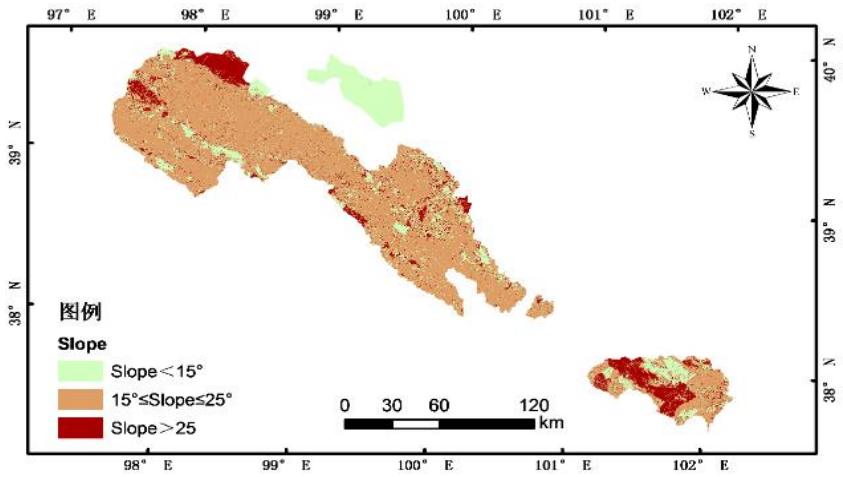

Figure 3 The slope classification map in Sunan County

2.2 Data Source and Processing

The data sources are mainly adopted from Landsat TM satellite images from 1985, 1995, 2005, and 2015 with a spatial resolution of 30 m (dataset available at https://www.earthdata.nasa.gov/) and 1:100,000 topographic maps, as well as Gansu Statistical Yearbook data from 1999 to 2009. The Earth Resources Data Analysis System software used false-colour composite images of 4, 3, and 2 bands to reflect the growth status of vegetation and the type of land cover. The basic data of LULC changes was obtained by using the Geographical Information System overlay analysis module on the fourth phase of LULC.

2.3 Research Methods

The data was analysed through ArcGIS and ERDAS software. The change characteristics and transformation process of the LULC in Sunan County from 1985 to 2015 were studied by using the LULC conversion matrix. The response process of LULC structure to slope factors and watershed distribution was studied based on slope data and the Digital Elevation Model.

2.4 Land Use and Land Cover Conversion Matrix

The LULC conversion matrix expressed the changing trend of LULC types in the study area. The mathematical expression of the conversion matrix is as shown in Equation 1.

$$S_{ij} = \{S_{11} \ \dots \ S_{1n} \ \vdots \ \ddots \ \vdots \ S_{n1} \ \dots \ S_{nn}\} \quad (1)$$

Where S is the land area, n is the number of LULC, and i and j are the converted areas of LULC types at the beginning and end of the study period. The row value of each row in the conversion matrix represents the conversion destination and size of each type of land, while the sum of the rows represents the total number of all LULC types at the beginning of the study. The column value of each column in the conversion matrix represents the source of each type of land conversion and conversion size, and the sum of the columns represents the total number of all LULC types at the end of the study period. The technical workflow of the study is presented in Figure 4.

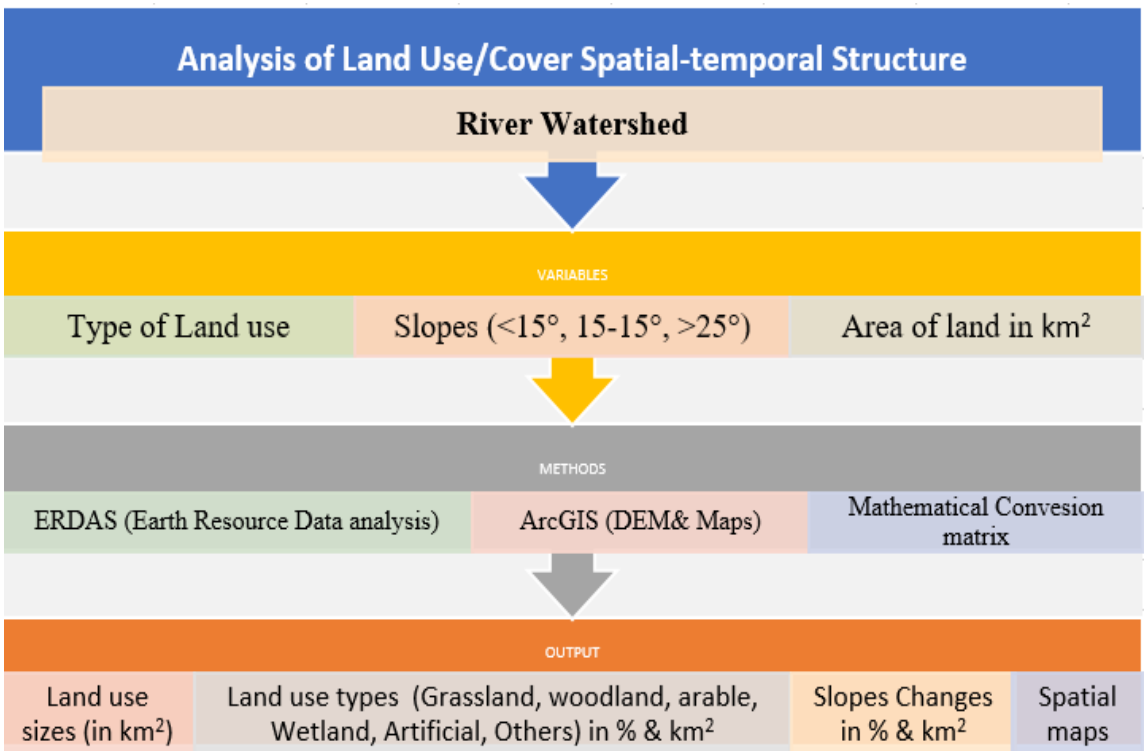

Figure 4 Technical workflow of the study

3. RESULTS AND DISCUSSION

3.1 Analysis of the Temporal and Spatial Structure of Land Use and Land Cover

The analysis established that the main types of land cover in Sunan County were grassland, woodland and others in 1985 to 1995, 1995 to 2005 and 2005 to 2015. Figures 5 to 7 show the grassland, woodland and other land covers in parts of the Sunan Yugu region of study. Figure 7 shows the source of streams from the mountainous region.

Figure 5 Grassland cover

Figure 6 Woodland cover

Figure 7 Other Land cover

The sums of these three types of areas were 98.67%, 98.60%, and 98.37%, respectively. The average total area exceeding 98% of the region, including the areas of cultivated land, wetland and artificial surface, was relatively small during the same period, which amounted to 0.12%, 0.11% and 0.11%, respectively. Since the artificial surface accounted for less than 0.12%, it therefore proved that the LULC structure that is dominated by woodland and grass cover was relatively stable. Figure 8 shows the trends in land use structure in Sunan County from 1985 to 2015.

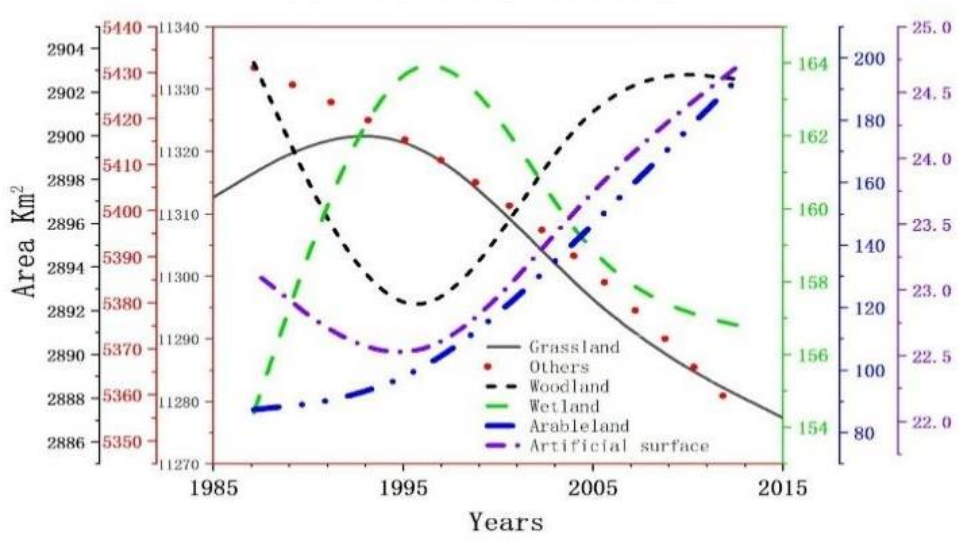

Figure 8 Land use pattern in Sunan County

In the past 30 years, as shown in Figure 8, the area of woodland suffered first a decline and then a rise, with spatial-temporal dynamic shifts. The area of grassland shows a trend of first rise and then decline; the area reduced by 35.28 km^2. Other types of areas have shown declining trends with a decrease of 75.45 km^2, which was the fastest decrease that occurred in 20 years from 1995 to 2005 and 2005 to 2015, accounting for 53.49 km^2 and 60 km^2, respectively. The area of arable land continued to increase with an increase of 107.51 km^2, which was from 87.29 km^2 in 1985 to 194.8 km^2 in 2015. This increase was the fastest during the 20-year periods from 1995 to 2005 and 2005 to 2015, increasing by 49.25 km^2 and 52.91 km^2, respectively.

The woodland was mainly distributed in the south-central part of Huangcheng Town; Kangle; Mati Tibetan, Dahe, and Qifeng Tibetan townships in the northwest part of the county. The area of woodland in these five (5) townships in 1985 accounted for 13.71%, 9.59%, 7.34%, 16.62%, and 44.32% of the total wood area,

respectively. It was also observed that the proportion of grassland area was less than 10% in Kangle, Mati Tibetan, Minhua, Baiying Mongolian Group, and Hongwansi townships. Hongwansi had almost no grassland.

Arable land was mainly distributed in Huangcheng and Mati Tibetan in the southeast and Dahe in the central and western regions. In 1985, the arable land area of these three townships accounted for 45.02%, 22.34%, and 10.28% of the total arable land area, respectively. The amount of arable land was less than 10% in Qifeng Tibetan, Kangle, Minghua, Baiyin Mongolian, and Hongwansi townships, which accounted for 6.62%, 4.86%, 7.81%, and 2.74% of the total arable land area, respectively. Hongwansi Township had the lowest at 0.36% in arable land. Other LULC types were mainly distributed in Qifeng Tibet to the west, Huangcheng to the southeast, and Minghua Township to the north. Wetlands were mainly distributed in Qifeng Tibetan in the northwest, Huangcheng in the southeast, and Dahe Township in the central and western regions. From the years 1985 to 1995, the LULC types mainly changed, with the conversion of woodland to grassland in Dahe; some grassland and other kinds of land to forestry in Qifeng Tibetan; and part of other types of land and woodland to grassland and cultivated and wetland in Huangcheng Township.

The main changes in LULC type occurred when woodland was converted to grassland in Dahe and when other types of land and grassland were converted to arable land in Minghua during the period from 1995 to 2005. The change of LULC types was mainly experienced when there was a conversion of the other types of land and grassland into arable land in Minghua Township from 2005 to 2015. The overall changes of LULC types from 1985 to 2015 were mainly due to conversion of other types of land that accounted for 64.57 km^2, and grassland accounted for 33.51 km^2, which was transformed into arable land amounting to 97.25 km^2 in Minghua Township. Figure 9 shows the arable land in the region, while Figures 10 to Figure 13 show the spatial-temporal structure changes in Sunan County from 1985 to 2015.

Figure 9 Arable Land

Figure 9 shows the windward side of the Qilian Mountains and the arable land in Huangcheng and Mati, Tibet, in the southeast, as earlier discussed. The region experienced increased immigration, settlements, and woodland conversions to cultivated lands, as clearly shown in the picture.

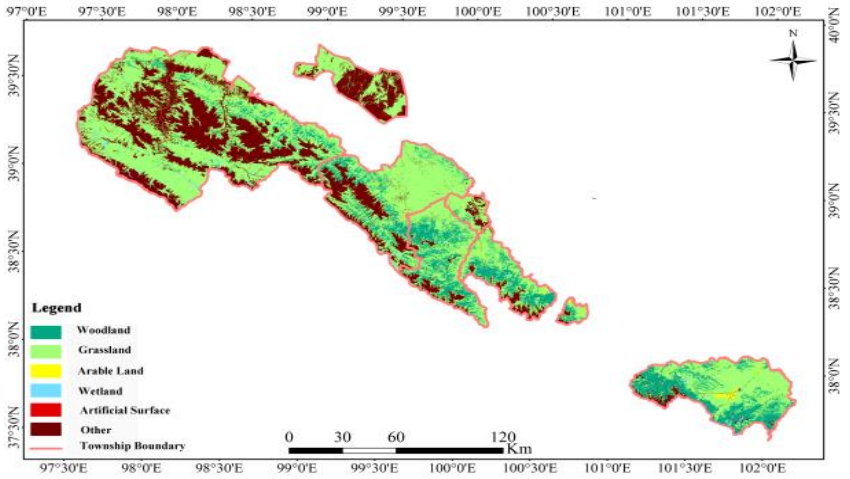

Figure 10 LULC area in the Sunan County in 1985

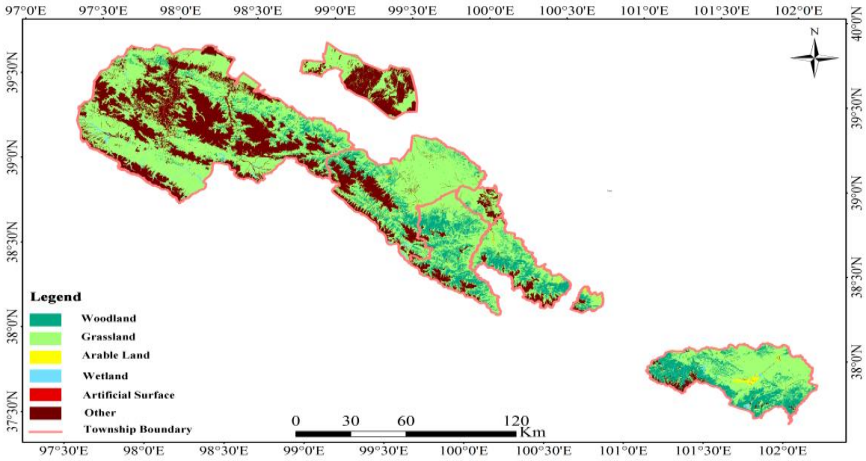

Figure 11 LULC area in the Sunan County in 1995

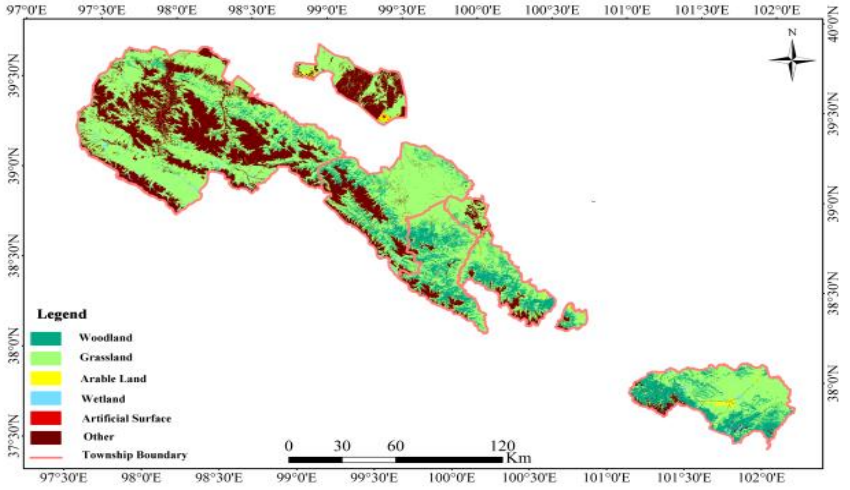

Figure 12 LULC area in the Sunan County in 2005

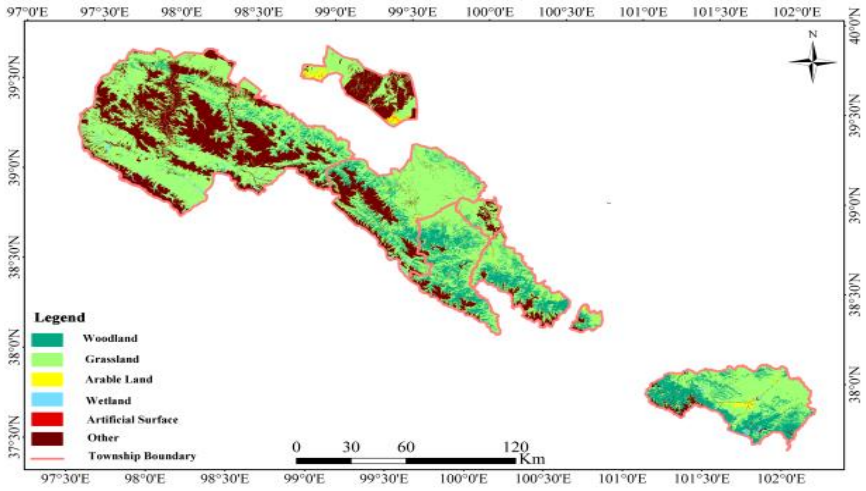

Figure 13 LULC area in the Sunan County in 2015

3.2 Analysis of Conversion Characteristics of Land Use/Cover from 1985 to 2015

As shown in Figure 10 to Figure 13, the conversion direction mainly emanated from woodland and other types of land to grassland, wetland, and arable land from 1985 to 1995. The direction of conversion from 1995 to 2005 was mainly from grassland, wetland and woodland, including other types of LULC.

The LULC conversion established that woodland was restored to the level of 1985, which was mainly converted from grassland and wetland. The increase of arable land was significant, and the artificial surface changes were not obvious; the conversion direction from 2005 to 2015 was from grassland and other types of land use to arable land. Holistically, the changes were gradual, whereby woodland, grassland and other types of land use were transformed into arable land and wetland from 1985 to 2015. In this regard, grassland decreased by 35.28 km^2, arable land increased by 107.51 km^2, wetland increased by 2.36km^2, while other types of LULC decreased by 75.45 km^2.

3.3 Response of Land Use and Land Cover Structure Changes to Slope and Watershed

The LULC area trends for grassland and arable land for slopes of <15°, 15-25° and >25° from the years 1985 to 2015 are presented in Figure 14 and Figure 15. For grassland, the slope areas for the mentioned three slope categories were at 2,411 km^2, 7358.2 km^2, and 1630.7 km^2, and accounting for 21.15%, 64.55%, and 14.30% of total area, respectively.

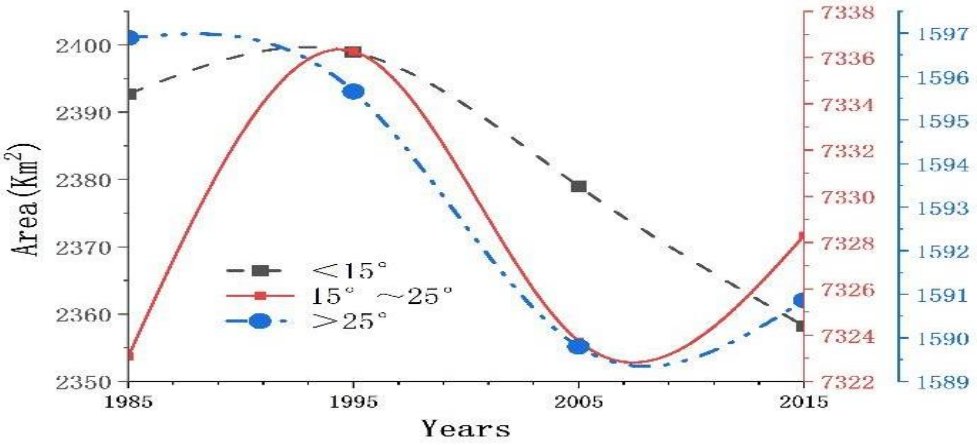

Figure 14 Grassland changes for different slopes from 1985 to 2015

From Figure 14, the LULC types were mainly distributed on slopes of 15-25°, which increased from 1985 to 1995, reduced marginally from 1995 to 2005, and thereafter had an upward trend. However, as shown in Figure 15, the proportions of arable land were slightly different from 1985 to 2015; the average proportions of arable land in slopes of <15°, 15-25°, and >25° were 42.25%, 27.05%, and 30.70%, respectively, which shows that arable land and grassland were mainly distributed in slopes of 15°-15-25°.

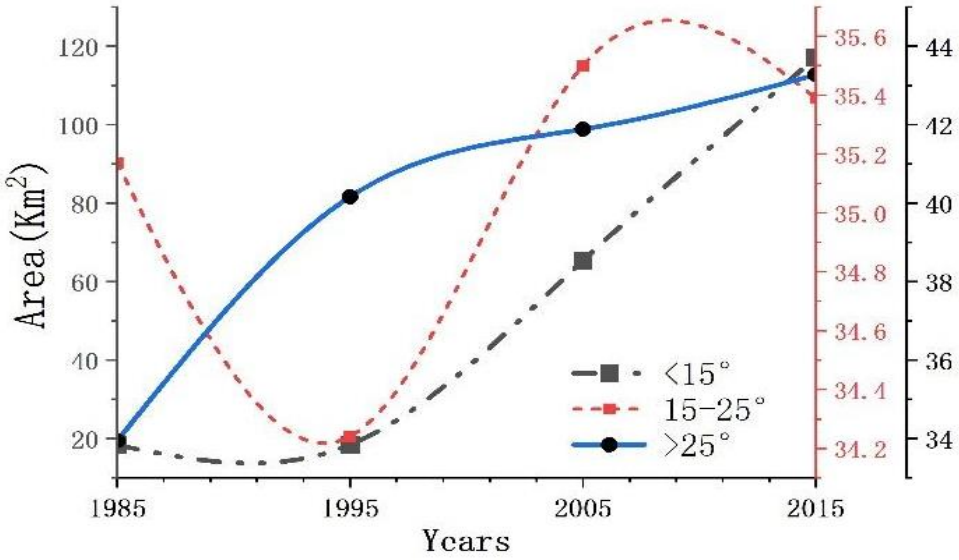

Figure 15 Arable land changes for different slopes from 1985 to 2015.

The total area at different slopes slightly changed from 1985 to 2015. Figure 16 shows that changes in slopes of <15° from 1985 to 1995, 1995 to 2005, and 2005 to 2015 experienced an increasing trend amounting to 6.31 km^2, 26.96 km^2, and 30.88 km^2, respectively. Changes in slopes of 15-25° had an increase of 12.26 km^2, a reduction of 11.27 km^2 and an increase of 4.46 km^2 respectively in the same period. For slopes of >25°, there was an increase of 4.99 km^2, a reduction of 4.14 km^2 and an increase of 2.45 km^2, respectively. The total changes for different slopes of <15°, 15-25°, and >25° experienced an increase of 88%, 7.48%, and 4.53%, respectively. Therefore, generally, the most changes occurred in slopes of <15°. Grassland was mainly distributed in the Heihe River, Liyuang River, Beida River, Hongshui River, and rivers below the sixth-level watersheds.

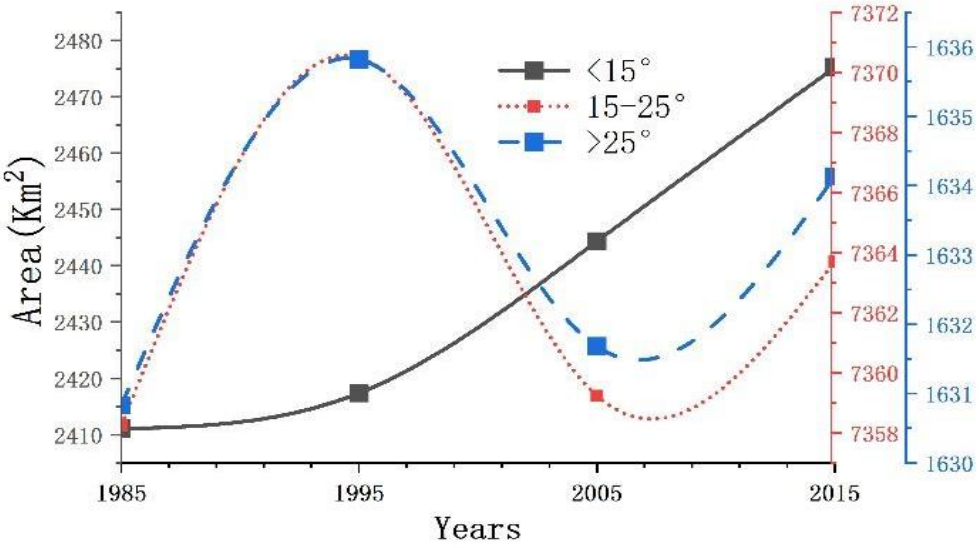

Figure 16 Area changes from 1985-2015 for different slopes in Sunan County

The average proportion of grassland area to total grassland area in these five basins from 1985 to 2015 was up to 80.86%, whereby the Heihe River, Liyuang River, Beida River, Hongshui floodplain, and rivers below the

sixth level amounted to 11.74%, 14.86%, 33.05%, 9.18%, and 12.03%, respectively. Figure 17 shows the changes in grassland for selected watersheds as of 1985–2015.

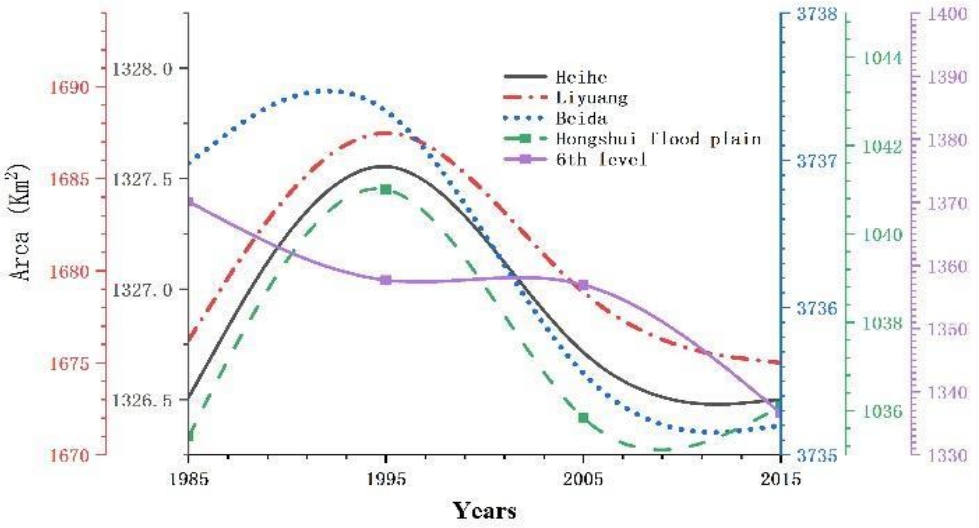

Figure 17 Grassland changes from 1985-2015 for five selected watersheds

The total area of grassland in these five watersheds decreased by 35.29 km^2. From this reduction, it was noted that the area of grassland from 1985 to 1995, 1995 to 2005, and 2005 to 2015 experienced changes by -18.21 km^2, 38.34 km^2, and 15.16 km^2, respectively. It was worth noting that the area of rivers below the sixth level decreased by 33.48 km^2, with Beida River and Liyuang River in the basins decreasing by 1.82 km^2 and 1.25 km^2, respectively. The reduced grassland areas were mainly located on the slopes of rivers below the sixth level with <15°, the slopes of Beida River in >25° and <15°, and the slopes of Liyuang River in 15-25° and <15°. The arable lands were mainly distributed in the Hongshui floodplain, Liyuang River, Beida River, and rivers below the sixth level.

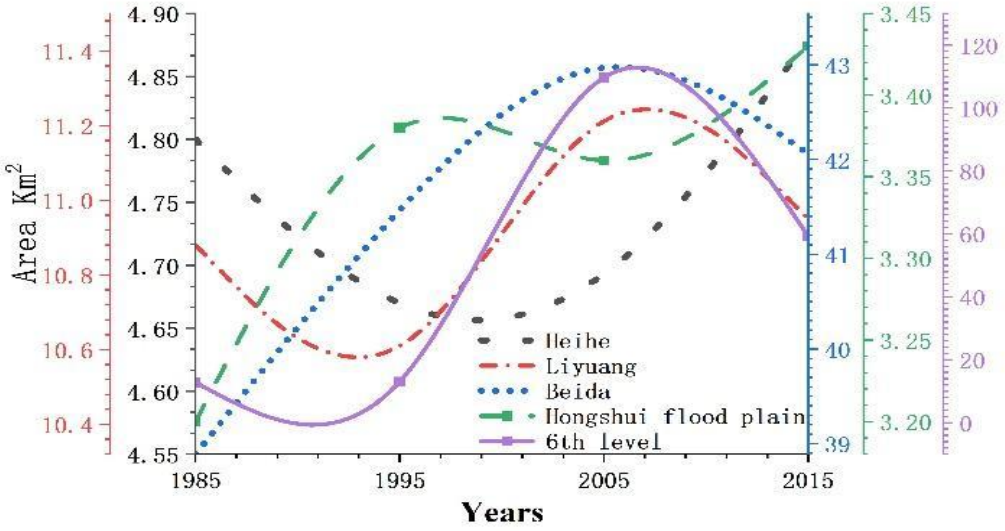

Figure 18 Arable land changes from 1985-2015 for five selected watersheds

From 1985 to 2015, the average proportion of arable land in these five river basins was 84.86%. The proportions of the Hongshui River, Liyuang River, Beida River and rivers below grade six were 6.86%, 8.42%, 32.02% and 37.56%, respectively. Figure 18 shows the changes in arable land for selected water sheds as from 1985 to 2015.

The area of arable land in these four watersheds increases by 108.19 km^2 from 1985 to 2015. The increases from 1985 to 1995, 1995 to 2005, and 2005 to 2015 were by 5.35 km^2, 49.89 km^2 and 52.95 km^2, respectively. The Hongshui and Liyuang River basins experienced minimal changes in arable land area over time. The arable land area of the Beida River and rivers under the sixth level increased by 4.65 km^2 and 96.84 km^2 respectively. The increased arable land area was mainly in the slopes of the Beida River >25° and rivers below the sixth level at <15°.

3.4 Discussions

Sunan Yugu administrative unity is autonomous and situated within the Qilian Mountain and Water Conservation Ecological Function Zone, which is a crucial component of the national key ecological function areas. 75% of the county's area is under the jurisdiction of the Qilian National Nature Reserve and is considered the "lifeline" and "Green Reservoir" of five cities in Hexi, including western Inner Mongolia. Past efforts of regressing farmland to woodland and grassland establish a momentous ecological restoration initiative aimed at combating soil erosion and desertification nationwide, serving as a fundamental strategy for ecological transformation in Gansu Province [33]. In this study, findings indicated that in Sunan, the woodland area experienced a decline of 16.57 km^2 from 1985 to 1995 but relatively experienced an increase of 16.66 km^2 between 1995 and 2005 and an overall decline of 0.77 km^2 in the last 30 years.

Implementation of conservation projects had led to the restoration of woodland areas in Sunan, compensating for the loss due to agricultural activities between 1985 and 1995. In a comprehensive effort to address the pressing ecological challenges in the Qilian Mountain area, the ecological migration project within the Qilian Mountain Nature Reserve was initiated. This involved relocating herdsmen from the nature reserve to Minghua Township in Sunan County.

Plenty of grassland was reclaimed into farmland due to the relocation of immigrants and the construction of agricultural development projects. This study revealed that in Minghua Township, the area of grassland diminished by 5.29 km^2, while the area of arable land expanded by 47.0 km^2 between 1995 and 2005; furthermore, from 2005 to 2015, the grassland area decreased by an additional 19.92 km^2 and the arable land area grew by 50.37 km^2 (an increase of 107.51 km^2). The relocation of immigrants caused a total reduction of 33.51 km^2 of grassland and 97.25 km of arable land.

From the above analysis, we establish that the ecological environment in the Qilian Reserve area has improved and the destroyed woodland has been restored due to the implementation of farmland-to-forest restoration and ecological migration projects in recent years. However, greater attention must be directed toward addressing the livelihood and production challenges faced by the immigrants. Such action is crucial to prevent secondary ecological degradation, particularly in light of the rapid reduction in grassland area and the corresponding expansion of cultivated land as shown in Figure 19 in the mountainous region. This affects the stability of the slopes and the region prone to land degradation and other ecological challenges.

Figure 20 shows expansion of cultivation in floodplains and settlements upstream. It is evident that the once-flowing stream is drying up due to cultivation activities and settlement upstream.

Figure 21 presents a flattened area under corn plantation. This figure demonstrates the spatial-temporal structure changes through conversion of other forms of land structure to cultivated lands in the region.

Figure 19 Rapid expansion of cultivation in mountainous regions

Figure 20 Expansion of settlement and cultivation in floodplains

Figure 21 Arable land under corn plantation

4 CONCLUSIONS AND RECOMMENDATIONS

4.1 Conclusion

Over the past three decades, the Sunan Yugu Autonomous administrative unit has experienced gradual yet significant transformations in LULC, influenced by natural topographical conditions and human activities. While woodland and grassland remained as the dominant land cover types, notable changes in grassland degradation and arable land expansion reshaped the region's landscape. The key findings of this study are summarised as follows:

(1) Over the last three decades, the LULC structure in Sunan County, predominantly characterised by woodland and grassland, maintained relative stability. The woodland area remained largely constant, while the grassland area experienced a marginal decline. Additionally, the area categorised under other LULC types witnessed a decrease of 75.45 km^2, contrasting with an increase of 107.51 km^2 in the arable land area.

(2) Grassland extensively blankets Sunan County, with woodland primarily located in the central and southern sections. Other LULC types are found across the central and western areas, whereas arable land predominantly lies in the southeast and spans across central to western regions. In the past 30 years, other types of LULC and grassland have transformed into arable land in Minghua Township in the north of the county. The analysis revealed that the Beida River played a dominant role in land-use/cover changes due to its large watershed area; Liyuang and rivers under the sixth level and Heihe watersheds, in that order, contribute moderately, while the Hohngshui floodplain has a minimal impact.

(3) Woodland grassland and other types of LULC were mainly sloped land of 15-25°. Arable land was roughly equally distributed on <15°, 15-25°, and >25°, and the artificial surface is mainly at <15° and on slopes of 15-25°. From 1995 to 2015, grassland was mainly converted on slopes of 15-25° to other areas; grassland and other areas were converted on slopes of <15° and >25° to cultivated land.

(4) Grassland is mainly distributed in the Heihe River, Liyuang River, Beida River, Hongshui River, and rivers below sixth level. In the three decades, the decrease of grassland area was mainly located on slopes <15° of rivers below the sixth level from 1995 to 2005, Beida River on the slopes of >25° and <15°, and Liyuang River on the slopes of 15-25° and <15°. Arable land is mainly distributed in the Hongshui River, Liyuang River, Beida River, and rivers below the sixth level. The expansion of arable land from 1995 to 2015 was notably swift, with significant additions primarily on slopes greater than 25° along the Beida River and on slopes of less than 15° in areas of rivers below the sixth level.

4.2 Recommendation for Sustainable Land Use Management in Sunan County

This study recommends that watershed management should prioritise conservation efforts to be focused on the Beida River watershed due to its large watershed area and significant contribution to LULC changes. Implementation of measures to mitigate deforestation, promote reforestation, and protect riparian zones should be embraced. Further, a balanced management of other watersheds is called for to ensure sustainable land-use practices, and finally specific causes of LULC changes in each watershed are investigated to tailor responsive management strategies and interventions.

Conflicts of Interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Acknowledgement

This research was funded by the Gansu Province Water Conservancy Science Experimental Research and Technology Promotion Plan (No. 24GSLK012) and The National Key Research and Development Program (No. 2016YFC0400301).

Supplementary Data

The datasets used and/or analyzed during the current study are available from the corresponding author on reasonable request.

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