Sustainability in Environment
ISSN 2470-637X (Print) ISSN 2470-6388 (Online)
Vol. 11, No. 4, 2026
www.scholink.org/ojs/index.php/se

Original Paper

Frontier Theories and Practice of the Soil Underground Loss in Karst Areas

Zirong Shi[1,2], Jingfei Wu[1,2], Yiting Wu[1,2], Liming Yang[1,2], & Qinglin Wu[1,2*]

[1] School of Karst, Guizhou Normal University, Guiyang, Guizhou, China

[2] State Engineering Technology Institute for Karst Desertification Control, Guiyang, Guizhou, China

[*] Corresponding author

Received: September 27, 2026 Accepted: October 29, 2026 Online Published: November 10, 2026

doi:10.22158/se.v12n4p85 URL: http://dx.doi.org/10.22158/se.v12n4p85

Abstract

Soil underground loss (SUL) is a distinctive erosion process in karst regions, where soil infiltrates into underground conduits through bedrock fissures, posing a severe threat to land resources. This paper reviews the frontier theories and practice of SUL, clarifying its mechanisms driven by soil properties, geomorphological settings, hydrological constraints, and human disturbances such as vegetation destruction and land cultivation. Conceptually, SUL has evolved from a slope-scale subsurface process to a catchment-scale surface–underground continuum, necessitating an integrated definition. Current estimates of SUL's contribution to total soil erosion vary widely due to methodological and scale discrepancies. Among influencing factors, slope gradient and rainfall intensity consistently emerge as dominant drivers, while fissure degree and rock exposure rate show context-specific effects, highlighting the complexity of factor interactions. Future research should prioritize integrating field tracing with simulation experiments, establishing long-term observation networks, developing process-based models embedding epikarst conduit geometry, and translating findings into targeted mitigation measures. Advancing these directions will provide robust support for rocky desertification control and sustainable land management in karst regions globally.

Keywords

SUL, karst, mechanisms, conceptual evolution, contribution rate

1. Introduction

The karst area accounts for around 15% of the world's land area [1]. Of the three karst areas in the world, Southwest China Karst covers the largest area of the thickest carbonate rocks [2], and has an exposed area of nearly 0.53 million km^2 [3]. In this area, the regions with the most widely distributed karst

involve eight provinces: Guizhou, Chongqing, Guangxi, Yunnan, Hunan, Hubei, Sichuan, and Guangdong [4].

Located in the tropical-and-subtropical-monsoon region, karst regions is the typical tropical-and-subtropical karst [5]. This features the intensive rainfall in summer and the complex and various geomorphologic types with high mountains and deep rivers. Soil has thus been seriously eroded by SUL (soil underground loss), and rocks are largely exposed, leading to KRD—a process of land degradation in karst areas characterized by severe soil loss and a sharp decline in land productivity [6]. As suggested by the name of "the earth's cancer", KRD has been one of the most serious ecological disasters [7] and the severest Eco-environmental problem in south China karst [8]. It has badly restricted the social and economic development of karst regions [1]. So far, a body of studies have supported the idea that the key to resist KRD lies in the harness of soil erosion [9].

Soil erosion is widely recognized as one of the most severe threats to global arable land [10], no exception to the karst area in south China, either. Specifically, soil erosion in this area is caused by three reasons: the low rate of soil formation [11, 12], the destruction of vegetation by human activities [1, 13, 14], and the serious dual soil loss from both surface and underground [15, 16].

The SUL, was formally proposed in 2007 [17] and has been consistently studied as a particular form of soil erosion in karst areas [18, 19]. This concept, from then on, has expanded the research field of soil and water conservation for researchers in China and been attached more importance. It leads to the transformation from the previous focus only on the surface soil and water loss in karst areas to explore both the surface loss and underground loss, more comprehensively reflecting the reality of soil erosion in karst regions.

Although research on SUL has made some progress in theoretical studies and monitoring technologies, several issues remain to be further explored. These include the research scale corresponding to the concept, the mechanisms and influencing factors of SUL, the applicability and limitations of monitoring methods, and the contribution rate of SUL. Investigating these issues will help to comprehensively grasp the characteristics of SUL in karst areas, and provide theoretical and technical support for rocky desertification control and ecological restoration.

2. The Mechanisms of SUL

On the natural side, SUL in karst regions is driven by an interplay of soil properties, geomorphological settings, and hydrological constraints. Although the high-calcium environment in karst areas promotes the formation of soil aggregates, these aggregates are inherently unstable and exhibit poor water stability due to high clay content (often exceeding 40% and reaching up to 80%) [20]. Under disturbance, carbon and nitrogen in calcareous soils are prone to mineralization-induced loss [21], and the aggregates readily disintegrate into fine particles. These fine-grained particles, combined with the region's discontinuous soil cover, abundant exposed bedrock, and well-developed underground conduits and fissures, are easily transported downward by infiltrating water into karst pipelines, generating

suspended loads in underground runoff and causing substantial SUL.

Human activities are taken as the other factor for SUL. The “sieve hole” theory regards the slopes in karst areas as stone sieves full of ‘holes’ while the karst ditches, grooves and depressions as ‘sieve holes’ blocked by soil, through which the soil loss to underground [17]. Such SUL can be accelerated by human activities in three ways. First, vegetation tends to be destroyed in the process of deforestation, land reclamation, overgrazing and other activities. Once the soil loses the net solidity provided by plant root system, it is likely to move into the underground space through fissures. Second, the destroyed vegetation fails to provide a strong canopy interception for precipitation, leading to the surface runoff increase. Surface sediment, along with surface runoff, enters underground space in low-lying cracks and pores, resulting in more SUL. Land cultivation may also have the soil layer loose and then increase the underground runoff. Third, the “stone sieves” may be shaken during the road construction, quarrying and other human activities, which will promote SUL.

3. Conceptual Evolution and Redefinition of SUL across Slope and Catchment Scales

The concept of SUL can be defined at two distinct scales: slope and catchment. At the slope scale, SUL refers to the process in which subsurface chemical dissolution of bedrock and conduits erosion within underground caves and rivers cause soil subsidence in grike, groove, depressions and rock cracks on sloping land [17], emphasizing that soil erosion is an underground process. At the catchment scale, SUL is defined as a process in karst regions with well-developed dual-surface and underground spatial structures, where surface soil infiltrates downward into underground rivers through karst conduits such as sinkholes and karst fissures under the combined action of mechanical erosion and chemical dissolution by flowing water [22], emphasizing the surface process of soil-water loss, with underground rivers merely serving as the final destination of surface soil. Chronologically, the concept of SUL has evolved from the slope scale to the catchment scale. In terms of where erosion occurs, slope-scale SUL takes place beneath the soil layer, while catchment-scale SUL begins at the surface but ultimately delivers soil into underground conduits. In fact, however, soil erosion in karst regions can occur either at the soil surface or beneath the topsoil, regardless of scale. Therefore, the concept of SUL should be redefined as follows: the process by which soil and water enter underground caves and rivers, and other subterranean spaces through karst conduits such as surface fissures, pores, sinkholes.

4. The Contribution Ratio of SUL to Soil Erosion in Karst Areas

While most studies back the positive correlation between SUL and soil erosion in karst areas, researchers’ views are divided as to the amount of SUL in the total soil and water loss. According to the first view, SUL is the main body of soil erosion. As karst conduits offer massive passages for SUL from underground, karst karren and depressions-whether grass slopes or arable lands, soil and water loss is mainly SUL in the areas with massively-developed depressions and severe rocky desertification, in some regions the SUL accounting over 70% to even 100% [23, 24]. It has also been supported from the

research conducted by [25]. In Huanjiang county, Guangxi, Wang et al. calculated, through the matching formula, the contribution rates of surface soil erosion and SUL in karst watershed as 12% and 88% respectively. Proponents of the second view argue that SUL constitutes only a minor fraction of total soil erosion. For instance, surface water and soil loss rates have been estimated at 10–100 t km^{-2} a^{-1} (with extreme cases exceeding 1000 t km^{-2} a^{-1}), whereas concurrent SUL rates are merely 0–20 t km^{-2} a^{-1} [26]. Similarly, monitoring in the Wangjiazhai small watershed revealed that SUL accounted for just 0.81% of the total soil erosion within the basin [8, 27]. Consistent with these findings, SUL contribution ratios have also been reported to be very low in karst mountain areas [28, 29]. Disagreements over whether SUL contribution is high or low stem from variations in monitoring methods, study scales, geomorphological types, and rainfall patterns. The only solution is more research and monitoring to identify the patterns of SUL contribution under varying conditions.

5. The Correlative Degrees of SUL Factors

Soil subsurface loss (SUL) in karst regions is governed by multiple interdependent factors, including rock exposure rate, rainfall intensity, rainfall duration, slope gradient, and bedrock fissure degree, and simulation experiments have substantially advanced the understanding of how these variables interact to regulate infiltration and runoff partitioning. A representative study quantified the relative contribution of each driver and established the following order of correlative strength: slope gradient > rainfall intensity > fissure degree > rock exposure rate [30]. This ranking indicates that topographic and meteorological factors exert a stronger influence on SUL than substrate characteristics under the experimental conditions tested. Specifically, steeper slopes enhance surface runoff velocity and shear stress, promoting preferential flow into fissures, while high rainfall intensity increases the hydraulic gradient that drives soil particles into underground conduits. Fissure degree, reflecting the connectivity of the epikarst system, acts as a critical threshold variable: once a certain density is exceeded, even moderate rainfall can trigger substantial leakage. In contrast, rock exposure rate showed a comparatively weaker correlation, likely because its effect is mediated by runoff interception and redistribution rather than directly controlling infiltration capacity. It is worth noting that other simulation studies have produced divergent rankings depending on experimental design, soil type, and fissure geometry, which reveals that the correlative degrees of SUL factors are highly context-dependent. Such variability actually highlights the complexity of SUL processes and reflects the fact that laboratory approaches, while useful for isolating individual mechanisms, inevitably simplify the nonlinear feedbacks among factors in real karst landscapes. Nevertheless, the consistent emergence of slope and rainfall intensity as dominant drivers across multiple studies confirms their central role in SUL processes, and future work should prioritize multivariate interaction experiments and long-term field validation to refine these correlative assessments and support the development of targeted mitigation strategies for karst soil conservation.

6. Conclusions and Outlooks

SUL is a distinctive erosion process in karst regions, driven by the interplay of soil properties, geomorphological settings, hydrological constraints, and human disturbances. Conceptually, the understanding of SUL has evolved from a slope-scale subsurface process to a catchment-scale continuum where erosion may initiate at the surface but ultimately delivers soil into underground conduits, necessitating an integrated definition that bridges both scales. Current estimates of SUL's contribution to total soil loss vary widely—from negligible to dominant—largely reflecting differences in monitoring methods, spatial scales, and geomorphological contexts rather than inherent contradictions. Among the multiple influencing factors, simulation experiments consistently identify slope gradient and rainfall intensity as dominant drivers, while fissure degree and rock exposure rate exhibit context-specific effects, confirming that the correlative degrees of SUL factors are highly environment-dependent. These findings underscore that SUL is not merely a subsidiary of surface erosion but a threshold-dependent process governed by complex factor interactions that laboratory approaches alone cannot fully capture. Looking ahead, future research should prioritize integrating high-resolution field tracing with multivariate simulation experiments, establishing long-term observation networks to quantify SUL contributions under varying rainfall and land-use regimes, developing process-based models that embed epikarst conduit geometry, and translating mechanistic understanding into targeted mitigation measures for high-risk zones. Advancing these directions will resolve current disputes over factor rankings and contribution rates, ultimately providing robust theoretical and technical support for rocky desertification control and sustainable land management in karst regions worldwide.

Acknowledgements

This study was supported by the National Natural Science Foundation Cultivation Project of Guizhou Normal University (Grant No. [2026]21).

References

[1] Peng, J., Xu Y. Q., Zhang R., et al. Soil erosion monitoring and its implication in a limestone land suffering from rocky desertification in the Huajiang Canyon, Guizhou, Southwest China. Environ Earth Sci. 2013; 69(3): 831-41.

[2] Feng T., Chen H., Wang K., et al. Modeling soil erosion using a spatially distributed model in a karst catchment of northwest Guangxi, China. Earth Surface Processes and Landforms. 2014; 39(15): 2121-30.

[3] Jiang Z., Lian Y., Qin X. Rocky desertification in Southwest China: Impacts, causes, and restoration. Earth-Sci Rev. 2014; 132 1-12.

[4] Zeng F., Jiang Z., Shen L., et al. Assessment of multiple and interacting modes of soil loss in the karst critical zone, Southwest China (SWC). Geomorphology. 2018; 322 97-106.

[5] Wu Q., Liang H., Xiong K., et al. Eco-benefits coupling of agroforestry and soil and water conservation under KRD environment: frontier theories and outlook. Agrofor Syst. 2019; 93(5): 1927-38.

[6] Wang S.J., Liu Q.M., Zhang D.F. Karst rocky desertification in southwestern China: geomorphology, landuse, impact and rehabilitation. Land Degrad Dev. 2004; 15(2): 115-21.

[7] Bai X.Y., Wang S.J., Xiong K.N. Assessing spatial-temporal evolution processes of karst rocky desertification land: indications for restoration strategies. Land Degrad Dev. 2013; 24(1): 47-56.

[8] Kangning X., Jin L., Mingzhong L. Features of soil and water loss and key issues in demonstration areas for combating karst rocky desertification. Acta Geographica Sinica. 2012; 67(7): 878-88.

[9] Wu Q., Liang H., Xiong K., et al. Frontier theories countermeasures for integrated regulation of soil and water loss and mountainous agroforestry in rocky desertification environment. J Soil Water Conserv. 2018; 32(2): 11-8+33.

[10] Lieskovský J., Kenderessy P. Modelling the effect of vegetation cover and different tillage practices on soil erosion in vineyards: a case study in Vráble (Slovakia) using WATEM/SEDEM. Land Degrad Dev. 2014; 25(3): 288-96.

[11] Wang S., Ji H., Ouyang Z., et al. Preliminary study on weathering and pedogenesis of carbonate rock. Science in China Series D: Earth Sciences. 1999; 42(6): 572-81.

[12] Feng Z., Wang S., Liu X., et al. Impact of acid-insoluble residua of carbonate rocks on developing intensities of their weathering crusts. Acta Geologica Sinica. 2009; 83 885-93.

[13] Zhang X., Bai X., Li H., et al. Contrast of 137Cs content in SULope soil with depressions, and pond sediments: sediments sources, transportation and balance of karst basin in SW China. Earth and Environment. 2017; 45(3): 247-58.

[14] Raya A.M., Zuazo V.D., Martínez J.F. Soil erosion and runoff response to plant-cover strips on semiarid slopes (SE Spain). Land Degrad Dev. 2006; 17(1): 1-11.

[15] Luo W., Jiang Z., Han Q., et al. Soil distribution and erosion characteristics of different landforms in karst peak cluster depression. Soil and Water Conservation in China. 2008; (12): 46-9.

[16] Jiang Z., Luo W., Deng Y., et al. Features and treatment of soil erosion in karst areas of Guangxi. Guangxi Sciences. 2018; 25(5): 449-55.

[17] Zhang X., Wang S., He X., et al. Soil creeping in weathering crusts of carbonate rocks and underground soil losses on karst SULopes. Earth and Environment. 2007; (3): 202-6.

[18] Zhang X., Wang S. A discussion on the definition of soil leaking in a karst catchment. Carsol Sin. 2016; 35(5): 602-3.

[19] Dai Q., Yan Y. Research progress of karst rocky desertification and soil erosion in southwest China. J Soil Water Conserv. 2018; 32(2): 1-10.

[20] Wang H., Xiong K., Yang Y. Mechanism research of soil and water loss underground in karst region. Soil and Water Conservation in China. 2009; (8): 11-4+64.

[21] Xiao S., Ye Y., Zhang W., et al. Carbon and nitrogen contents in calcareous soil aggregates affected by disturbance and land use in karst region, China. Chinese Journal of Ecology. 2016; 35(5): 1140-6.

[22] Jiang Z., Luo W., Deng Y., et al. The leakage of water and soil in the karst peak cluster depression and its prevention and treatment. Acta Geoscientica Sinica. 2014; 35(5): 535-42.

[23] Tang Y., Zhang X., She T., et al. Wet sieving for stability of brown clayey in karst rocky desertification area in Puding county, Guizhou province. Journal of Engineering Geology. 2009; 17(6): 817-22.

[24] Luo W., Jiang Z., Ouyang R., et al. Typical soil and water conservation technology of karst peak-cluster depression. Soil and Water Conservation in China. 2013; (1): 37-41+69.

[25] Wang K., Su Y., Zeng F., et al. Ecological process and vegetation restoration in karst region of southwest China. Research of Agricultural Modernization. 2008; 29(6): 641-5.

[26] Zhang X.-B., Wang S., Cao J. Mass balance of silicate minerals in soils and soil losses in the karst mountainous regions of Southwest China. Earth and Environment. 2009; 37(2): 97-102.

[27] Li J., Xiong K., Wang X. Observation of subterranean soil and water loss of karst area. Soil and Water Conservation in China. 2012; (6): 38-40+76.

[28] Canora F., Fidelibus M.D., Sciortino A., et al. Variation of infiltration rate through karstic surfaces due to land use changes: A case study in Murgia (SE-Italy). Engineering Geology. 2008; 99(3-4): 210-27.

[29] Xingping W., Deti X., Jiupai N., et al. Soil erosion and loss on slope in karst valley area, Chongqing with 137 Cs. Journal of Basic Science and Engineering. 2015; 23(3): 462-73.

[30] Hu Y., Dai Q., Wang P. Runoff features and the influencing factors on karst SULoping farmland. J Soil Water Conserv. 2012; 26(6): 46-51.