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Original article

Complex influence of relief on the erosion of Red Ferrallitic soils at a local scale

Influencia compleja del relieve en la erosión de los suelos Ferralíticos Rojos a escala local

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ABSTRACT: Studying the relief through morphological analysis allows typifying forms, elements and structures of the karst relief that help in the understanding of the genesis, evolution and dynamics assumed by the erosion of the Red Ferrallitic soils. It is a particularly important circumstance in the Southern karst Plain Havana-Matanzas, to understand how and why certain information is preserved and others are lost as the research is carried out from one scale to another, which has led to certain myths and uncertainties about the degradation processes of these soils. The present work aims to analyze the complex influence of relief and geographic scale on the understanding of karst-erosive processes in the areas of influence of karst depressions from a baseline of more than three decades, which demonstrates the unidirectional advance of karst-erosive dynamics in accordance with the conditions of use and management to which they have been subjected. It is concluded that the recognition and spatio-temporal evolution of erosion forms is only possible at a local scale and not from a simple rescaling of the variables to large areas, in order to avoid different interpretations in the erosion maps of the Red Ferralitic soils in Cuba.

Key words: degradation, karst, relief.

RESUMEN: Estudiar el relieve a través del análisis morfológico permite tipificar formas, elementos y estructuras del relieve kárstico que auxilian en el entendimiento de la génesis, evolución y dinámica que asume la erosión de los suelos Ferralíticos Rojos, circunstancia particularmente importante en la Llanura Kárstica Meridional Habana - Matanzas, para comprender cómo y porqué cierta información es preservada y otra se pierde conforme la investigación se ejecuta de una escala a otra, lo que ha propiciado ciertos mitos e incertidumbres sobre los procesos de degradación de estos suelos. El presente trabajo tiene como objetivo analizar la influencia compleja del relieve y la escala geográfica en la comprensión de los procesos kárstico - erosivos en las áreas de influencia de las depresiones kársticas, a partir de una línea base de más de tres décadas, que demuestra el avance unidireccional de la dinámica kárstico - erosiva, en conformidad con las condiciones de uso y manejo a que han estado sometidos. Se concluye que el reconocimiento y evolución espacio - temporal de las formas de erosión solo es posible realizarla a escala local y no a partir de un re-escalamiento simple de las variables a grandes áreas, para así evitar diferentes interpretaciones en los mapas de erosión de los suelos Ferralíticos Rojos en Cuba.

Palabras clave: degradación, karst, relieve.

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INTRODUCTION

Soil studies carried out in the South Plain of Havana have shown that the relief and permeability of the supporting material mainly influence the variability of the ferrallitic coverage. If these two factors are evaluated at a larger scale, it is found that the development of karst forms (dolines, , poljes, etc.) and their consequences on the micro-relief create favorable conditions for the differentiated manifestation of erosive processes closely related to the variations of the micro-relief (1).

In this context, scale is an integrating concept widely used in various disciplines to refer to the qualities and geographical extension of the objects of study. Also, to specify some methodological principles of scientific research in relation to the methods of sampling and inference, from which are derived the properties of geographical objects that emerge or are visualized differently according to the level at which they are defined (2, 3).

Circumstance particularly important in the Southern Karstic Plain Havana - Matanzas to recognize the specific modalities of the erosion of the Red Ferrallitic soils and to determine how and why certain information is preserved and lost as the investigation is executed from one scale to another. It has propitiated certain myths and uncertainties on the degradation processes of these soils, to which the MINAG (4); CIGEA (5); Soil Institute (6) and IGT (7), continue to classify them as "not eroded". It is due to the conceptual generalization imposed by the scales of representation, where it is not possible to handle the concept of extension provided by the object, a situation on which it is imperative to reconsider given the unquestionable edaphological-heritage value of these soils (8).

Reflecting on these considerations, taking as a reference research, and published articles that reveal the effects of karst morphogenesis in Red Ferrallitic soils in western Cuba, the present work aims to analyze the complex influence of relief and geographic scale in the understanding of karst-erosive processes in the areas of influence of karst depressions. It is based on a baseline of more than three decades, which demonstrates the unidirectional advance of the karstic-erosive dynamics, in accordance with the conditions of use and management to which the soils have been subjected.

MATERIALS AND METHODS

Description of the investigated areas

The research was carried out in the polje of San José de Las Lajas, Mayabeque province, specifically, in the reference locality Rosafé Signet with an extension of 107 ha (Figure 1), where the karstic-erosive dynamics show different degrees of development in accordance with the conditions of use and management to which the soils have been subjected (9).

This agroecosystem has been classified as one of the most humid of Cuban plains, receiving around 76 - 80 % of the precipitations that occur in Mayabeque and Artemisa provinces (10,11). The most widespread soils are predominantly of the Ferrallitic Red Leached Type, which can be correlated with the Rhodic Eutric Nitisol (12) and the Oxisol order of the Soil Taxonomy (13), where the type of land use and the distribution of horizons give the differences.

The methodology was based on the application of the Integrating System of Qualitative and Quantitative Methods for karst regions (14), characterizing the karst depressions and their flooding regimes, as well as four main soil profiles

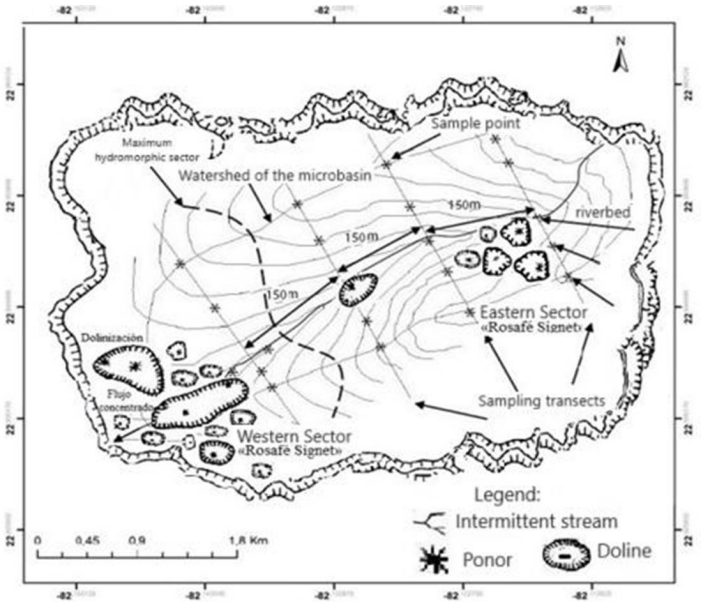

Figure 1. Transects and sampling sites in "Rosafé Signet" locality of the San José de Las Lajas polje, Mayabeque province

at depths of 0-20 cm, as well as at the level of the erosive diagnostic horizons A+B0-50 cm. All this in correspondence with geological-geomorphological variations and agricultural use (Figure 1).

The morphometric analysis of the karst absorption forms (dolines) was carried out at a scale of 1: 5,000 and was constituted the fundamental diagnostic index to evaluate the manifestations and intensity of karstification (Table 1). It should be noted that in 1966, when the "Rosafé Signet" Artificial Insemination Center was created, there was no karst depression in its agricultural production areas.

With the karst depressions identified, the maximum elevations (scarps) and minimum elevations (bottoms) of each depression were recognized. Once the bottoms and scarps of the depressions were marked, they were converted to polygons and, subsequently, an ID was assigned to each scarp, to conserve their height fields within their attributes, according to the proposal of (15).

Soil loss values in units of mass (t ha^{-1}> y r^{-1}), corresponding to the periods 1986 to 2019, were converted into units of length (mm y r^{-1}) (16). The interpretation of the loss tolerance limits considered were those proposed by the USLE model (17), which provided measurement criteria and changes in the system, from a baseline during the period $t0:_{1986 - 1996}$ and subsequent monitoring in the interval $t1:_{1996 - 2019}$.

RESULTS AND DISCUSSION

Historical-evolutionary analysis of morphogenesis in karst depressions

Studying the relief in long-standing reference localities allows typifying forms, elements and structures of karst depressions in their dynamic evolution. Especially when the research carried out in Cuba has underestimated the specific modalities assumed by the erosion of the Red Ferrallitic soils in these enclaves, which show phenomena not susceptible to be mapped or practically absent at scales of greater magnitude.

However, during each heavy rainfall, rainwater and surface irrigation water, usually carrying a certain content of carbon dioxide in solution, when they run off through the different elements of the meso- and microrelief (Figure 1). They do so in a diffuse way, directed towards the karst depressions because of the obvious concavity of the slopes, as well as the marked horizontal dismemberment of the territory, where the absorption forms and their component elements sequentially gain in magnitude, gradually exerting greater control over surface runoff.

Indeed, the sustained increase in the morphometric dimensions of dolines from the baseline t0:1986-1996 and subsequent monitoring during the period t1:1996-2019 (Table 2), confirm that an erosive process or modality inherent to the Red Ferrallitic soils is developing, whose most evident manifestations are the amplitude of their average dimensions at the reduction expense of interfluvial spaces (t0: 1986-1996: 27.80 % and t1:1996-2019: 30.77 % of the total agricultural area), as the emergence of other absorption forms detected in several exploration stages, which demonstrates the irreversible advance of karstification in its unidirectional evolution (18).

Complementarily, the sequential evolution of the morphometric parameters leads to increases in soil loss volumes, mainly in the wash collector type slopes with slope values between 5 and 8 %. They facilitate areal runoff through epigean absorption forms, mainly dolines and uvalas that tend to acquire ellipsoid or amoeboid forms (19), where the magnitudes of soil losses exceed the tolerance threshold values of 12.5 t ha^{-1} y r^{-1}, which is the maximum acceptable value proposed by the USLE (20). Accordingly, in the period t0(1986-1996) 51.14 % of dolines exceeded this threshold value, which increased during t1(1996-2019) to reach 87.5 % of the dolines, a dynamic that corroborates the observations in similar regions (21).

In contrast, in some cases the ferrallitic soil cover can model by accumulation these depressions with a red clay, called "*terrarossa*", which masks in a certain way the related mechanism of action. It has caused, largely, the undervaluation of this complex process, which is only possible to notice *in situ* and cartographically when it is represented at local scale, because as it is known, each investigation is carried out at a certain scale and its results cannot be valued without considering the adopted scale of analysis.

All this confirms the importance of long-term studies in karst ecosystems, since the transformations of landforms are complex and cannot be fully assessed in the short term, which has led to erroneous conclusions and inaccurate predictions in decision making for the management of Red Ferrallitic soils (22).

Sometimes, this maturity phase of karst morphogenesis has been favorable for the partial enlargement of some dolines under a process of capture or fluvial piracy (Figure 2). There the most favored depression, either by the shape of the slopes in its contours or the width of its micro-basin, manages to widen by the regressive or remontant

Table 1. Formulas used for the calculation of morphometric parameters

Circularity index	Flattening index	Diameter ratio
$IC = \frac{Dm + dm}{DM}$	$IA = \frac{Dm + dm}{4h}$	$Rd = {Dm}/{dm}$
Where: Dm = major diameter dm = smallest diameter	DM= average diameter h = height difference (surface - bottom)	

Table 2. Volume of losses of the Red Ferrallitic soils with the equivalence values of surface removal in the karst depressions and their areas of influence. Rosafé Signet" locality, Mayabeque province

Doline No.	Baseline/Monitoring t0:$_{1986-1996}$/t1:$_{1996-2019}$								Baseline t0:$_{1986-1996}$		Monitoring t1:$_{1996-2019}$	
	Area		IC		IA		RD		Volumen (t ha^{-1} year^{-1})	Superficial (mm year^{-1})	Volumen (t ha^{-1} year^{-1})	Superficial (mm year^{-1})
	(ha)				(m^2)							
• LOCALITY «ROSAFÉ SIGNET»												
1	1.90	2.26	1.70	1.72	8.65	8.57	6.50	5.66	16.89 A	1.24 A	17.87 A	1.30 A
2	1.13	1.33	1.74	1.47	8.51	6.12	9.01	6.96	17.27 A	1.29 A	20.16 A	1.46 A
3	3.53	3.91	1.52	1.36	5.65	5.40	14.84	9.82	21.74 MA	1.59 MA	23.63 MA	1.74 MA
4	1.90	2.30	1.73	1.55	14.08	9.86	9.19	6.87	14.55 A	1.06 A	14.65 A	1.09 A
5	2.91	3.44	1.37	1.13	11.74	8.89	30.90	22.17	9.18 T	0.67 T	11.99 A	0.88 A
6	1.37	1.74	1.54	1.33	13.07	11.80	14.07	10.61	9.56 T	0.70 T	10.72 A	0.79 A
7	2.28	2.73	1.29	1.04	7.39	7.82	105.5	76.51	13.91 A	1.02 A	12.43 A	0.89 A
8	2.45	2.80	1.74	1.56	13.41	11.17	9.11	6.82	11.03 A	0.80 A	12.69 A	0.93 A
9	1.30	1.57	1.33	1.12	13.52	10.18	46.93	28.20	9.58 T	0.70 T	10.87 A	0.80 A
10	1.50	1.96	1.38	1.28	9.67	9.66	29.66	21.23	11.12 A	0.81 A	12.55 A	0.91 A
11	3.08	3.53	1.98	1.85	9.66	8.96	6.71	5.17	18.15 MA	1.33[a]	19.70 MA	1.43 A
12	1.43	2.23	1.34	1.15	7.91	8.20	66.00	32.08	13.06 A	0.95 A	14.75 A	1.12 A
13	1.27	1.51	1.83	1.66	8.99	8.19	8.00	6.03	17.39 A	1.27 A	18.91 A	1.39 A
14	1.88	2.19	1.66	1.18	10.26	8.58	22.70	17.92	10.95 A	0.80 T	13.52 A	0.99 A
Media	**1.99**	**2.39**	**1.58**	**1.38**	**10.18**	**8.49**	**27.08**	**17.26**	**12. 89 A**	**0.97 A**		
• DOLINES DETECTED DURING THE MONITORING OF 1996												
15	----	0.89	----	1.26	----	8.53	----	12.88	------	0.49 T	14.53 A	1.39 A
16	----	0.93	----	1.52	----	3.87	----	7.17	------	0.76 T	15.55 A	1.97 MA
Media	**----**	**0.91**	**----**	**1.39**	**----**	**6.2**	**---**	**10.02**	------	----	**15.28 A**	**1.19 A**
• DOLINES DETECTED DURING THE MONITORING OF THE YEAR 2019												
17	----	0.65	----	1.70	---	8.17	---	5.45	----------		8.23 T	0.38 T
18	----	0.90	----	1.49	---	7.23	---	8.01	----------		9.05 T	0.41 T
19	----	0.54	----	1.33	---	9.48	---	15.67	----------		10.69 A	0.63 A
20	----	0.64	----	1.29	---	7.66	---	9.28	----------		8.97 T	0.46 T
21	----	0.45	----	1.44	---	6.65	---	7.73	----------		9.45 T	0.74 T
Media	**----**	**0.64**		**1.45**	**----**	**7.84**		**9.23**	----------		**9.28 T**	**0.52 T**

L.B. (Línea base t0:$_{1986-1996}$); M (Monitoreo t1:$_{1996-2019}$). A: Alto; MA: Muy alto y T: Tolerable L.B. (Baseline t0:$_{1986-1996}$); M (Monitoring t1:$_{1996-2019}$). A: High; MA: Very high and T: Tolerable.

erosion of its headwaters at the expense of the less favored one, which can originate an uvala.

This advance in karstification intensifies the conditions of hydromorphism and dissolution of the underlying materials with an uneven temporal seepage and with a strong effective porosity (between 5 and 15 %). It is demonstrated morphometrically by the decrease in depth (up to 5.34 m) and increase in karstification, as has occurred with dolines No. 2 and 3 (Table 1), where the latter, with a microbasin of greater receiving capacity decapitates or strips the head of runoff from doline No. 2 (Figure 3).

Similar dynamics can be expected with dolines 10 and 11 in a future scenario, generating different associations or miniaturization phenomena in the territorial complex itself at the micro and nano relief level, inducing "dolinization" (with a marked tendency towards endorheism). This process is due to the effect of management practices, changes in the use of soil cover, extreme hydrometeorological events associated with climate change and the karst process can reach its paroxysmal phase with a substantial reduction of the agroecosystem's useful land base, which coincides with the results obtained by (23, 24) in similar regions.

However, this morphodynamics may be modified by the peculiarities that characterize the development and maintenance of the slopes (slope, length and shape), the lithological structure regularity, as well as by the diffuse drainage lines that show the sectors that descend towards the karst absorption forms (Figure 4), with outcrops of fragmented subangular limestone oriented towards these depressions. In this, the hydrophilic vegetation is located at levels below 50 m in the bottoms of the sinkholes, etc., which constitute, at first sight, features of a degradative process in full development, which at micro-relief level can adopt their own modalities, influencing soil losses (25).

It is necessary to indicate that the relationship between doline area and morphometric parameters is not a *sine qua non* condition for the analysis of soil losses, since this relationship is highly dependent on the degree of irregularity of the contours of the absorption forms and conditions of use of the soil cover, in the same space over time (26).

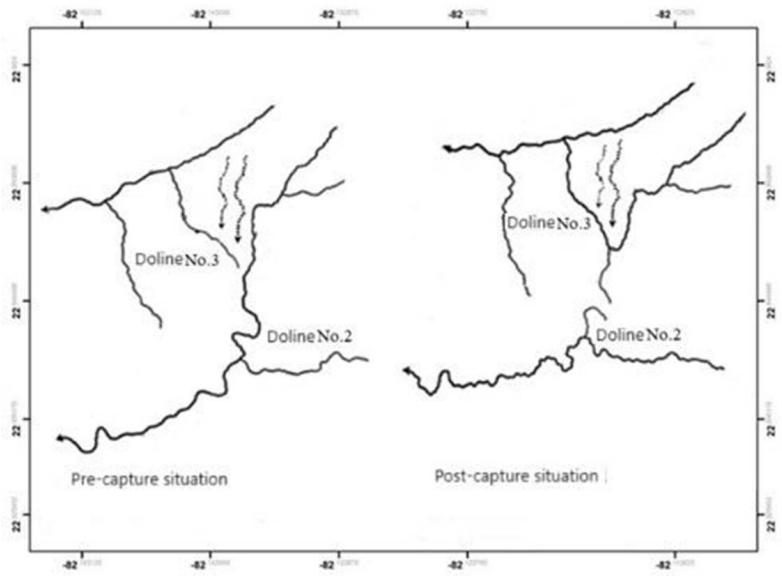

Figure 2. Fluvial catch in the western sector of the "Rosafé Signet" locality, Mayabeque province, Cuba

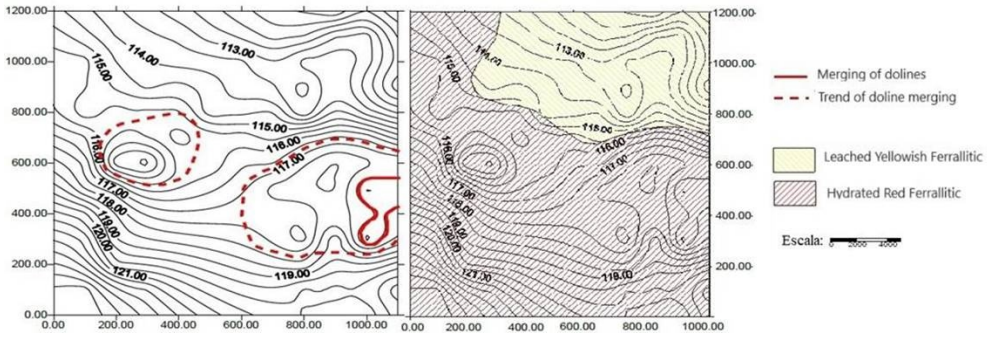

Figure 3. Union trend of two sinkholes to originate an uvala in the locality "Rosafé Signet", Mayabeque province, Cuba

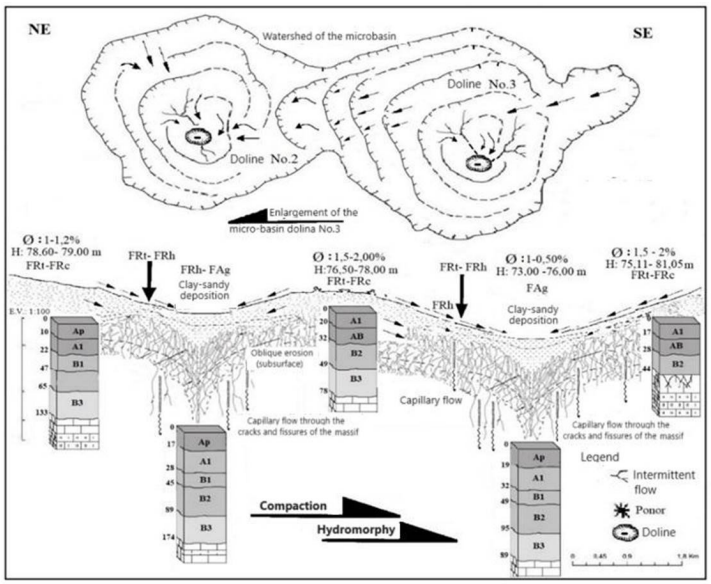

Figure 4. Union trend of two sinkholes to originate an uvala in the locality "Rosafé Signet", Mayabeque province, Cuba

The geographic scale as an integrating concept in the understanding of karstic-erosive processes

Taking these aspects into consideration (27-29) it is necessary to incorporate the local scale as a resolution level associated with a specific and physically delimitable area to differentiate at the meso-, micro- and nano-relief level the set of processes that simultaneously participate in the formation or degradation of Red Ferrallitic soils. Also, to understand how water and karst-erosion manifestations are generated or expressed differently as one moves from one scale to another (Figure 5) (30). Thus contributing to a better understanding of the spatio-temporal dynamics that take place in the depressions and their areas of influence, since these areas are characterized by being part of a whole that contains it and is much broader.

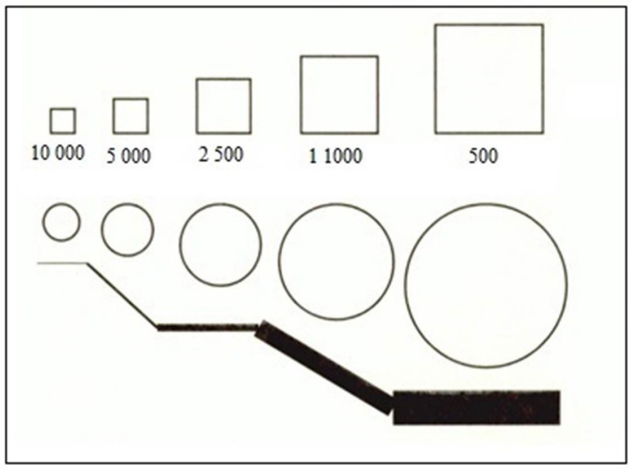

Figure 5. The cartographic perception of the doline and area of influence depends on its surface

It is important to keep in mind that this suggests problems at the level of analysis or synthesis, since they are limited or are biased by the cartographic scale that represents the phenomenon. Thus denying the possibility of perceiving what happens at higher or lower scales, significantly affecting the analysis and explanation of the karst-erosive phenomenon.

"Rosafé Signet" center authorities, aware of the progressive advance of the karstic depressions and, in an attempt to recover the land bottom destined to the cultivation of pastures for fodder. It dumped in sinkhole No. 3 in 2003, 20 trucks with a capacity between 5 - 7 t, which represented a volume of more than 100 t (E. Lamoroux, *commun. pers.*). It is to be noted that in the executive phase of the investigation it was found that the doline was not refilled, and that the process of dissolution through the ponor continues. Therefore, this practice was not at all effective from the environmental point of view, because it obstructed the drainage ways through which the runoff takes place (functional ponors). Nor was it effective from an economic point of view.

However, the presence of sinkholes is often not considered a problem for the prevention of soil loss and other natural disasters, since these forms are usually relegated in terms of geological risks. Even their environment of influence is close to urban centers, agricultural or industrial areas, which can alter the initial conditions of the pedogenesis-morphogenesis balance, where the preservation of the karst landscape should be a priority, hence the importance of scale to explain correctly these geographic phenomena.

CONCLUSIONS

- The recognition and spatio-temporal evolution of the forms of water erosion and karst-erosion in the areas of influence of karst depressions is only possible at a local scale and not from a simple rescaling of the variables to large areas, in order to avoid different interpretations in the erosion maps of the Ferrallitic Red soils in Cuba.
- Whatever the concept adopted, the relativity in the vision of the same fact, from different scales, constitutes an extremely enriching option to demonstrate definitively the erosion of Red Ferrallitic soils in karst regions.

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