Impact of fire on savanna vegetation trends in Madagascar assessed using a remote sensing based statistical analysis

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Impact of fire on savanna vegetation trends in Madagascar assessed using a remote-sensing based statistical analysis

Anne JACQUIN[a,1] , Véronique CHERET[a] , David SHEEREN[b] and Michel GOULARD[c]

[a] *Université de Toulouse, Ecole d'Ingénieurs de Purpan, 75 voie du TOEC, BP57611, F-31076 Toulouse Cedex 3, France*

[b] *Université de Toulouse, INPT-ENSAT, UMR 1201 DYNAFOR, BP32607, F-31326 Castanet-Tolosan, France*

[c] *INRA, UMR 1201 DYNAFOR, Chemin de Borde-Rouge, Auzeville, F-31326 Castanet-Tolosan, France*

Abstract. Fire is a factor in the disturbance of savanna vegetation dynamics. This factor interacts in a complex way with other factors such as land use and climatic conditions. Fire could be considered as a factor that maintains savanna or as an agent of its degradation. In a context of land degradation prevention, the goal of this study is to clarify the role of fires in trends of savanna vegetation cover. The study site is located in the Marovoay watershed, on the north-west coast of Madagascar. This is one of the five pilot sites of a national programme of soil erosion control called PLAE. The role of fires in trends of savanna vegetation cover was addressed though a landscape-scale analysis of the spatial relation between a fire regime indicator, which combines fire seasonality and frequency, and an indicator of vegetation cover change. These data were derived from MODIS remote sensing time series data covering the 2000-2008 period. For each type of savanna vegetation cover trends observed (negative, positive or stable), different multivariate regression models were fitted. The results of this study clearly support the idea that fires have widely varying impacts on savanna vegetation cover. Fires are a savanna management tool. But, their usages through the seasonality and the frequency should be adapted according to land use (agricultural area, pastoralism, protected area). To define a fire management plan on the landscape-scale, it will be necessary to study locally the interactions between fire usage, land use and vegetation cover trends. The methods based on remote sensing time series analysis provide relevant results. There are statistically significant relations, according to land use, in the Malagasy savanna between fire regime and vegetation cover trends.

Keywords. Savanna, fire, vegetation trend, remote sensing, Madagascar

Introduction

Savannas constitute a complex ecosystem marked by the coexistence of an herbaceous layer and one or more shrub and/or tree layers under the effect of interactions between several environmental factors: varied rain

1 Corresponding Author: Anne Jacquin, Laboratoire de Télédétection et Gestion des territoires, Ecole d'Ingénieurs de Purpan, 75 voie du TOEC, BP57611, 31076 Toulouse Cedex 9, France ; e-mail : anne.jacquin@purpan.fr

regimes, role of fire and of stockbreeding. Purely herbaceous and purely ligneous ecosystems represent the extremes of a “savanna” continuum which can be defined as a functional entity linked to the grass-tree equilibrium [1]. Savannas have a highly heterogeneous spatial structure, resulting from the spatial distribution of trees (density) and from the characteristics of the soil (capacity to retain water, and organic matter content). This has consequences on the intensity of the environmental factors which also have a great spatial variability. Fire is more or less intense depending on the amount of herbaceous biomass. Herbivores prefer to graze in certain areas rather than others depending on the quality, quantity and availability of herbaceous resources. The elimination or modification of one of the factors linked to grass-tree equilibrium results in savanna functioning being disturbed. This disturbance leads to a change in plant cover structure depending on the intensity of the pressure factors and/or their length.

Even if fire is acknowledged to be a factor for explaining the dynamics of savanna vegetation, its importance and role are not always clearly defined [2]. Two parameters, the occurrence period and frequency of the fires, define the fire regime [3] and affect the vegetation cover. These two parameters take into account two time scales. On the intra-annual scale, early fires in the dry season favour the development of ligneous species to the detriment of herbaceous species [4]. However, this same type of fire promotes the development of new growths which have a high fodder value [5]. Furthermore, these fires are easier to control and contribute less to aggravating the risk of soil erosion than do fires at the end of the dry season [6]. On the inter-annual scale, regular burning can lead to a degradation of the herbaceous savanna by altering the relations of inter-species competition [7]. The absence of fire pressure favours forest regeneration that could be equated with a form of savanna degradation from the pastoral viewpoint. Thus, the ways fire is used vary and, as a consequence, the impact it has on savanna vegetation varies too [8].

We studied the relationship between savanna vegetation dynamics and the ways fire is used. The goal is to produce knowledge to better understand how to manage the utilisation of fire to maintain plant cover in savannas. Given the elements presented above, fire can be considered as responsible for changes in the structure of savannas, causing a regressive evolution of the herbaceous layer towards a desert shrub formation [9,10]. Inversely, fire may also be considered to be a constituent element of savanna ecosystems [11], as a factor maintaining them [12], acting as a regulatory [13] and stabilising agent in the coexistence of grasses and trees [14-19]. There is therefore no general agreement on the conditions under which fires should be used to ensure the sustainability of those environments. It is likely that these conditions are not identical in all types of savanna. The space-time variability of the surrounding conditions and of the environmental factors results in a great heterogeneity of the observed plant dynamics. “The problem of savannas appears to be extremely varied: there is not one savanna problem, but several savanna problems” [20]. We chose a methodological option to analyse space-time variations of the plant cover dynamics of savannas together with space-time variations of the ways of using fires. These space-time variations were measured on the series of remote-sensing images. We qualified the importance and the role of the fire factor in the changes for a given savanne ecosystem with a statistical approach. This method produced a spatialised assessment of the effects of fire on plant dynamics for the savannas being studied.

1. Study site

The Marovoay watershed is the second largest rice-producing region in Madagascar, after the Lake Alaotra region. It is situated in the North West of the island (16.11 S, 46.64 E), 200 km from Mahajanga (Figure 1). On this site, divided in two by the River Betsiboka, the savanna and forest ecosystems, surrounding a rice-farming plain, cover 126,000 ha that is to say slightly more than 80 % of the watershed’s total surface area, with the forest dominated by the savannas.

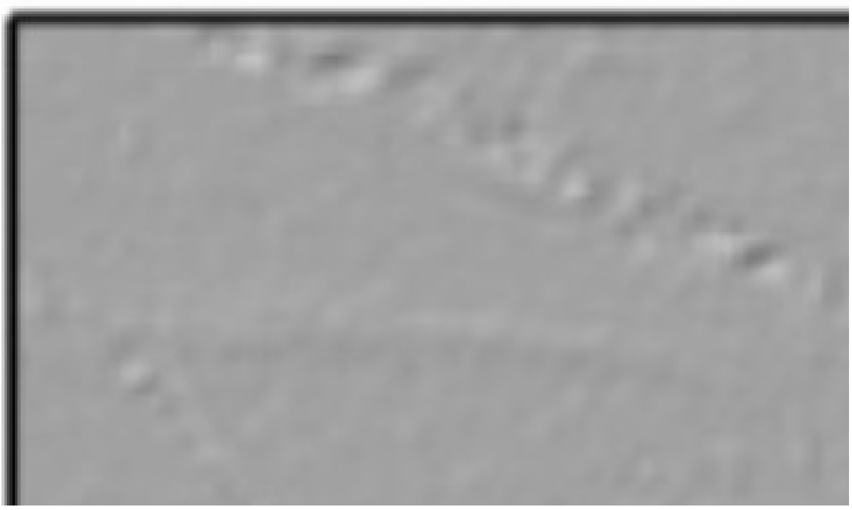

Figure1. Location of the study area on the island, and delimitation of the rice-growing plain and of the savana and forest areas.

The vegetation consists of more or less degraged savanna, and closed shrubby or tree-covered formations. All the relief zones are covered with savanna, on the slopes summits, and plateaux. The tree formations are concentrated in the low grounds. However, in the hollows where erosion has brought in clay and nutritive elements, the soil is more fertile and the natural plant formations have been replaced by food crops. On the right bank of the Betsiboka, to the south, on the edge of the savannas, there is a forest zone situated on a large Jurassic limestone plateau: Ankarafantsika forest is included in a National Park and protected because of the wealth of its fauna and flora. This is an original, dense, dry, deciduous forest representing the climax of the western Madagascar zone [12].

The savannas are characterised by a highly heterogeneous structure. A distinction must be made between two types:

- Degraded savanna (or steppe): it presents sparse plant cover dominated by *Aristida* and *Heteropogon contortus*, species that are indicative of highly degraded soils.
- Herbaceous savanna: this is dominated by an herbaceous layer made up of *Andropogon* and *Hyparrhenia*, two spieces that indicate a lesser degree of soil degradation, and a ligneous layer made up of *Anacardium*, *Dalbergia* and *Ziziphus Jujuba*.

These savannas with a low specific richness could constitute quite recent secondary vegetation [21]. Their current spatial distribution could be closely tied to stockbreeding activities [12]. Their phenological cycle is influenced by the rainy season/dry season alternation.

The Marovoay region is representative of the general fire utilisation situation observed in the western region of Madagascar: currently, more than 95% of fires are of anthropogenic origin [21]. The maintenance of pastures, slash and burn farming and agricultural plot clearing are the three most common practices in Marovoay. Fires are observed throughout the dry season, that is to say between April and October.

2. Data

The results of several studies [8,22-24] make it possible to set out the types of information obtained from remote sensing suitable for studying the “fire-vegetation dynamics” relationship in savannas.

- Information on vegetation dynamics: this is a question of characterising significant changes materialising a modification in plant cover activity and/or a modification in its structure. Thus we defined classes of change with which the vegetation dynamics can be associated whatever the intensity of the disturbances.
- Information on the fires: here the fire regime must be characterised by monitoring the area burned annually for which the fire occurrence period and the frequency were determined.

2.1. Plant cover change data

Savanna plant dynamics are characterised by analysing the inter-annual variations of a phenological indicator calculated, for each pixel of savanna, from a NDVI-MODIS time series acquired every 16 days with a spatial resolution of 250 m, over the period February 2000 – November 2007 (MOD13Q1 product). The proposed method, described in detail in [25], is based on three steps: 1) Calculation of the phenological indicator for each year, corresponding to the NDVI accumulation during the plant growth phase and materialising plant activity during that period of the phenological cycle, 2) Modelling of the phenological indicator trend by linear regression, 3) Comparison of the linear regression slope values with a null slope using a Student statistical test. A distinction can be made between:

- The situations where the trends are not significantly different from a null slope trend and therefore classified as being a stable series indicating maintained plant activity.
- The situations where the trends are significantly different from a null slope trend. In this case we analyse the sign of the linear regression slope to distinguish between the positive or negative changes which we associate respectively with progressive or regressive series, materializing a significant increase or decrease in plant activity during the period being studied.

Figure 2 represents the cartographic result of the change analysis carried out on the study site's savannas.

Figure 2. Dynamic map of the savanna vegetation established for the period 2000-2007 in the Marovoay watershed.

2.2. *Fire utilisation data*

In order to assess the different types of use made of fires, we used a fire regime indicator measured over the 2000-2007 period. It was calculated from the analysis of a time series of MODIS Surface Reflectance data (red and near infrared bands), acquired every 8 days with spatial resolution of 250 m (MOD09Q1 product). The method proposed by [26] is based on the following three steps.

1) Identification for each year of the burned areas and of the fire occurrence periods (early or late), information validated by comparison with burned area baselines obtained from SPOT-5 and Landsat TM images and from field campaigns.

At this level it is important to point out we could not use the MODIS burned areas product - MCD45 [27] - mainly due to its spatial resolution (500 m): 99 % of the burn scars to be identified have a surface area smaller than the MODIS pixel surface area of 500 m.

2) Calculation for the study period of the fire occurrence frequency and of the predominant occurrence period.
3) Calculation of the fire regime indicator from the combination of the fire frequency and seasonality information and the definition of five classes: no fire, infrequent and early fire, infrequent and late fire, very frequent and early fire, and very frequent and late fire.

In this work, we defined as infrequent or very frequent, fires occurring less than once or more than once every two years. We defined as early or late, burned pixels whose ‘number of early fires / number of late fires’ ratio is respectively higher than or lower than 1. Figure 3 shows the cartographic result of the fire regime indicator for the study site’s savannas.

Figure 3. Fire regime map established for the 2000-2007 period in the Marovoay watershed.

2.3. *Plant formation data*

A plant formation map was made by classifying a SPOT-5 image acquired on 10 June 2005 and using terrain baselines to identify the extent of the savannas (herbaceous savanna + degraded savanna) (Figure 1) and select the studied MODIS pixels. In this work, we kept for the study of the savannas all the MODIS pixels whose herbaceous savanna and/or degraded savanna surface area represents 90 % of the pixel's total surface area (that is to say 5.625 ha).

3. Methodology

Based on the hypothesis that the impact of fire varies according to the interactions between environmental factors, the study zone was stratified into nine homogeneous analysis units according to the characteristics of the soils' agronomic potential, land use and human pressure [8,28]. This made it possible to distinguish between savanna zones virtually exclusively dedicated to stockbreeding, degraded savanna zones, zones where land use is divided between cultivated plots and pasturelands with a very high level of human pressure and savanna zones on the edge of forests in the Ankarafantika National Park.

The vegetation dynamics map was superposed over the fire regime map within the limit of the savanna zones and of the nine analysis units defined. Statistical analysis was based on the utilisation of regression models (Generalised Linear Models - GLM) to study, in each analysis unit, the relations between the two types of variables defined:

- The vegetation dynamics indicator was defined as being the variable of interest or dependent variable.

We kept the regressive and stable series classes. The time step defined by the length of the MODIS time series (2000-2007) did not make it possible to study progressive series of savannas.

- The explanatory variables or independent variables are represented by the fire regime indicator's five classes.

To enable us to carry out our statistical analyses, we described the explanatory variables quantitatively proceeding by squaring [29]. A regular mesh grid was thus applied to all the analysis units and superposed over the vegetation dynamics and fire regime maps. The size of each cell in the grid was set at 1 km^2 (giving a total of 1,369 cells to cover the whole study zone). Each cell contains 16 MODIS pixels, each one being characterised by one class of vegetation dynamics and of fire regime. For each cell we calculated the percentages of pixels belonging to each class of fire regime and to each class of savanna vegetation dynamics with reference to the total number of pixels contained in a cell. We thus transformed our explanatory variables of interest, which were initially qualitative, into quantitative variables.

For the size of the grid cell, we didn't fond any "objective" criteria allowing us to make the right choice [29]. There were two reasons for our choice of cell size corresponding to 4*4 MODIS pixels at 250 m: 1) to minimise any possible adjustment problems between the two sources of data used, and 2) to proceed with the transformation of the qualitative variables into quantitative variables [8]. The regressive and stable series variables were analysed separately.

STEP 1: Calculation of the regression model and extraction of its parametres.

The "fire – vegetation dynamics" relationship were characterised by analysing the generalised linear models (GLM) established for each analysis unit, in which we sought to determine whether the vegetation dynamics variables (Y_i) could be explained by the fire regime variables (X_i).

In each analysis unit, the “fire – vegetation dynamics” relationship was modelled using two equations of the Eq. (1) type, one equation for each vegetation dynamics variable to be explained (regressive or stable series).

$$Y_i = \beta_0 + \beta_1 X_1 + \beta_2 X_2 + \beta_3 X_3 + \beta_4 X_4 + \beta_5 X_5 \quad (1)$$

where Y_i is the variable of interest, X_1 to X_5 represent the fire regime variables and β_1 to β_5 correspond to the model’s coefficients for each explanatory variable.

In order to analyse the relationship between the variable of interest and the explanatory variables, we used several descriptors: the number of degrees of freedom, the model’s residual deviance, the model’s coefficients and the values of the model’s normalised coefficients.

STEP 2: Test of the model’s significance.

For all the models, a *Fisher*-F test or a *Chi* test was used to verify the significance of the proposed model by comparison with a null model (that is to say a model that does not contain any explanatory variables). The null hypothesis (H_0) corresponds to a tested model that is not significantly different from the null model. This means that the difference between the residual deviance of the tested model and that of the constant model is slight. The alternative hypothesis (H_1) corresponds to a tested model that is significantly different from the null model.

In order to choose the test to be performed, we analysed the ratio of the tested model’s residual deviance with respect to the number of degrees of freedom. There were two possible cases: 1) If the value of the residual deviance of the tested model / degree of freedom ratio was lower than or close to 2, we used a *Chi* test to test the significance of the models; 2) Otherwise we used a *Fisher*-F test.

STEP 3: Qualification of the model’s explanatory power, test of the explanatory variables’ significance and classification according to their weight in the model.

For all the significant models, with the value of the residual deviance / degree of freedom ratio, we were able to qualify the variability part of the savannas’ vegetation dynamics indicator that could be explained by the fire regime variables. If the value was lower than or close to 2, that meant that the model was able to explain an important part of the variable of interest’s variability. Above 2, the part explained by the model was considered to be low. Then, with a *Chi* test, we checked the significance of each of the model’s variables. In order to sequence the significant variables according to their weight in the model, we used normalised coefficients, that is to say corrected by the value of the standard deviation; the greater the absolute value of the normalised coefficient, the greater the importance of the weight of the variable in the proposed model.

4. Results

In this part, we present the results of the statistical study of the “fire-vegetation dynamics” relationship for the savannas on the study site. For the nine analysis units, the calculated regression models are all significant.

4.1. Importance of the fire factor in the evolution of the savannas

Table 1 presents the values of the “Residual deviance / Degree of freedom” ratio per analysis unit and per vegetation dynamics variable.

Table 1. Values of the “Residual deviance / Degree of freedom” ratio per analysis unit.

	Residual deviance / Degree of freedom	
Analysis unit	**Regressive evolution**	**Stable evolution**
1	5.20	5.20
2	5.93	5.97
3	6.10	6.10
4	6.90	6.40
5	5.74	5.74
6	**1.35**	**2.02**
7	**0.64**	**2.01**
8	6.40	6.40
9	**1.65**	**1.65**

According to the value of this ratio, two classes of analysis units appear.

- Class 1: class grouping together the analysis units for which the value of the “Residual deviance / Degree of freedom” ratio is higher than 2.
- Class 2: class characterising the analysis units for which the value of the “Residual deviance / Degree of freedom” ratio is lower than or close to 2.

Class 1 groups together the analysis units characterising the zones with the highest population density or the greatest concentration of human activities, including agriculture (No. 1, 2, 3, 4, 5 and 8). The values of the “Residual deviance / Degree of freedom” ratio show that the models proposed explain a small part of the variability of the vegetation dynamics of the savannas observed in the Marovoay watershed. This tends to prove that in these zones, the vegetation dynamics of the savannas result from complex interactions between various human and environmental factors including fire.

Class 2 consists of analysis units No. 6, 7 and 9 (they are shown in bold on greyed lines in the table). It comprises the zones on the study site with low human pressure and land use dominated by stockbreeding. This concerns situations where the proposed model, based on fire regime variables, makes it possible to explain a large part of the variability of the vegetation dynamics variables.

4.2. *Impact of fire use on the evolution of savannas*

Tables 2 and 3 present the characteristics of the models established to explain respectively the degradation or conservation of the savannas between 2000 and 2007 on the nine analysis units. For each model, the significant independent variables (at the threshold $\alpha = 1$ %) are shown in blue. Their coefficients may have positive or negative signs. An independent variable presenting a coefficient with a negative sign means that it cannot be used to explain the variable of interest. Inversely, a coefficient with a positive sign characterises the independent variables that explain the variable of interest. The figures in brackets indicate the classification of those variables according to their weight in the model (1 means the independent variable with the greatest weight). The one that contributes the most to explaining the variable of interest in each model is shown in grey (positive-signed coefficient with the greatest weight).

Table 2. Regression models for the "Savanna degradation" variable.

Independent variables	Coefficient	Standard deviation	p(|Chi|)	Significance code
Model for analysis unit 1				
Constant	.884	.948		
No fire	-.031 (4)	.068	.000	***
Infrequent and early fire	-.176 (3)	.125	.000	***
Infrequent and late fire	-.190 (2)	.099	.000	***
Very frequent and early fire	-.522	.725	.091	n.s.
Very frequent and late fire	-2.153 (1)	2.365	.004	**
Model for analysis unit 2				
Constant	1.159	.477		
No fire	-.164 (2)	.054	.000	***
Infrequent and early fire	-.137 (3)	.069	.000	***
Infrequent and late fire	-.127 (4)	.047	.000	***
Very frequent and early fire	.451 (1)	.338	.000	***
Very frequent and late fire	-.047	.074	.128	n.s.
Model for analysis unit 3				
Constant	-1.253	.449		
No fire	-.057 (3)	.052	.000	***
Infrequent and early fire	-.014 (5)	.055	.000	***
Infrequent and late fire	.025 (4)	.042	.000	***
Very frequent and early fire	.433 (1)	.164	.000	***
Very frequent and late fire	.105 (2)	.053	.000	***
Model for analysis unit 4				
Constant	.030	.678		
No fire	-.169 (3)	.149	.000	***
Infrequent and early fire	-.173 (2)	.094	.000	***
Infrequent and late fire	.030 (4)	.084	.000	***
Very frequent and early fire	-.283 (1)	.204	.000	***
Very frequent and late fire	.053	.069	.045	n.s.
Model for analysis unit 5				
Constant	-1.630	1.538		
No fire	.153 (2)	.559	.000	***
Infrequent and early fire	.408 (1)	.235	.000	***
Infrequent and late fire	.122 (3)	.147	.007	**
Very frequent and early fire	.614	.594	.012	n.s.
Very frequent and late fire	.063	.163	.354	n.s.
Model for analysis unit 6				
Constant	-3.191	.436		
No fire	-.516 (1)	.148	.000	***
Infrequent and early fire	.121	.060	.029	n.s.
Infrequent and late fire	-.088	.061	.074	n.s.
Very frequent and early fire	.049	.060	.413	n.s.
Very frequent and late fire	-.163 (2)	.065	.065	**
Model for analysis unit 7				
Constant	-4.924	.490		
No fire	.147 (2)	.062	.002	**
Infrequent and early fire	-.100 (3)	.086	.005	**
Infrequent and late fire	.227 (1)	.076	.005	**
Very frequent and early fire	-.303	.452	.424	n.s.
Very frequent and late fire	-15.144	953.245	.061	n.s.
Model for analysis unit 8				
Constant	.754	1.091		
No fire	.162 (3)	.135	.000	***
Infrequent and early fire	-.271 (2)	.141	.000	***
Infrequent and late fire	-.139	.136	.032	n.s.
Very frequent and early fire	.010	.391	.949	n.s.
Very frequent and late fire	-.699 (1)	.380	.000	***
Model for analysis unit 9				
Constant	-2.325	.453		
No fire	-.196 (2)	.139	.001	***
Infrequent and early fire	-.014	.063	.653	n.s.
Infrequent and late fire	.018	.060	.485	n.s.
Very frequent and early fire	-.030	.040	.444	n.s.
Very frequent and late fire	-.224 (1)	.065	.000	***

Table 3. Regression models for the "savanna conservation" variable.

Independent variables	Coefficient	Standard deviation	p(|Chi|)	Significance code
Model for analysis unit 1				
Constant	-.884	.948		
No fire	.031 (4)	.068	.000	***
Infrequent and early fire	.176 (3)	.125	.000	***
Infrequent and late fire	.190 (2)	.099	.000	***
Very frequent and early fire	.522	.725	.091	n.s.
Very frequent and late fire	2.153 (1)	2.365	.004	**
Model for analysis unit 2				
Constant	-1.151	.476		
No fire	.161 (2)	.054	.000	***
Infrequent and early fire	.136 (3)	.069	.000	***
Infrequent and late fire	.126 (4)	.047	.000	***
Very frequent and early fire	-.452 (1)	.337	.000	***
Very frequent and late fire	.046	.074	.132	n.s.
Model for analysis unit 3				
Constant	1.253	.449		
No fire	.057 (3)	.052	.000	***
Infrequent and early fire	.014 (5)	.055	.000	***
Infrequent and late fire	-.025 (4)	.042	.000	***
Very frequent and early fire	-.433 (1)	.164	.000	***
Very frequent and late fire	-.105 (2)	.053	.000	***
Model for analysis unit 4				
Constant	.006	.647		
No fire	.122 (3)	.139	.000	***
Infrequent and early fire	.166 (2)	.089	.000	***
Infrequent and late fire	-.032 (4)	.080	.000	***
Very frequent and early fire	.246 (1)	.188	.000	***
Very frequent and late fire	-.055	.066	.036	n.s.
Model for analysis unit 5				
Constant	1.630	1.538		
No fire	-.153 (2)	.559	.000	***
Infrequent and early fire	-.408 (1)	.235	.000	***
Infrequent and late fire	-.122 (3)	.147	.007	**
Very frequent and early fire	-.614	.594	.012	n.s.
Very frequent and late fire	-.063	.163	.354	n.s.
Model for analysis unit 6				
Constant	2.189	.439		
No fire	.075 (4)	.068	.000	***
Infrequent and early fire	-.080 (3)	.062	.000	***
Infrequent and late fire	.136 (2)	.058	.001	**
Very frequent and early fire	.058	.070	.212	n.s.
Very frequent and late fire	.140 (1)	.063	.000	**
Model for analysis unit 7				
Constant	2.417	.251		
No fire	-.004 (2)	.044	.000	***
Infrequent and early fire	.003	.043	.233	n.s.
Infrequent and late fire	-.069	.050	.124	n.s.
Very frequent and early fire	-.065	.089	.316	n.s.
Very frequent and late fire	1.029 (1)	.490	.000	***
Model for analysis unit 8				
Constant	-.754	1.091		
No fire	-.162 (3)	.135	.000	***
Infrequent and early fire	.271 (2)	.141	.000	***
Infrequent and late fire	.139	.136	.032	n.s.
Very frequent and early fire	-.010	.391	.949	n.s.
Very frequent and late fire	.699 (1)	.380	.000	***
Model for analysis unit 9				
Constant	2.367	.451		
No fire	.180 (2)	.136	.003	***
Infrequent and early fire	.018	.063	.608	n.s.
Infrequent and late fire	-.026	.060	.426	n.s.
Very frequent and early fire	.029	.039	.458	n.s.
Very frequent and late fire	.198 (1)	.063	.001	***

In the following part we analyse in detail the characteristics of the models contained in tables 2 and 3 by dissociating several types of situations for which we put forward hypotheses concerning the impact of the fire regime on the vegetation dynamics of savannas that we seek to verify on the basis of the results obtained.

4.2.1. *Effect of non-utilisation of fire on changes in savanna vegetation*

The first hypothesis tested concerns savanna vegetation dynamics in the absence of fire. Over an eight-year period, it was assumed that the absence of fire would result in the savannas being maintained (hypothesis 1), except in the case of peri-forest savannas (gradual return of the forest in the absence of fire).

To verify this hypothesis, we analysed the results of the “No fire” variable in Table 3 corresponding to the models established per analysis unit to explain the “Savanna conservation” variable. This variable is significant in all the models. For analysis units No. 1, 2, 3, 4, 6 and 9, it is characterised by a positive coefficient. That means that the absence of fire contributes to explaining savanna conservation, which confirms hypothesis 1. For analysis units No. 5, 7 and 8, on the contrary, the sign of the coefficients is negative. In Table 2, this variable’s coefficients for these analysis units are positive, which invalidates hypothesis 1: the absence of fire in these units is not a factor explaining conservation but, on the contrary, it could explain to a certain degree the degradation of savannas.

4.2.2. *Effect of the fire regime in zones where anthropogenic pressure is great*

In zones where the population or human activities are dense, fire interacts with many other environmental factors. Fire is used in many different ways (fire frequency or date of the fire occurrence period) but always to preserve the herbaceous cover. However, the degradation of the herbaceous cover cannot be explained solely by the fire regime: it results from a combination of different anthropogenic pressure factors (hypothesis 2).

To verify this hypothesis, we analyse the models obtained for the analysis units No. 1, 4 and 8, where the greatest amount of pressure linked to human activities is concentrated. In the most densely populated zone (analysis unit No. 1), all the fire regime variables have a coefficient with a positive sign in Table 2: they all contribute significantly to explaining savanna conservation. Furthermore, in Table 1, they are characterised by coefficients with a negative sign, which means they do not explain the degradation of savannas (except the “Very frequent and early fires” variable which is not significant). In the two zones close to the irrigated areas (analysis units No. 4 and 8), characterised by soils with an average agronomic potential, the fire regime variables are not linked to the degradation of savannas (negative coefficients in Table 2). Some of them, however, make it possible to explain their conservation. For analysis unit No. 4, this concerns infrequent and very frequent and early fires whereas for analysis unit No. 8, it is the very frequent late and infrequent and early fires. All these results tend to confirm hypothesis 2.

4.2.3. *Effect of the fire regime in degraded savanna zones*

In the degraded savanna zones (steppe), the fire frequency (whatever the date of the fire) contributes to explaining a stable (infrequent fire) or regressive (very frequent fire) evolution of the savannas [7] (Hypothesis 3).

We verified this hypothesis by analysing the models for analysis units No. 2 and 3, representing the most degraded savanna zones on the study site, with soils severely marked by erosion. In these zones, the degradation can be explained by a very frequent and early fire regime (Table 2) and plant cover maintained by infrequent fires but with a low weight in the models (Table 3). These results allow us to confirm the negative impact of very frequent fire regimes on the state of conservation of degraded savannas.

4.2.4. *Effect of the fire regime in zones where anthropogenic pressure is slight*

In the savanna zones predominantly dedicated to stockbreeding, for a short observation period (such as the one we are analysing), a very frequent and late usage of fire promotes the production of herbaceous biomass and is materialised by a stable evolution of savannas [30]. However, for this time step, the degradation of these environments cannot be explained by the fire regime alone (Hypothesis 4).

This hypothesis is verified by analysing the models proposed for analysis units No. 6 and 9 which, in the Marovoay watershed, represent the savanna zones predominantly dedicated to stockbreeding. In Table 2 (models used to explain the degradation of savannas), the coefficients of the significant fire regime variables are negative, which means that the degradation of the savannas cannot be explained by these variables. However, the conservation of the savannas, in Table 3, is linked to a late and, above all, very frequent fire regime. These results partially confirm hypothesis 4.

4.2.5. *Effect of the fire regime in peri-forest savanna zones*

In savannas situated in peri-forest zones, the conservation of those areas depends on fire frequency if we consider a short observation period: the higher the frequency, the more the savannas are kept open (Hypothesis 5).

To verify this hypothesis, we studied the two models obtained for analysis unit No. 7, which represents savannas on the edge of or inside forest zones. The degraded zones are explained by infrequent and late fires and the absence of fire (light weight in the model) and the zones where the savannas are maintained by very frequent and late fires. This result shows that the fire “frequency” factor affects these savannas’ vegetation dynamics: the higher the fire frequency, the more the environment is kept open, thus confirming hypothesis 5.

4.3. *Summary of the results*

The summary of the results presented in this work evidences three key points in the study of the “fire-savanna vegetation dynamics” relationship in the Marovoay watershed.

1- **Fire is a factor in the maintenance of savannas.** According to the results obtained on the study site, we did not come across any situation where the absence of fire is an important variable for explaining the conservation of this ecosystem.

2- **In situations where the pressure linked to anthropogenic activities is slight** (predominantly stockbreeding zones or protected areas), **fire is a decisive factor in the vegatation dynamics of savannas**. For the time step analysed, the fire regime’s “**frequency**” parameter appears to be the most important factor for explaining the conservation or degradation of plant cover.

3- For all the other situations, elements appear relative to the effect of the fire regime on the vegetation dynamics of savannas. However, **interpretation of the results remains difficult and complex**, very probably due to the **action of multiple anthropogenic factors**. In these zones, the initial hypothesis that fire may be factor in the degradation or maintenance of savannas must be reformulated in a more complex way.

5. Conclusion

The utilisation of regression models to explain the vegetation dynamics of savannas by means of fire regime variables makes it possible to study, on the scale of the study site, the “fire-vegetation dynamics” relationship. The method described in this work has several advantages with respect to earlier works [8,22-24,28].

- **Better characterisation of the fire regime by integrating fire frequency and seasonality**

The characterisation of the fire regime, by monitoring the burned areas for which the fire occurrence period and frequency are known, gives results that are more precise than with data on active fires or burned area data only providing information on the impact of fires according to their date. This provides an improvement in the estimation of the fire regime variable with respect to the works of [23].

- **Better characterisation of the vegetation dynamics of savannas using a method based on processing continuous NDVI time-series data**

The characterisation of the vegetation dynamics of savannas based on NDVI time-series data makes it possible to identify subtler changes in plant cover than by using a diachronic approach [31].

- **Same time and space scale for measuring the dependent (classes of vegetation dynamics) and independent (classes of fire regime) variables for which a relationship is established in the regression models**

Data provided by a single sensor (MODIS) with the same spatial resolution (250 m) and covering an identical time interval (8 years) were used to characterise the fire regime and vegetation dynamics. This makes it possible to assign a type of vegetation dynamics to a class of fire regime, unlike the approaches proposed by [8,23] which explain a class of vegetation change by a class of fire regime observed over one year.

The perspectives, resulting from this work, are twofold:

- of a **methodological** order: pursue the search for a method for characterising vegetation dynamics by testing other approaches based on the analysis of time series, of the time breakdown method type [25,32,33] ; pursue the acquisition of baseline data on fires and changes of vegetation for testing the effect of seasonality for the same fire frequency; improve the approach by stratification in the zones subject to high anthropogenic pressure to progress in the interpretation of the statistical analysis results.
- of an **applied** nature: due to the nature of the data used and the methods proposed, extend this type of work to all the savannas in western Madagascar. This would make it possible to multiply the study sites, and make comparisons, which would contribute, *in fine,* to improving the genericity of the results obtained with such an approach.

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