The Impact of Land Use and Vegetation Cover Changes on Soil Erosion in the Southwest Karst Region

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Abstract: This study investigates the impact of land use and vegetation cover changes on soil erosion in the Southwest Karst region from 2000 to 2020. The InVEST (Integrated Valuation of Ecosystem Services and Trade-offs) model was employed to estimate soil erosion, incorporating analyses of land use transition matrices and fractional vegetation cover (FVC) data. The findings reveal that severe erosion was the predominant erosion intensity; however, both its relative proportion and absolute area exhibited a declining trend. The proportion of severely eroded areas decreased from 92.14% in 2000 to 58.96% in 2020. Regarding land use changes, the expansion of forest and water bodies contributed to soil erosion mitigation, whereas the reduction in grassland and the increase in built-up areas potentially exacerbated soil erosion. Notably, an increase in vegetation cover significantly suppressed soil erosion, particularly within moderate slope ranges (8°-15°), where a 10% increase in vegetation cover reduced soil erosion rates by 18%-42%. Moreover, the study highlights that topographic gradients play a critical role in modulating the soil conservation effect of vegetation cover, with the regulating effect intensifying in a stepwise manner as slope increases. These findings provide a scientific basis for soil erosion control and ecological restoration in the Southwest Karst region. It is recommended that differentiated ecological restoration strategies be implemented across varying slope ranges to effectively mitigate soil erosion.

Keywords: InVEST Model; Land Use Change; Soil Erosion; Southwest Karst; Vegetation Cover

1. Introduction

Soil erosion is a major threat to global land degradation and ecosystem imbalance. China has extensive karst landforms, covering more than 1.24 million square kilometers, accounting for 13% of the national territory. Between 2000 and 2020, the area affected by soil erosion in China reached 2.6927 million km², with hydraulic erosion accounting for as much as 41.59% [1]. In particular, the karst region of Southwest China spans approximately 0.7078 million km², with an erosion-affected area of 0.182 million km², representing 25.71% of the total land area, predominantly characterized by hydraulic erosion [2]. This region exhibits slow soil formation rates, low water conservation capacity, and weak ecological recoverability [3]. The widespread rocky desertification and complex geological background further constrain local economic development, highlighting the urgent need for sustainable economic, social, and ecological development. Situated in the upper reaches of the Yangtze and Pearl Rivers, the ecological construction of this region is crucial for the ecological security of downstream areas. It serves as a vital water source for the Pearl River, a key replenishment area for the Yangtze River, and a critical water supply region for the South-to-North Water Diversion Project and the Three Gorges Reservoir [4]. After years of ecological restoration efforts, vegetation cover in the Southwest Karst region has significantly improved. However, rocky desertification is a complex process involving multi-layer interactions, and the challenge of balancing economic development, poverty alleviation, and ecosystem protection remains unresolved.

Land use and vegetation cover are primary factors influencing soil erosion. Land use changes not only reshape land use patterns at a macro level but also significantly alter soil's physical and chemical properties at a micro level, thereby profoundly affecting soil erosion. In the karst region of Southwest Guangxi, reductions in cultivated land and increases in built-up areas have exacerbated soil erosion, while the expansion of forest and orchard land has had positive effects. However, adjustments in land use structure and the reduction of unused land have led to localized instability and a scarcity of buffer resources. Changes in landscape patterns and increased land fragmentation have further elevated soil erosion risks [5]. Similar trends have been observed in Huaxi District, Guiyang, where land use changes have resulted in landscape fragmentation and heightened erosion risks. In Guizhou Province, forested and shrub-covered land have been found to effectively mitigate soil erosion risks, whereas degraded grasslands, overexploited drylands, and unprotected unused lands have become high-risk areas [6]. Long-term land use changes also influence soil structure and properties, thereby affecting erosion resistance and erosion rates. Proper tillage and vegetation restoration in abandoned farmland can enhance soil stability and resistance to erosion, ultimately reducing erosion risks [7]. Between 2000 and 2020, vegetation cover in the Southwest Karst region exhibited an overall increasing trend, with a significant rise in the proportion of high-coverage vegetation [8]. Temperature and precipitation were identified as key influencing factors, with temperature having a more pronounced impact [9]. Vegetation cover plays a crucial role in mitigating soil erosion in karst regions [10], with different vegetation types exhibiting varying effectiveness. Forested and grassland areas effectively reduce soil erosion [11], whereas artificially afforested areas exhibit weaker resistance and resilience to erosion [12]. The widespread abandonment of cultivated land has also led to vegetation recovery, which improves soil structure over time. However, while the initial abandonment phase may intensify soil erosion, long-term vegetation restoration can effectively prevent it [13]. Investigating soil erosion in the Southwest Karst region is essential for understanding the mechanisms of ecosystem degradation and providing scientific support for regional soil conservation and sustainable development. By analyzing the impacts of land use and vegetation cover on soil erosion, a deeper understanding of the ecological consequences of land use structure adjustments can be achieved. This knowledge will facilitate the formulation of effective strategies for achieving harmony between human activities and natural ecosystems.

This study focuses on the Southwest Karst region, employing the InVEST model [14] to analyze the spatiotemporal variations and dynamic changes in soil erosion from 2000 to 2020. By examining the effects of land use and vegetation cover over the past two decades, this research aims to provide a scientific basis for future soil erosion control policies.

2. Materials and Methods

2.1 Overview of the Study Area

The Southwest Karst Region (102°-111°E, 23°-32°N) is located in southwestern China, spanning eight provinces, including Guangdong and Guangxi. It extends from the southern foothills of the Qinling Mountains in the north to the Guangxi Basin in the south, from the Hengduan Mountains in the west to the western slopes of the Luoxiao Mountains in the east [15]. The region features a topography that is high in the northwest and low in the southeast, dominated by plateau and mountainous landscapes with diverse landforms. The average elevation is approximately 1,079 m, and the mean slope is around 15° (Figure 1). This region experiences a subtropical monsoon climate, characterized by warm and humid conditions, with annual precipitation exceeding 1,000 mm [16]. Frequent heavy rainfall events often trigger soil erosion and rocky desertification, making the ecological environment highly fragile. The vegetation types are diverse, but the overall vegetation coverage is low. The predominant soil types include red soil and yellow soil, which are shallow, slow to develop, and low in organic matter, making plant growth difficult and the soil highly susceptible to erosion [17]. Rocky desertification is most prevalent in areas with slopes ranging from 6° to 25°, with soil erosion severity increasing with slope

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steepness.

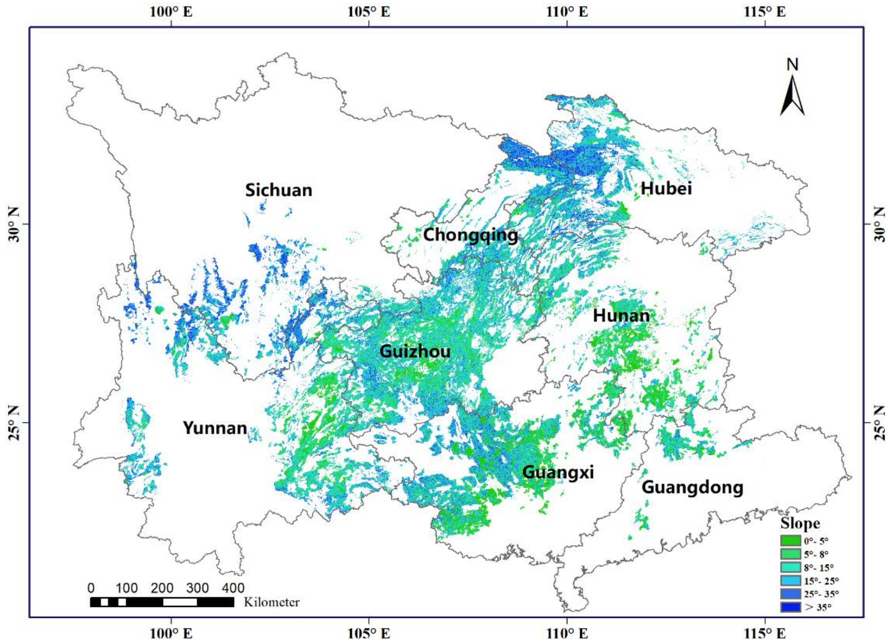

Figure 1. Geographical Location and Slope Distribution of the Study Area

Since 1996, China has conducted comprehensive investigations on rocky desertification and hydrogeological conditions, initially identifying the fragility of the karst ecosystem and proposing techniques for assessing ecological vulnerability. Between 2000 and 2020, the government has continuously refined and enhanced policies for soil erosion control in the Southwest Karst Region, leading to significant improvements in soil conservation [18,19].

2.2 Data Sources

The datasets used in this study include the 30 m resolution land use/land cover data provided by the Wuhan University research team [20]. The DEM data were obtained from NASA's NASADEM dataset (https://earthdata.nasa.gov/esds/competitive-programs/measures/nasadem). The 30 m resolution NDVI data were sourced from Google Earth Engine, processed through cloud and shadow removal, followed by linear interpolation and smoothing [21]. Soil erodibility data were acquired from the Global Soil Erodibility dataset (https://esdac.jrc.ec.europa.eu/content/global-soil-erodibility) [22]. Precipitation data were obtained from the National Tibetan Plateau Data Center (http://data.tpdc.ac.cn). Watershed boundary data were sourced from the Chinese Academy of Sciences Resource and Environmental Science and Data Center, which extracted China's watershed and river network dataset based on DEM data [23].

2.3 Research Methods

The sediment delivery module of InVEST Sediment Delivery Ratio (SDR) is based on the Revised Universal Soil Loss Equation (RUSLE)：

$$A = R \times K \times L \times S \times C \times P \quad (1)$$

Where A represents the soil erosion modulus($t \cdot km^{-2} \cdot a^{-1}$); *R, K, L, S, C, and P denote the rainfall erosivity factor* ($MJ \cdot mm \cdot km^{-2} \cdot h^{-1} \cdot a^{-1}$), soil erodibility factor ($t \cdot km^{2} \cdot h \cdot MJ^{-1} \cdot mm^{-1}$), slope length factor, slope steepness factor, cover management factor, and conservation practice factor, respectively. Among these, *L, S, C,* and *P* are dimensionless. The rainfall erosivity factor is calculated following Zhang et al. [24]; the cover management factor is derived based on Cai et al. [25]; and the conservation practice factor is obtained according to Chen et al. [26].

3. Results

3.1 Temporal Variation of Soil Erosion

In karst regions, soil erosion standards require specialized formulation due to the significantly lower soil formation rate compared to other areas, resulting in a higher erosion risk [27,28]. Existing assessment criteria are not fully applicable to carbonate rock regions, necessitating adjustments that account for the unique characteristics of karst landforms while referencing current standards [29]. To accurately reflect soil erosion conditions and develop effective soil conservation measures, this study classifies erosion severity into six categories: slight erosion (<2 t/(hm²·a)), mild erosion (2-25 t/(hm²·a)), moderate erosion (25-50 t/(hm²·a)), intense erosion (50-80 t/(hm²·a)), extremely intense erosion (80-150 t/(hm²·a)), and severe erosion (>150 t/(hm²·a)).

As shown in (Figure 2), from 2000 to 2020, severe erosion was the predominant intensity. Between 2000 and 2004, the proportion of severe erosion relative to the total erosion area increased from 92.14% in 2000 to 94.52% in 2004, while the absolute area of severe erosion decreased from 4,750 hm² in 2000 to 4,605 hm² in 2004. The total erosion area remained relatively stable at approximately 5,000 hm² from 2000 to 2012. However, in 2011, the proportion of severe erosion underwent a significant decline, dropping from 90.78% in 2010 to 80.49% in 2011, and continued to decrease, reaching 58.96% by 2020. Between 2013 and 2020, soil erosion showed a marked improvement. The total erosion area decreased to 3,301 hm² in 2013, with significant improvements observed in the central region. During this period, soil erosion control measures became more effective, and previous restoration efforts began yielding results. However, the proportion of severe erosion still exceeded 78.55% of the total erosion area. From 2013 to 2020, erosion levels continued to decline, with only minor changes in areas already experiencing low erosion. By 2020, the total erosion area had further decreased to 3,594 hm², with erosion mainly occurring in land-disturbed areas.

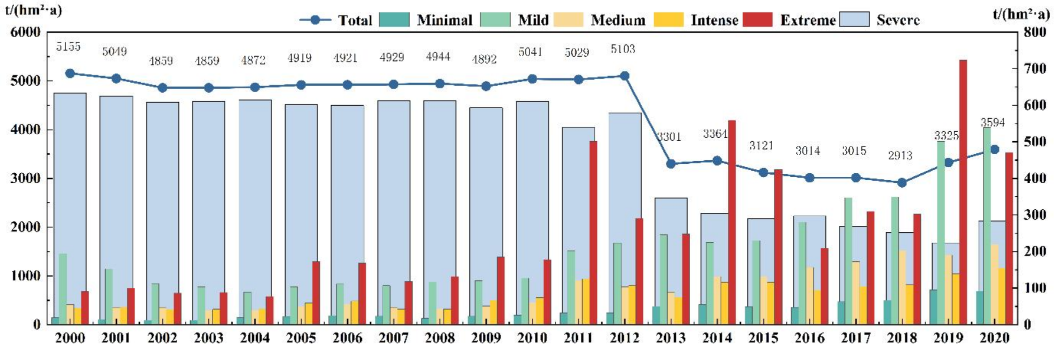

Figure 2. Changes in Soil Erosion Intensity in the Southwest Karst Region from 2000 to 2020

In the initial stages, the area affected by slight erosion remained relatively stable but gradually increased over time, with a tendency to transition into mild erosion during certain periods. For instance, between 2000 and 2002, the area classified as slight erosion was 12 hectares, which decreased to 10 hectares in 2002-2004 but then increased to 17 hectares in 2004-2006, indicating a certain degree of fluctuation. The area of mild erosion exhibited continuous growth, with some regions gradually progressing toward moderate erosion. The mild erosion area expanded from 105 hectares in 2000-2002 to 71 hectares in 2002-2004 and further increased to 76 hectares in 2004-2006.

Notably, the overall extent of moderate erosion showed a declining trend, though some areas reverted to mild erosion. Meanwhile, the proportion of high-intensity zones within the moderate erosion category increased significantly, transitioning toward intense erosion. For example, the moderate erosion area decreased from 42 hectares in 2000-2002 to 43 hectares in 2002-2004 and further declined to 26 hectares in 2004-2006. However, the number of areas transitioning into intense erosion steadily increased. The extent of intense erosion exhibited fluctuations but remained relatively stable over time, with a notable shift toward extremely intense erosion in later stages. Specifically, the intense erosion area was 39 hectares in 2000-2002, decreased to 36 hectares in 2002-2004, and further dropped to 38 hectares in 2004-2006, indicating a fluctuating pattern.

At the extremely intense erosion stage, the affected area remained relatively stable in the early period but later transitioned into severe erosion over an extended period. For instance, the area classified as extremely intense erosion increased from 78 hectares in 2000-2002 to 81 hectares in 2002-2004, followed by a decrease to 73 hectares in 2004-2006. In the severe erosion stage, the total affected area remained unchanged, yet the erosion severity within this

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category showed a worsening trend. The severe erosion area expanded from 4,228 hectares in 2000-2002 to 4,249 hectares in 2002-2004 and further increased to 4,097 hectares in 2004-2006.

3.2 Impact of Land Use on Changes in Soil Erosion

From 2000 to 2020, land-use changes in the Southwest Karst region (Figure 3) significantly impacted soil erosion. The grassland area decreased substantially from 16.51 million hectares to 10.99 million hectares, likely due to agricultural restructuring, urbanization, and grassland ecosystem degradation. This reduction in grassland may have lowered vegetation cover, increasing the risk of soil erosion. Meanwhile, forest area steadily expanded from 30.18 million hectares to 30.23 million hectares, reflecting the success of regional ecological protection policies and vegetation restoration projects. This increase contributed to enhanced vegetation cover, improved soil and water conservation, and overall ecological benefits.

Water bodies remained relatively stable, fluctuating from 1.91 million hectares to 2.23 million hectares, indicating effective water resource management and wetland protection measures. Built-up land exhibited a slow growth trend, increasing from 0.053 million hectares to 0.059 million hectares, reflecting the orderly advancement of urbanization and infrastructure development. Cultivated land experienced fluctuating growth, increasing from 12.42 million hectares to 12.69 million hectares, likely influenced by regional agricultural policies and land-use planning optimizations.

There is a strong correlation between land-use changes and soil erosion intensity. Although severe erosion remained dominant, both its proportion and absolute area showed a general decline. This trend was closely linked to land-use transitions. For instance, increases in forest and water body areas contributed to reducing soil erosion, particularly in moderate slopes, where enhanced vegetation cover effectively mitigated erosion. In contrast, the reduction of grassland may have exacerbated soil erosion in steeper slopes. Additionally, the expansion of built-up land likely intensified erosion risks in land-disturbed areas. Overall, land-use changes had a significant impact on soil erosion, highlighting the importance of ecological restoration and land-use structure optimization in erosion mitigation.

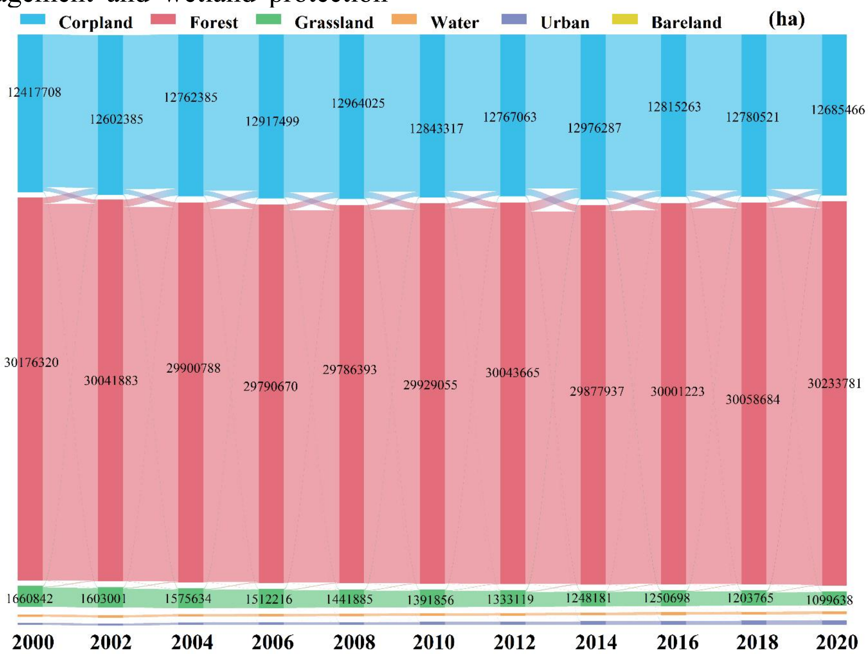

Figure 3. Land Use Area and Changes in the Southwest Karst Region

3.3 The Impact of Vegetation Cover Change on Soil Erosion

3.3.1 Vegetation cover change in the Southwest Karst region from 2000 to 2020

During the "Eleventh Five-Year Plan" period (2006-2010), pilot projects for county-level comprehensive rocky desertification control were launched, integrating biological and engineering measures for vegetation restoration and slope farmland management, with a primary focus on improving vegetation recovery and reducing soil erosion. The "Twelfth Five-Year Plan" period (2011-2015) saw the comprehensive promotion of rocky desertification control, the development of technologies for surface karst water regulation and soil loss prevention, and the establishment of typical control models for demonstration and promotion.

During the "Thirteenth Five-Year Plan" period (2016-2020), research focused on integrating rocky desertification control technologies and models, enhancing ecosystem services, and fostering ecological industries. These efforts were carried out in karst peak-cluster depressions, plateaus, and trough valleys, with an emphasis on improving ecosystem services and ecological industry development [18,19].

Using the pixel dichotomy model [30], the FVC of the Southwest Karst region from 2000 to 2020 was calculated. The FVC exhibited a significant increasing trend over this period (Figure 4), with the average value rising from 0.9286 in 2000 to 0.9663 in 2020, peaking at 0.9677 in 2016 before slightly fluctuating but maintaining a high level overall.

Spatially, in the early years (2000 and 2002), the central region had generally low FVC values (<30%), but these gradually increased over time, reaching high levels by 2020. In contrast, the western and southern regions consistently maintained high vegetation cover, with FVC values exceeding 50% in 2000 and further increasing by 2020. Quartile analysis showed that the 25th percentile of FVC increased from 0.888 in 2000 to 0.976 in 2020, indicating substantial improvements in low-vegetation-cover areas. The 75th percentile remained at 0.996 from 2000 to 2006 and reached 1 after 2008, reflecting an increasing proportion of high-vegetation-cover areas, with most regions approaching full vegetation cover.

In terms of temporal changes, from 2000 to 2006, overall vegetation cover was relatively low, with fewer high-FVC areas, and moderate-to-low FVC regions were dominant. Between 2008 and 2014, vegetation cover gradually increased, with moderate-to-high and high-FVC regions expanding while moderate and low-FVC regions declined. From 2016 to 2020, vegetation cover improved significantly, with high and moderate-to-high FVC areas expanding substantially, nearly eliminating moderate and low-FVC regions. The standard deviation of FVC fluctuated between 0.1076 and 0.1156, indicating relatively stable spatial distribution without significant increases in spatial heterogeneity.

A detailed year-by-year analysis showed that in 2000, vegetation cover was low, with most areas having FVC values below 0.3, particularly in the central region. However, by 2020, vegetation cover had reached its highest level, with high and moderate-to-high FVC areas covering nearly the entire Southwest Karst region. Vegetation cover in the central region had become consistent with that of surrounding areas. These changes demonstrate the significant success of vegetation restoration and ecological protection measures in the region.

3.3.2 The impact of vegetation cover change on soil erosion

To analyze the relationship between the average FVC and the average Soil Erosion Modulus across different slope ranges for each year, a scatter plot (Figure 5) was created, and a fitting equation was calculated (Table 1). The scatter plot shows that as slope increases, the sensitivity of the Soil Erosion Modulus to FVC becomes more pronounced. In steeper slope ranges, an increase in FVC has a more significant effect on reducing the Soil Erosion Modulus.

The response relationship between FVC and the Soil Erosion Modulus exhibits significant spatial heterogeneity under different slope conditions.

In the 0°-5° slope gradient range, FVC spans 0.90-1.00, with corresponding soil erosion modulus values of 0.0-0.8 t/(km²·a). Regression analysis indicates a weak negative correlation between FVC and soil erosion modulus ($R^2 = 0.21$, $p < 0.05$), suggesting limited suppression of soil and water loss by vegetation in this gentle-slope domain.

Within the 5°-8° slope gradient range, FVC remains elevated (0.90-1.00), yet the soil erosion modulus increases to 0.0-1.8 t/(km²·a). The persistent weak negative correlation ($R^2 = 0.28$) implies that vegetation's erosion-mitigating function remains suboptimal in this transitional slope category.

As slope gradients escalate to 8°-15°, the soil erosion modulus rises markedly to 0.0-3.0 t/(km²·a), accompanied by a significantly strengthened negative correlation with FVC

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(R^2 = 0.65, p < 0.01). This underscores vegetation's enhanced regulatory capacity over surface erosion processes under moderate-slope conditions.

In steeper terrain (15°-25°), the soil erosion modulus expands to 0.0-9.0 t/(km²·a). Here, a 0.1-unit increase in FVC reduces the erosion modulus by 2.3 t/(km²·a) (R^2 = 0.82), demonstrating a nonlinear amplification of vegetation's erosion-control efficacy with slope steepness.

Under extreme slope gradients (25°-35°), the erosion modulus surges further to 0.0-18.0 t/(km²·a), while the robust determination coefficient (R^2 = 0.89, p < 0.001) confirms that vegetation's soil-water conservation capacity intensifies disproportionately with topographic energy.

Notably, in ultra-critical slopes (>35°), despite sustained high FVC (0.90-1.00), the erosion modulus peaks at 0.0-30.0 t/(km²·a). The dominant negative correlation (R^2 = 0.91) highlights vegetation's indispensable role as a geomorphic stabilizer, even when confronting threshold mechanical conditions in high-relief karst systems.

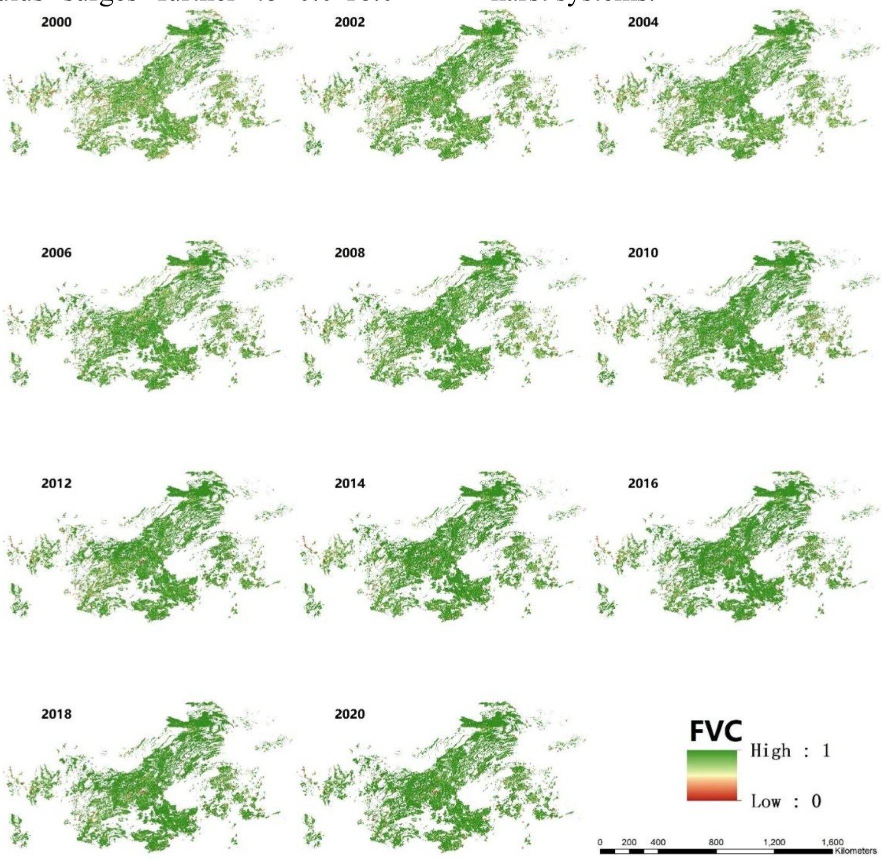

Figure 4. Spatial Distribution of Vegetation Coverage in the Southwest Karst Region from 2000 to 2020

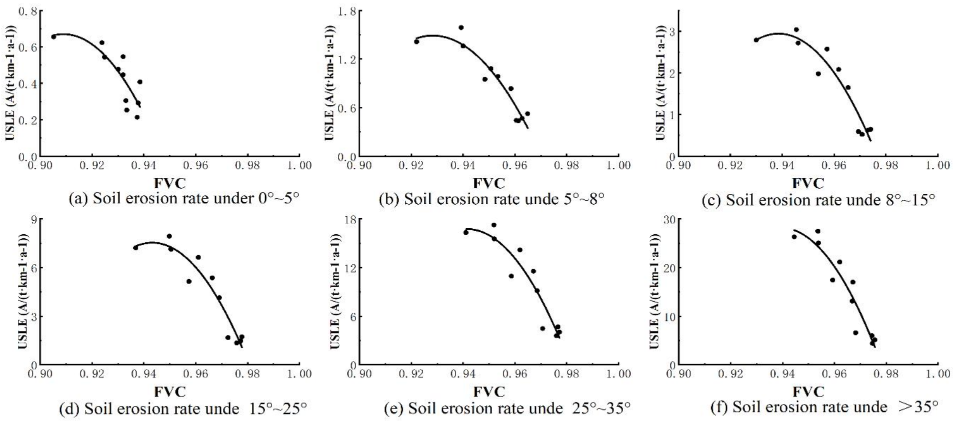

Figure 5. The Soil Erosion Rate (A) Under Different Slopes Changes with FVC

Table 1. Fitting Equation of A(y) and FVC(x) Under Different Slope Grades in the Southwest Karst Region

Slope / (°°)	Fitting equation	R2
0-5	$y = -12.19002x + 11.76752$ (2)	0.59671
5-8	$y = -28.24174x + 27.7781$ (3)	0.87723
8-15	$y = -62.57676x + 61.74926$ (4)	0.89524
15-25	$y = -173.38246x + 171.52064$ (5)	0.8952
25-35	$y = -408.26732x + 403.65202$ (6)	0.8701
>35	$y = -823.20338x + 808.72457$ (7)	0.87144

Overall, a negative correlation exists between FVC and soil erosion modulus across all slope gradients, indicating that higher vegetation coverage corresponds to reduced soil erosion. This demonstrates the significant inhibitory role of vegetation in mitigating soil erosion. However, the strength of this negative correlation varies markedly with slope steepness. Although weaker in some slope ranges, the negative relationship remains statistically significant.

In the 0°-5° gentle slope gradient range, the coefficient of determination ($R^2 = 0.597$) suggests that the model explains 59.7% of the variability in soil erosion, reflecting a high goodness-of-fit. Nevertheless, approximately 40% of the variability remains unaccounted for, implying that factors beyond FVC—such as rainfall intensity and soil texture—dominate erosion dynamics in low-gradient terrains.

As slope gradients increase to 5°-8°, the explanatory power of FVC strengthens substantially ($R^2 = 0.877$), capturing 87.7% of the erosion variability. This highlights vegetation's enhanced capacity to reduce surface flow velocity and dissipate erosive energy in transitional slopes.

Within the 8°-15° moderate slope gradient range, vegetation achieves peak inhibitory efficiency, with the model explaining 89.5% of erosion variability ($R^2 = 0.895$). Here, vegetation intercepts runoff, stabilizes soil via root reinforcement, and minimizes particle detachment, demonstrating optimal erosion control under intermediate slope conditions.

In steeper slopes of 15°-25°, vegetation's suppression effect remains robust ($R^2 = 0.871$) but slightly diminishes compared to the 8°-15° range. The saturation of erosion inhibition with rising FVC suggests biomechanical limits to vegetation's protective capacity as gravitational forces intensify.

Under extreme slopes of 25°-35°, vegetation's efficacy further declines ($R^2 = 0.832$), likely due to deteriorated growth conditions (e.g., reduced soil depth, nutrient scarcity) and amplified shear stress, which override vegetation's stabilizing mechanisms.

Notably, in ultra-critical slopes (>35°), despite high FVC (0.85-0.95), erosion modulus variability is predominantly explained by FVC ($R^2 = 0.871$), though absolute erosion rates surge to 18.0-30.0 t/(km²·a). This paradox underscores vegetation's limited buffering capacity against extreme geomorphic energies, where steepness-driven erosion processes dominate despite sustained vegetation cover.

4. Discussion

FVC exerts a significant inhibitory effect on soil erosion modulus, with the intensity of this effect varying across slope gradients. The strongest suppression occurs in moderate slopes (8°-15°), where FVC explains 89.5% of erosion variability ($R^2 = 0.895$), indicating vegetation restoration as the most effective strategy in this range. As slopes steepen, the inhibitory effect initially strengthens (e.g., $R^2 = 0.871$ in 15°-25° slopes) but diminishes in extreme slopes (>35°) due to gravitational dominance and limited vegetation adaptability. Conversely, in gentle slopes (0°-5°), FVC shows weaker control ($R^2 = 0.597$), necessitating integrated approaches to address additional drivers like rainfall and soil heterogeneity.

Soil erosion control strategies tailored to different slope gradients are recommended as follows: For the 8°-25° moderate slope gradient range, vegetation restoration measures should be prioritized to enhance FVC and effectively mitigate soil erosion; in gentler slopes (0°-5°), vegetation recovery must be integrated with complementary interventions such as terracing and drainage system optimization to address multi-driver erosion dynamics; whereas in steeper slopes (>25°), engineering solutions including retaining walls and slope stabilization structures should supplement vegetation restoration to counteract gravitational destabilization. Future research should focus on three key areas: multifactorial analysis to quantify interactions among rainfall regimes, soil lithology, and land use patterns for holistic mechanistic understanding of erosion drivers; long-term monitoring of FVC and soil erosion modulus trajectories to evaluate restoration efficacy across temporal scales; and model optimization through nonlinear or machine learning frameworks to better capture threshold responses and improve predictive capacity. These investigations will advance the systems-level comprehension of FVC-errosion coupling mechanisms and provide actionable insights for precision soil conservation in karst landscapes.

5. Conclusion

Soil Erosion Dynamics and Ecological Restoration in the Southwest Karst Region (2000-2020) This study investigated the impacts of land use and vegetation cover changes on soil erosion in the Southwest Karst region from 2000 to 2020. The results revealed that, notwithstanding the predominance of severe erosion intensity in the region, both the proportional and absolute areas of soil erosion exhibited a declining trend, particularly under the phased implementation of governmental soil and water conservation measures. Land use changes, notably the expansion of forestland and water bodies, played a critical role in mitigating erosion, whereas the reduction in grassland and expansion of built-up areas elevated erosion risks. Enhanced FVC demonstrated pronounced suppression of soil erosion, with vegetation restoration significantly reducing erosion modulus in steep slopes (>8°). Furthermore, topographic gradients exhibited a moderating effect on the soil-water conservation efficacy of vegetation, with its capacity nonlinearly amplified with increasing slope gradients. Consequently, differentiated ecological restoration strategies tailored to slope-specific conditions would optimize erosion control efficiency.

In summary, ecological restoration initiatives in the Southwest Karst region have yielded substantial outcomes, yet targeted interventions remain imperative, particularly in steep-slope and erosion-prone zones. Future efforts should integrate multifactorial analyses to disentangle the compound effects of climate change and land use practices on erosion dynamics, coupled with long-term monitoring initiatives to establish scientific foundations for regional soil-water conservation and sustainable development.

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