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Study of the Landslides in the Lesser Antilles: The Plant Dynamics between the Trigger Factor and the Spatio-Temporal Risk Indicator

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Abstract **-Landslides are of variable magnitude events, often one-off and low occurrence, sometimes scattered, inducing direct (destruction of homes, road infrastructure) and indirect (obstruction of traffic beyond the area affected, economic and social costs) there are well-defined area of territory. The definitions concerning landslides are relatively complex, because there are a plurality of phenomena with features and different mechanisms. Overall, these movements more or less brutal ground or basement, under the effect of natural and / or man. In the 1970s, there was talk of "ground movement", but experts have opted for the term "landslide" [1], more encompassing all forms and manifestations of displacement. Clearly, these phenomena represent natural potential risk for companies and a major challenge in development issues at all scales of territory, hence the need to put in place risk management systems and efficient alert. In this regard, a draft analysis was performed on the linkage between vegetation dynamics and landslides in a specific insular space: the Lesser Antilles and especially at the island of Martinique.**

Keywords**-Landslide, vegetation dynamics, natural hazards, risk management, territory, Lesser Antilles.**

I. INTRODUCTION

The common geologic history for the majority of the Lesser Antilles islands, in fact of the Territories is fully affected by landslides. Martinique is an interesting area as the prevailing morpho-climatic conditions are particularly conducive to the occurrence of these phenomena and tovegetation development. It is worth noting that in the same way as for earthquakes, there is no warning for most landslides as there are for floods or volcanic eruptions, which enhances the effect of surprise, or/and the occurrence of a crisis situation. However, according to the type of landslide (slide, mudflows, etc.), there are signs in the affected area which could be taken into account [2], but which are often overlooked, in principal the vegetation. These phenomena occur both in space and time, a study of the vegetation dynamics would be a contribution in understanding their mechanisms and their management. How can the plant canopy play a role in an area affected by a landslides? How can a study of vegetation dynamics reinforce the landslide risk management strategies?

The focus of this article is to emphasize that the vegetation reading in an island territory of the Lesser Antilles can be a key element for understanding landslides (spatial scope and recurrence) andespecially forunderstanding the affected territory in order to develop and optimise the management measures (monitoring, alarm systems).

II. RECURRING LARGE-SCALE EVENTS IN MARTINIQUE, PROOF OF THE LINK BETWEEN VEGETATION AND LANDSLIDES

Our last surveys of the Lesser Antilles (Fig. 1) regarding the landslide risk management structures, the databases and listsallowed us to emphasize that their existence can disrupt the functioning of these insular areas.

Fig. 1. Location of Martinique in the Lesser Antilles

The databases and surveys come from each island's risk management structures. For example the BRGM plays this rile in Martinique or the Office Disaster Management (FOM) for Dominica. The ubiquity of these phenomena also creates the need to mitigate their consequences.

A. Presentation of the field of study

Martinique's rocks and the tectonicconstraints they suffer have created itsgeological and geomorphological characteristics, conducive to the occurrence of landslides. The island is primarily made up of volcanic and volcano-sedimentary formations [3]. The oldest parts of the island are approximately 25-30 million years old and are located to the South and East. The geological formations become increasingly recent as we move towards the West and North. The active Peléevolcano is circa 300,000 years old. The distribution of these formations depending on the age and type, translates intomore rugged formations if they are young and even more modified ones when they are old [3]. Thus, the modification status of these formations essentially depends on their nature, their age, but also the rainfall regime to which they are subjected. The rainfall regime depends on their altitude and their upwind or downwind location. All these processes play an important role in the occurrence of landslides, and specifically of landslides and mudflows.

With a density of more than 346hab/km2 according to INSEE (2012), Martinique is one of the most densely populated French departments. The population is concentrated mainly in the centre, in the Schoelcher/Fort-de-France/Lamentin metropolitan area. There is a clear imbalance between the northern and southern parts. The North is much less populated than the South due to its steep terrain. However, there are houses in places, mainly on slopes or on the bottom of valleys and often in the vicinity of roads. It is precisely the high occupancy of these areas that is also a landslide trigger factor and increases their effects. In addition, the road infrastructures are present throughout the territory, constituting a real dense network,decreasing the soil protection, except in the Pelée and Pitons du Carbet mountains, which are little affected by the listed landslides. The road network also represents an essential element in the weakening of the slopes (Fig.2.).

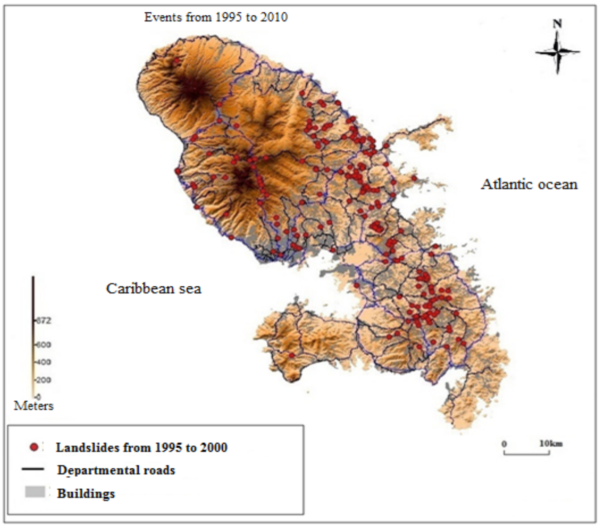

Fig. 2. Distribution of landslides listed from 1995 to 2010 based on the housing road network

B. Methodology

Given the plethora of landslide events recorded in Martinique, we had to establish a typology. It resulted in a classification of events according to two categories: diffuse and punctual events and recurring large scale events.Ifthe first are shallow landslides (less than 10 m from the surface, [4]) and a fewcentimetresthick [4], the second ones mobilize a more important materials volume or several tens of thousands of metres cube, on a large surface. They are also called "slow landslides" and therefore active ones, resulting in their recurring character. Actually, the recurrence of these large-scale landslides makes the relevant area hazardous for the exposed factors. Their specific features mean that stabilisation and reinforcement are impossible in the immediate future. The works would therefore require significantly more technological efforts and time. They are therefore of interest for our study because they generate a crisis situation due to their very important size involving many technical and financial resources. Their analysis will reveal a visible and usable relationship between "the plant dynamics" and landslides.

It is clear that there are relationships between soil and vegetation within the soil system, and therefore between the landslides and the vegetation development processes. That is why the study of vegetation dynamics seems important to integrate in the analysis of these stresses represented by recurring large scale landslides. These events occur both in time andspace, therefore the study of vegetation dynamics can highlight the different stages of large landslides evolution in Martinique but can also identify areas potentially at risk.

We have therefore conducted a general description, with the "plant formation"as the reporting unit [5], designating a community of plant species with a particular physiognomy, characterizing a specific landscape. The conducted field work consists of several phases(Table I).It is worth noting that we do not have a detailed floristic study. We note also that the delimitation of the areas under the influence of landslides carried out in "phase 1" depends on the measures collected in the field by BRGM.

Table I

Presentation of the different phases of the field study

PHASE 1	Delimitation of the zone characterized land slides
PHASE 2	Determination of the various evolutionary stages of vegetation
PHASE 3	Definition of biological types of dominant species in the study stations

III. THE ROLE OF VEGETATION IN UNDERSTANDING THE RECURRING LARGE-SCALE LANDSLIDES

In an area affected by recurring large scale landslides the vegetation dynamics can play a double role: initiating factor and spatio-temporal indicator. First of all we will see that it can be a trigger.

A. The vegetation: trigger factor of landslide phenomena

Three forces come into action when the land is destabilised and slides down the slope: the forces of gravity, friction and cohesion [6]. The force of gravity depends on the slope. There are several superimposed layers (strata) in the soil and underground. The force that slows down the layer of soft ground or rock against the underlying layer is the friction force. The cohesive force is based first on the attraction of the soil particles between each other and on the other hand on the attraction between these particles and the water in the soil. Gravity represents the driving force. The friction force and the cohesion force are resistance forces. To ensure that there is balance and therefore stability the resistance forces must be higher than the driving force. If the balance is broken, there is a break in the strata and a land mass begins to slide down the slope. The resistance forces can be reduced by the importance of vegetation (Fig.3). It should be noted that the impact of these forces including the driving force varies depending on the soil formation. For example, a soil can form from an existing rock, a rock on a modified site, from fossil soil or even a superficial formation.

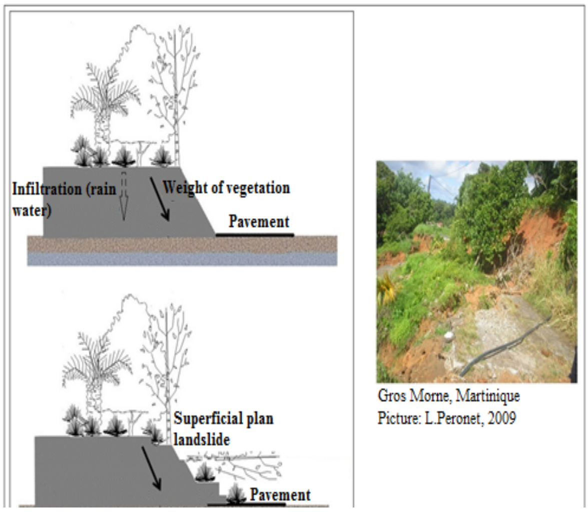

Fig. 3 Examples of landslides supported by vegetation

It is true that the latter can represent a soil cohesion factor through root networks and it can also limit erosion. However, very high trees and too dense vegetation can have the opposite effect by catching the wind, it's called “the lever arm effect”. The best would be to maintain a certain height of the vegetation to maintain the soil/vegetation equilibrium. In our study areas affected by landslides we could in factsee a lot of vegetation mostly at the level of road infrastructures, and these spaces were not maintained. This vegetation had several strata. First, an herbaceous layer (between 5 and 80cm) mainly composed of ferns. Then a shrub layer (from 80cm to 5 m) with woody plants, especially young trees and a tree stratum (individuals over 5 m and reaching beyond 10m).

B. The vegetation as a stabilizer and temporal and spatial indicator of slope mobility

We must not forget, on a smaller scale, the vegetation’s mechanical action. Roots help stabilize the soils by vertical anchorage, increasing resistance to wind. Admittedly, this action is more significant on a large scale. Research regarding the negative effects of logging on the landslide activity on the island of Vancouver in Canada in 2000 proved it [7]. However, the anchoring effect is limited by the depth of the roots, and can destabilize the soil creating preferential pathways for infiltration water.

However, the vegetation dynamics can also be a temporal indicator of slope mobility. This is particularly visible in the case of recurring events of great magnitude. Works of general natureon the composition, changes in floristic and vegetation dynamics represent a branch of biogeography, which starts from the observation that different plant species do not colonize a given space by chance. Therefore every moment of the landslide evolution corresponds to the appearance or disappearance of a species, or even of several species.

Accordingly, the analysis showed that there are still active large-scale landslides and that others have stabilized. This difference is based on the various stages of vegetation evolution. Thus, for example, the presence of the tree vegetation stage, with the most advanced physiognomy [8], and the recovery rate of the trees allow us to note the stabilisation of the landslide. In fact, after a landslide has stabilized the zone can allow vegetation to recolonize the area. Conversely, the presence of herbaceous vegetation (less advanced) proves its instability and a recurring landslide. It also allows us to observe the imprint left by man(reinforcement work, earthworks, clearing, etc.). We can make this observation for some “major landslides” in Martinique.

IV. COMPREHENSIVE APPROACH TO PLANT DYNAMICS IN THE STUDY OF “MAJOR LANDSLIDES” IN MARTINIQUE

Formany years Martinique experienced landsides phenomena which have the particularity of having significant scope and reactivating due to rainy episodes. In addition, they have serious consequences and therefore cause almost chronic crises with paroxysmal stages.

Only the most significant cases in relation to the vegetation cover have been retained in the study, namely: the landslide at a place called "la Medaille" at Fort-de-France, the landslide of the Bellefontaine cliff, the landslide of “Porte d’Enfer”in Fonds-Saint-Denis and the "Soleil Levant"landslide in François. The Table II below allow us to understand the magnitude and the gravity of some of these events and the need to implement efficient management measures.

Table II

Main information about some great landslides of the study field

	“ Soleil Levant “ 2004 Landslide	**“ Bellefontaine “ 1991 Rockfall**
Size	250 m long 300 m area Depth 13,000 m^2 (BRGM 2004)	Displaced Volume 150,000 m^3 200 m wide 500 m in height (BRGM)
Years of reactivation	2004, 2008 (BRGM)	
Consequences	15 houses affected among which 8 have been demolished and 5 in demolition project. (BRGM, 2005) 19 persons evacuated and relocated. (France ANTILLES. 2004).	National road (RN2) blocked for 24 days. Caribbean coast paralyzed. Traffic diverted by alternate routes.
Total costs		Cost of debris removal and work circa 8,000,000 € (DDE, 1991)
	“ la Medaille “ 1915 Land slide-water run	**Fonds-Saint-Denis “Porte d’enfer” 1988 Landslide**
Size	21 m depth 125 m long 110 m wide displaced Volume 13,000 m^3 Slope 50° (BRGM. 1966)	Displaced volume 800,000 m^3 25 m depth 150 m width 300 m long (General Council)
Years of reactivation	1966.1967 1976, 1980, 1983, 1993, 2002,2007 (BRGM)	Gradual acceleration of the movement from 1994 to 1998. (General Council)
Consequences	10 dead in 1915 RN3 closed for 3	Interruption of the RDI road on 150

	months in 2002 Continuous problems on the RN3 from 2002 to the present day (BRGM 2002)	m RDI closed from 1998 to 2007 2007 progressive reopening (General Council 2008)
Total costs	Earthworks and reconstruction of the RN3 road work estimated at 1600 000€ (General Council 2007)	Thelandslide monitoring 250,000 € Reconstruction of road (earthworks, drainage. etc.) 8,000,000 € (General Council 2008)

A. The "la Medaille" and "Fonds-Saint-Denis" landslides, two significant cases

The different stages of vegetation with specific physiognomyare very visible in the"la Medaille" landslide. Three parts are clearly distinguishable in the landslide area (Fig. 4). We see a central part in a grass stage (zone 2) bordered on the sides by two wood formations with treesin different stages of evolution (areas 1 and 3).

This has allowed us to understand that one part has been mobilized recurrently (zone 2), because the grassy stage is maintained. The two parts in the tree stage are not populated by the same species, reflecting a different age of stabilisation. In the left area (area 1) the vegetation is denser consisting of "bois canon" trees (*Cecropiaobtusa*) between 12 m and 20 m, which means that it has been stabilized for a long time, circa 20 or even 30 years ago. In the right zone we see an endogenous species (zone 3): the tree fern (*Cyatheamedullaris*), which shows an ecosystem in the advanced colonization phase. We can therefore estimate the stabilisation of this part at circa 10 years ago, a much more recent stabilisation than that of zone 1. It is true that the humid microclimatic conditions of the area encouraged the development of ferns.

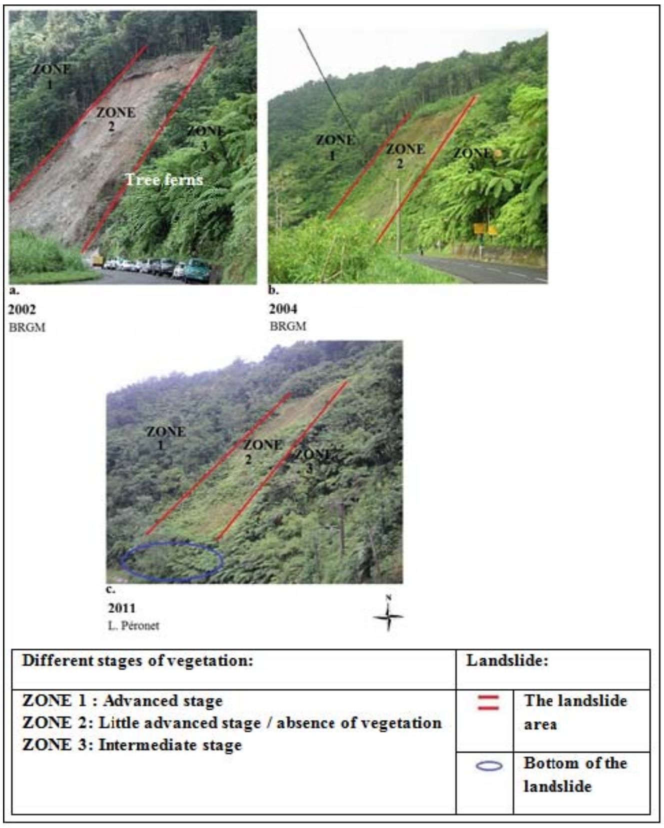

Fig.4. The evolution of vegetation based on landslide reactivation in the district of "la Medaille"

However, they also reveal an essential element, in other words the presence of water in the soil which is very favourable to the triggering of landslides. Thus, the massive invasion of this vegetation type is proof of the existence of a more or less important water circulation on the slope. In photography c. (status of the area of the "la Medaille" landslide in 2011), at the foot of the landslide we can also see the strong colonization of these tree ferns (see the area circled in blue), proof of water accumulation. Therefore, the basis of this slope part is weakened, increasing the risk of landslide recurrence. The consequences are also clearly visible on the RN3 road which has been undergoing significant problems since 2002 [9].In 2002 the national road RN3 (strategic axis serving the northern part of the island) was closed for three months.

Regarding theFonds-Saint-Denis landslide, the vegetation recolonization was also fast, following the stabilisation of the site by the construction of reinforcement work across the unstable area, which favoured a more advanced stage of vegetation (Fig. 5.).

Therefore, this picture shows a top to bottom gradient of the different stages of evolution. Zone 1 corresponds to the advanced stage with a tree vegetation type (stable area). Then we see the advanced herbaceous stage in zone 2 (relatively stable area more humid than the previous one) with the development of tree ferns as on the "la Medaille" site. And in zone 3 we see a less advanced grass stage, with the imprint of the landslide rupture area still visible.

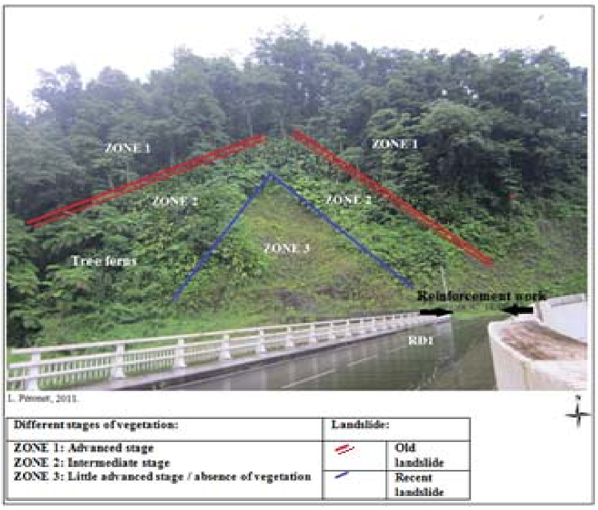

Fig 5.The different vegetation stages in the area of the Fonds-Saint-Denis landslide in 2011

The presence of water circulation isclearly notable depending on the areas. The expert assessments carried out by the General Council corroborate this fact by demonstrating a correlation between the level of the water table fluctuation and the landslide reactivation. In this sense, every increase in the monthly average piezometric level represents an acceleration of the landslide. The piezometric level varies with the rainfall rate. There is a double water circulation in other words: infiltration and runoff, which are increased during heavy rains, activating the landslide. As previously stated, this circulation promotes the presence of particular plant species such as ferns, but also explains the high vegetation density and its rapid growth (inthe stabilized areas).

B. *The vegetation dynamics, proof of significant anthropisation*

The Bellefontaine and the "Soleil Levant" landslides are different from the previous cases because we do not see the same type of vegetation and the evolution stages are less marked.

In the landslide area of the Bellefontaine cliff, we see a xerophytic type of vegetation with predominating thorny species, since this is a drier environment which faces the sea.This is the Leeward side of the island which suffers the foehn effect. The vegetation is less dense than previously, because after this very large landslide and anthropic actions (reprofiling the slope, setting up nets), the site’s vegetation recolonization was limited (Fig. 6.) and dependson the micro-topography (we must differentiate between the vertical walls and the little flat areas more favourable to the installation of a few pioneer plants).

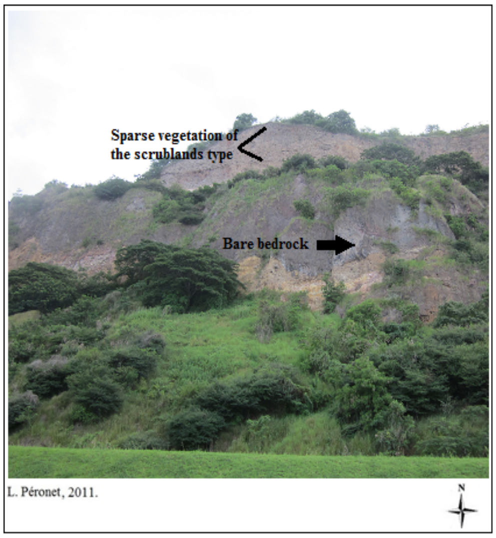

Fig 6.Evolution of the vegetation in the bulge area of the Bellefontaine cliff

The ground has virtually disappeared, and there is no adequate basis for vegetation development. The only places where it could grow correspond to accumulation zones with a mixture of rock debris. In addition, the presence of water is less obvious than in the previously mentioned cases, and we see that the area has stabilised since the works carried out to reshape the cliff slopes.

The relative stability can also be clearly seen in the landslide area of the "Soleil Levant" site (Fig.7.).

a.
Bottom part of the landslide at Soleil Levant in 2005
L. Péronet, 2005.

b.
Same area in 2011
L.Péronet, 2011.

Fig 7. Evolution of the vegetation in six years on the "Soleil Levant" landslide site in the François area

However, although this is an old stabilized phenomenon, the presence of the tree type vegetation is less advanced than in the previous ones. The plant response remains little visible, because there is strong anthropization in the area, with a housing area organised in a subdivision. Plant colonization takes place because part of the area is abandoned. In addition, a change was made to the morphology of the terrain with the creation of a bulge, caused by the land brought by the landslide. Numerous works were also carried out around the departmental road (RD6) in order to secure the area and allow the resumption of traffic.

V. CONCLUSION

The study shows a process of rapid vegetation recolonization in the relatively stabilised areas. And especially a relationship between vegetation and landslides. Each slope destabilisation causes different vegetation responses. Therefore, the instabilities result in the permanent rejuvenation of the vegetation. It has also allowed us to confirm the fact that these phenomena affect the territory not only due to their size, but especially due to their recurrence. The contribution of the vegetation analysis seems to be complementary to other field expert studies (topography, geology, etc.), in the sense that the vegetation is the visible proof of some important triggers, in principal the water. In the case of the La Medaille landslide, this knowledge was significant in the decision-making process concerning repeated works for the reinforcement of the national road.

This represents the start of a study that will be deepened by an analysis of the plant spatial morphology, in principal by studying the root system (length, depth, water retention...) of species colonizing areas affected by a study of the structural distribution of the vegetation cover (stratification, recovery rate and abundance dominance).

In the end, this will allow us to underline the importance of reading the vegetation in an island territory of the Lesser Antilles as a key element in understanding landslides (spatial scope and recurrence) and especially in the affected territory. Ultimately, we can certainly improvethe management methods (monitoring, alarm systems).

VI. ACKNOWLEDGEMENTS

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