

# SPATIOTEMPORAL DYNAMICS OF COASTAL SAVANNAS NESTED IN FRENCH GUIANA SPACE CENTER FROM PLÉIADES IMAGERY AND AERIAL PHOTOGRAPHS

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## Résumé

Les savanes et les forêts tropicales sont délimitées par des frontières nettes et sont deux écosystèmes stables. Quelle est l'évolution naturelle des forêts par rapport aux savanes ? L'équilibre dynamique entre avance et recul de la forêt est une réponse aux perturbations telles que les feux ou les sécheresses. Le feu préserve la savane par son action sur les zones de contact forêt – savane, alors qu'une sécheresse empêche l'expansion de la forêt. Cet article est consacré aux savanes côtières de Guyane Française au sein du Centre Spatial Guyanais (CSG) parfois menacé par des feux de savanes à la saison sèche. Cette étude porte sur 60 ans d'évolution du paysage autour du CSG et utilise un jeu d'images satellites Pléiades et aériennes géo-référencées. Les dynamiques forêt – savane ont été visualisées et caractérisées par le calcul d'indicateurs de forme. L'étude a montré que la forêt a progressé de 23% sur la savane, et surtout dans les zones de contact forêt-savane, ouvrant la perspective à une application opérationnelle pour lutter contre les risques au feu sur le site du CSG.

**Mots-clés:** Pléiades, Indices de Forme, Classification, Dynamique Forêt-Savane, Guyane.

## Abstract:

Savannas and tropical forests delineated by sharp boundaries are two alternative stable ecosystems. What is the natural evolution of forests over savannas in coastal savanna in French Guiana? The dynamic balance between forest advance and retreat is a response to disturbances such as fire or extreme drought events. Fire maintains savanna by its action on forest-savanna contact areas, while a dry climate prevents forest expansion. This paper focuses on coastal savannas of French Guiana nested in the Guiana Space Center (CSG) that is occasionally threatened by bushfires in the dry season. This study spanned over 60 years of landscape changes around the CSG and used a georeferenced set of aerial and Pléiades satellite images. Forest and savanna dynamics were mapped and highlighted with the computing of shape indicators. This study showed that the forest progressed of 23% onto savanna and mainly at the forest-savanna contact zones, paving the way to an operational application to fight against fire threats on the CSG area.

**Keywords:** Pléiades, Shape Indices, Classification, Forest – Savanna Dynamic, Forest, Savanna, Guiana.

## 1. Introduction

Savannas first appeared approximately 8 million years ago and are a major terrestrial biome. Worldwide, they cover between 15 and 24.6 million km<sup>2</sup> (Da Silva & Bates 2002). Current savannas are residues of surface areas covered by savanna vegetation in the dry glacial period from 18000 to 13000 BC (Fölster & Dezzio 1994). Savannas consist of a discontinuous tree cover in a continuous grass understorey (Beerling & Osborne 2006). Floras of forests and savannas ecosystems differ both in plant metabolism and in forms of life (Hoffmann et al. 2004; Ratnam et al. 2011). Savannas are predominantly composed of C4 grasses (Ratnam et al. 2011) that are fire tolerant and shade intolerant. In contrast, forests are composed by C3 woody plants that are shade tolerant and fire intolerant (Ratnam et al. 2011).

Savannas and closed tropical forests are two alternative stable ecosystems, delineated by sharp boundaries. The transition between savanna and forest is generally abrupt (Hoffmann et al. 2003) and the dynamic balance between forest advance and retreat is a response to disturbances such as (1) fire events and (2) extreme drought events (Rossatto et al. 2009). In particular, fires maintain the dynamic balance between savannas and forests as they restrict the development of forest species and thereby create space for the expansion of savanna species (Aubréville 1966; Beerling & Osborne

2006). Also a hot, dry, annual or seasonal climate predisposes to fire in savannas, contributing to their sustainability (Bowman et al. 2009). In undisturbed places, forests progress over adjacent savannas in India (Puyravaud et al. 2003), Southern Africa (Bond et al. 2005) and South America (Silva et al. 2008; Rossatto et al. 2009).

Fire, therefore, by its action at forest-savanna contact areas, but also by its ability to propagate in savanna, is essential to maintain savanna areas. Fire destroys forest species, plants and shrubs, preventing colonization (Hoffmann et al. 2004; Ratnam et al. 2011). However, in certain cases, fire does not seem to have a major incidence on the stability of savanna. Indeed, Chave (2000) showed that fire may slow forest progression in forest-savanna contact zones but can rarely block it in south of Congo.

Tropical savannas are an important component of the terrestrial vegetation in South America. In some regions as the Llanos of northern South America and Cerrado, savannas are the dominant vegetation and cover 72 % of these regions. Forest are found along the rivers or in small isolated patches (Da Silva & Bates 2002). In contrast, in large forested regions such Amazonia, savannas occur as isolated patches amidst a continuous cover of forests (Da Silva & Bates 2002). Savannas of Amazonia differ from other savannas: (i)

amazon basin is flat and the river system is not fixed, (ii) peri-forester savannas are often flooded savannas a part of the year, so the functioning of vegetation is particular.

In this study, we were interested in savannas of French Guiana. Guyanese plant landscape is characterized by almost exclusive predominance of forest. The total forest covers 97.7% of the surface of the Guyana (Granville 1990). Savannas cover only 1.7 % of the territory (Hoff & Brisse 1990). Savannas are located in the north of the French Guiana, along the coast, between Mana and Cayenne. They penetrate a little bit inside lands (Hoff & Brisse 1990). Many fires occur on the Guiana coast during the high summer dry season, sometimes burning coastal savannas (Iriarte et al. 2012). With climate change, there is more and more drought, so more and more fires.

Few studies have been conducted on Guiana coastal savannas. The evolution of these savannas is strongly connected to their origin which would depend on paléoclimatic (Hook 1971) and anthropological factors (Rostain 2008). The Guyanese savannas seem to resist at present to the natural reforestation. Indeed, Hook (1971) showed that forest development over savanna was limited by edaphic factors, disturbances (fires) or specific savanna micro-climate. In contrast, Aubréville (1966) showed that forest progresses over savanna in spite of disturbances. So, what is the natural evolution of forest over savannas in coastal savannas of French Guiana?

Usually, aerial photographs are appropriate tools to analyze the spatial distribution and temporal dynamics of forest-savanna contact zones. Indeed, Brook and Bowman (2006) and Ibanez et al. (2012) used methods of diachronic mapping to follow changes in Australia savannas and in forest-savanna contact areas in New Caledonia. Also, Hudak and Wessman (1998) used the textural analysis of digitized black and white aerial photographs with a spatial resolution of 2 meters to determine the tree colonization of African savannas. Mac Garigal and Marks (1995) proposed in FRAGSTATS a large number of indices to characterize the shape of objects in an image. Soledad et Santiago (2005) showed that some morphological indices were scale-dependent for forest fragmentation estimation. In this study, only on a few shape parameters were used. The focus was put on an accurate mapping of forests and savannas, and on the characterisation of the shape of objects and on their dynamism. A dataset of old aerial photographs and new Very High Resolution Pléiades images was used, in order to (i) study evolution of forest-savanna dynamic on a study period of 62 years (1950 to 2012), and (ii) characterize the dynamic of forest-savanna landscape with several indicators as landscape indices, and rate of forest edge extension.

## 2. Material and Methods

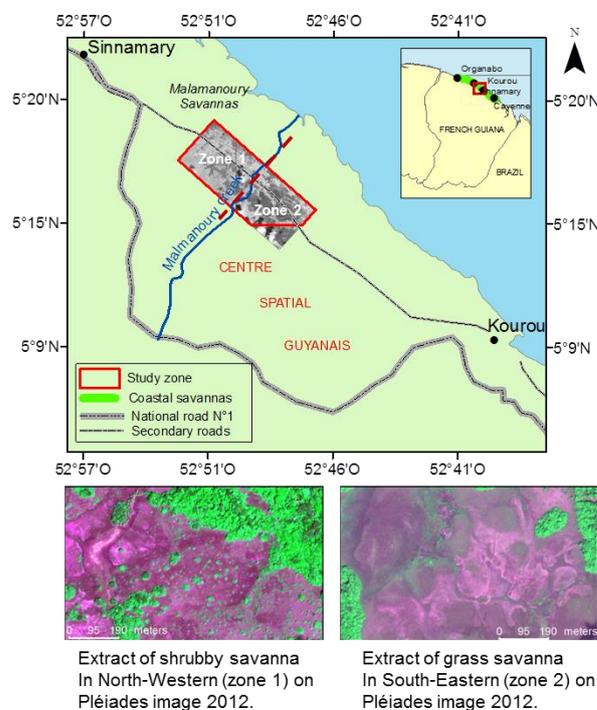
### 2.1. Study site

We chose to focus on coastal savannas of French Guiana nested in the Guiana Space Center (CSG) that constitute a representative sample of coastal savanna of French Guiana. Furthermore, these savannas are occasionally threatened by bushfires in the dry season. CSG area covers approximately 750 km<sup>2</sup> (Barret et al.

2001) and is located in the Malmanoury savannas (5°16'60" N, 52°51'0" W, see Fig1), about 20 kilometers east of Sinnamary, extending south of the old National Road #1 and alongside the west bank of the Malmanoury creek. These savannas are dry and swampy low herbaceous, evolving toward a shrubby low savanna in the south of the area. They are interspersed with forest patches and are bordered in the south by evergreen forest (Hook 1971). The Malmanoury savannas are part of French Guiana's coastal savanna which is mainly located between Cayenne and Organabo on the old coastal plain (Hook 1971) that covers approximately 150 km<sup>2</sup>. The study area is located around the CSG's Diane satellite control station and covers approximately 45 km<sup>2</sup>.

Altitude in the savanna is low and does not exceed 10 meters above sea level. The savanna is located on marine clay largely covered with fine sandy sediment dating back to the Pleistocene (Chaix 2002).

CSG savannas are characterized by a wet tropical climate subdivided into two main seasons: a long rainy season (April-June) and a long dry season (July-Nov).



**Figure 1:** Location of the Guiana Space Center study site in French Guiana (Map Projection WGS84).

### 2.2. Imagery

The spatiotemporal analysis of changes in savannas and forests, and their dynamics, between 1950 and 2012 was conducted by mapping a chronological series of aerial photographs and satellite images.

We used two aerial photographs taken in 1950 (scale: 1/50 000) and three taken in 1968 (scale: 1/30 000). These black-and-white photographs were scanned from negative photo at 1000 dpi and re-sampled with a 1-m pixel size by the French National Geographic Institute (IGN). We also obtained seven color aerial photographs from IGN 2006 BD ORTHO® with a resolution of 0.5 m. These photographs were already georeferenced in

WGS84 UTM 22N and served as a reference for geo-referencing the older aerial photographs. Because of the low altitude and the flatness of the study area, the ortho-rectification was not done. Moreover, it was better not to do it to avoid additional deformation. So, geo-referencing was made with more than 10 ground control points to allow a first order polynomial transformation. Horizontal root mean square errors (RMSE) were between 0.5 m and 2 m.

The photographs were arranged in a mosaic to cover the study area. No photograph, unfortunately, were available for the intermediate period between 1968 and 2006. A considerable period (38 years) between these two time points without any photographs therefore hindered our monitoring of this period.

Two Pléiades very-high-resolution (VHR) images taken during the main dry season were acquired in November 2012 within the area covered by the aerial images dataset. Each image covered part of the study area, i.e. roughly 6.5x9.5 km. The spatial resolution of the multispectral bands (2 m, delivered product resolution) was improved by a Brovey pansharping algorithm (Vrabel 1996) using the panchromatic band at 0.5 meter resolution (delivered product resolution). The final product was a multispectral image consisting of four spectral bands: Blue (0.43 - 0.56  $\mu\text{m}$ ), Green (0.5 - 0.61  $\mu\text{m}$ ), Red (0.59 - 0.72  $\mu\text{m}$ ) and Near-Infrared (0.74 - 0.94  $\mu\text{m}$ ) with 0.5 m pseudo-resolution. These images were visually analyzed as color (R-G-B) components of the Red-NIR-Green bands.

All images were re-sampled to achieve a common resolution of 1 m in order to be exactly superimposable.

### 2.3. Manual classification

A visual photo-interpretation was used to distinguish between the various types of vegetation coverage and to mark out the border between the two main covers, i.e. forest and savanna. Two photo-interpreters mapped the study area for the 2006 dataset with accuracy higher than 90 %.

The different classification themes corresponded to savanna, forest, built-up area, soil and forest island.

Savanna is defined by areas of grounds with grass and/or a few isolated trees.

We considered forest as a piece of land of more than 0.5 ha, with a closed tree canopy cover and the absence of other predominant land uses<sup>1</sup>.

Forest islands are considered as forest when their minimum surface area is 0.5 ha and when they are surrounded by savannas.

In order to quantify forest progression and to determine the dynamics of forest-savanna contact zones, a comparison was done between the manual classifications for each year (1950, 1968, 2006, and 2012).

The manual classification approach was preferred to automatic methods because it allowed a better accuracy to analyze the forest-savanna border. The study area is small, roughly 100 km<sup>2</sup>, and there is only

two classes to recognize, forest and savanna. They look very different for a photo-interpreter, so the manual classification was easy, fast and reliable: the accuracy is higher than 90% between different photo-interpreters, much higher than the commonly accepted threshold of 85% accuracy for a good classification, as mentioned in (Thomlinson et al. 1999). The accuracy is usually estimated with a Kappa index, a normalized Kappa index (Congalton 1991) or a Cohen's Kappa index (Smits et al. 1999). But this accuracy threshold of 85% is almost impossible to reach with semi-automatic or automatic methods, as stated by (Foody 2002). Moreover, there are a lot of different promising classification techniques (Lu and Weng 2007), but the scope of this study is not to find the best classification technique but to study the forest-savanna border dynamic. Automatic methods will be studied to analyze larger areas.

### 2.4. Dynamics of forest-savanna

To describe CSG area over the study period, we used landscape indices that reflect the effects of ecosystem fragmentation (Rutledge 2003). Fragmentation is the progressive replacement of large areas of native savannas by forests. The size of the fragments (or patches) was calculated from the polygons created by the digitalization of the forest and savannas areas from images dataset.

Two types of spatial indices were calculated: (i) composition indices that describe the basic characteristics of fragmentation (forest patch density) and (ii) shape indices that quantify patch complexity, fragmentation indice and shape factor.

- i. Savanna fragmentation is evaluated with forest patches density. It is the number of forest islands by area unit in savanna zones (Rutledge 2003).
- ii. The fragmentation indice illustrates the roughness/smoothness of the forest-savanna limit. Fragmentation indice =  $\text{Perimeter}/\text{Area}$ , (Krummel et al. 1987).

The shape factor used in this study reflects the elongation of the polygons. Its range is [1, + $\infty$ ]. The closer to 1 is the indice, the more circular is the polygon. The higher is the indice, the more irregular is the border of the polygon. It can be an elongated polygon or a disk with a very rough border.

Shape factor =  $\text{Perimeter}^2/(4\pi \cdot \text{Area})$ , (Coster & Chermant 1989) (Visilog, 1991).

According to (Youta Happy, 1998), the rate of forest edge extension was calculated :  $v = (S/L)/P$ , where S=forest surface developed between two dates, L=total length of the border in the date of the first shooting, and P=period between two dates.

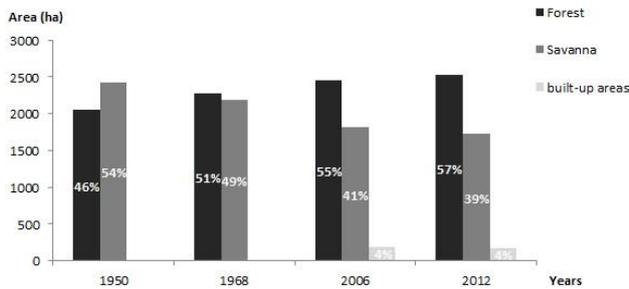
## 3. Results

### 3.1. Changes in forest – savanna zones at the CSG study site between 1950 and 2012

Forests expanded into adjacent savannas over this 62-year period at the Guiana Space Center. In 1950, the study site was mainly dominated by savannas (Fig.2;

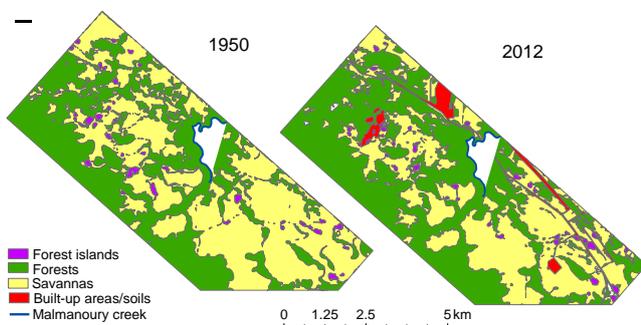
<sup>1</sup> according to the FAO definition, (Schoene et al. 2007).

54%) while forests covered the remaining (Fig.2; 46%). In 1968, savannas and forests were of equivalent sizes (49% and 51%, respectively) and built-up areas had just started to appear. Finally, in 2012, forest coverage reached 57% while savanna coverage was only 39%, and built-up areas 4%. Despite the building of roads and infrastructure, the trend of forest encroachment onto savannas in this area is obvious.

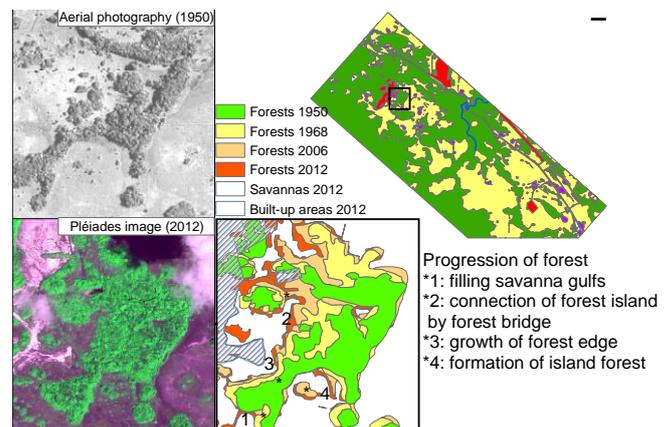


**Figure 2:** Changes in forest – savanna areas at the CSG study site in French Guiana, 1950 – 2012.

Spatial coverage (forests, savannas, forest islands and built-up areas) and local changes were mapped for 1950 and 2012 in figure 3. Changes in the vegetation cover occurred mainly at the forest-savanna contact zone. Savanna zones tended to be converted into forest as we can see with the closing of the forest areas. On the 62-year period, forest expansion reached 302 ha (data not shown) in the North-Western of the Malmanoury creek (zone 1, Fig. 1) which is mainly composed of the shrubby savannas. In the South-Eastern part (zone 2, Fig. 1), mainly composed of grass savannas, forest expansion was weaker (176 ha, data not shown).



**Figure 3:** Map of forest – savanna zones at the Guiana Space Center (CSG) study site between 1950 and 2012.

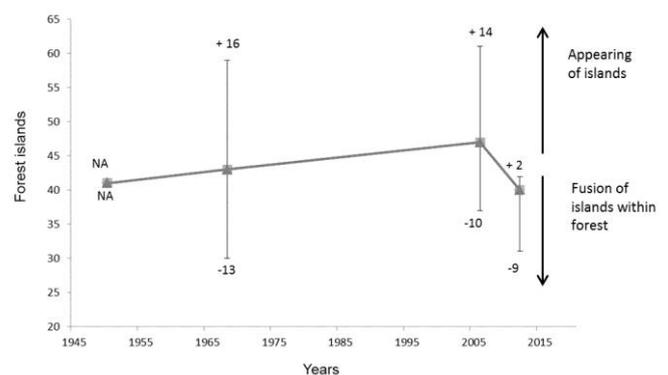


**Figure 4:** Example of the local progression of forest onto savanna from 1950 to 2012 in a specific zone of the Guiana Space Center (CSG) study area.

### 3.2. Dynamics of forest-savanna

By comparing the resulting maps for 1950, 1968, 2006 and 2012, we highlighted how forest cover progressed onto savanna in CSG area (Fig. 4). Our results showed that forest progression was irregular along the edge. A detailed extract from study area show that forest progressed in a number of steps: (1) filling savanna gulfs, (2) connecting forest islands by “forest bridges”, (3) progressing of forest edges onto savanna and, (4) appearing of forest islands in savanna.

If the changes in the vegetation cover occurred mainly at the forest–savanna contact zone, colonization by pioneer species and the apparition of new forest islands in savanna plays an important role. The number of islands was stable throughout the 62-year period (mean of 43 +/- 3, Fig. 5). The number of islands resulted from a clear balance between the appearance and disappearance of forest islands. This phenomenon illustrates the ability of the forest species (i) to conquer new savanna areas by always creating isolated forest islands and (ii) to absorb islands near the contact zone between savanna and forest.



**Figure 5:** Forest island dynamics in Guiana Space Center (CSG) study area between 1950 and 2012:

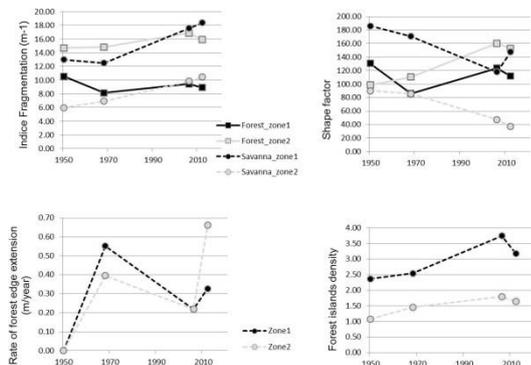
- The upper bars show the number of new islands appeared since the previous date.
- The lower bars show the number of absorbed islands (they disappear since the previous date).

Between 1950 and 2012, in the zone 1, the fragmentation indice of savanna increased and was higher than the fragmentation indice of forest. It means that savanna polygons split more for the benefit of the forest polygons that became bigger and more regular on the edges. On the contrary, in zone 2, fragmentation indice of savanna was lower than fragmentation indice of forest.

The decrease of the savanna shape factor in the two zones showed that the predominant finger-shaped polygons (1950) tend to disappear and to be transformed in more compact shapes (2006). In zone 2, savannas tended to be more circular while forests tend to be more elongated (Fig.6).

From 1950 to 2000, the rate of forest edge extension (Fig. 6) was faster (0.55 m/year) for zone 1 than for zone 2. This trend was reversed for 2012 (zone 1: 0.33 m/year). Conversely, the forest front in zone 2 accelerated from 0.4 m/year (1968) to 0.66 m/year (2012).

The forest islands density in savanna (Fig.6) was higher in zone 1. Indeed, between 2.37 and 3.75 new clusters appeared in zone 1 against 1.4+/-0.4 new clusters in zone 2 over the 62-year period.



**Figure 6:** Two different dynamic patterns of forestation between 1950 and 2012.

#### 4. Discussion

We focused in this study on two main objectives: (i) to study the evolution of forest-savanna dynamic on a 62-year period and, (ii) to characterize the dynamic of forest-savanna landscapes.

**Forest expansion on the coastal savanna of French Guiana.** The results obtained in this study clearly show that forest progressed of 23 % onto savanna over the 62-year period in the study area. We showed that the Guiana Space Center (CSG) in 1950 was mostly covered by savanna, whereas in 2012 forests mostly predominated. These results contradict the estimations of Hock (1971) who considered that edaphic factor, disturbances or specific savanna micro-climate would prevent the forest from colonizing them. Our results are consistent with those of some other authors (Rostain 2008; McKey et al. 2010) who showed that certain ancient Amerindian fields formerly located in coastal savannas of French Guiana are now covered by forest. Likewise, Aubréville (1966) observed increasing encroachment of forest onto savanna. Several studies

on forest-savanna contact zones confirm this forest progression over adjacent savannas in Brazil (Rossatto et al. 2009), India (Puyravaud et al. 2003) and Australia (Russell-Smith et al. 2004). Several factors may induce forest growth dynamics: more favorable climate and more suitable soil, lower sensitivity to anthropogenic pressure or bushfires (Hills & Randall 1968; Youta Happy 1998). Moreover, in instances where protection is provided against fire, forest tree species commonly colonize savanna (Hoffmann et al. 2003). This is the case here as the CSG area has been protected from bushfires since the site was first constructed. So, forest development in savanna corridors may close fire corridors, limiting the fire propagation to other savanna areas. Fire-protected savannas were then more prone to forest recolonization. This forest progression onto savanna (1) shows that many savannas are non-climax in French Guiana, and (2) is probably due to a decrease in bushfires than to climatic change as evoked for several African savannas (Schwartz et al. 1996).

**Dynamic of forest-savanna.** Over the 62-year period, forestation was very dynamic in coastal savanna of CSG. Forest progression at the study site may follow four steps: progression of forest domain edges onto savannas, filling of savanna gulfs, appearance of forest islands on savanna, and connection of these islands to the forest domain by "forest bridges". This type of forest progression has been described by Youta Happi (1998) in savannas of Cameroon. But, two others types of forest progression have been cited in the literature that we did not highlight in our study site: linear progression of forest edge without formation of forest islands in savannas (De Foresta 1990) and overall afforestation of savanna (Adjanohoun 1964; Eden & McGregor 1992; Louppe et al. 1995). We showed also that forestation took place through an positive balance between initiation and disappearance of forest islands, phenomenon shown by Gautier (1989).

Landscape analysis allows describing landscape changes in coastal savannas and a variability of forest progression in CSG area. We found in South-East, that fragmentation of savanna increased with more circular polygons while the forest cover increased with more elongated patches. In North-West, there is also an increase of fragmentation of savanna polygons in favor of forest cover, but forest polygons tended to become bigger with smoother edges. These landscapes indices allow us establishing a baseline for tracking savanna landscapes changes.

There is a relation between the type of forest-savanna contact and the speed of propagation of the forest: the longer is the contact of forest-savanna (ratio L/S), the higher is the speed. According to the morphological configuration of the forest border, the progress of the forest took place at different speeds (Youta Happy 1998). When forest borders are straight (case of the South-East) the progress of the forest is slow. In contrast, when the border is more winding (case of North-West), the forest progression is faster. Finally, the calculated rate of forest edge extension in CSG area was slow (between 0.33 and 0.66 meter a year) according with Schwartz (1996) and Youta Happy (1998).

In conclusion, this work showed that the various types of contact between savannas and forests are a key parameter for characterizing the forest progression.

This progression was clearly established here for two very different configurations. The dynamism of the contact zones depends on the morphology of the patches. Of course, this forest progression can be affected or slowed in case of a fire occurrence.

This work was visually possible thanks to the accuracy of the Pleiades data that allows a good recognition of the different land uses, very often based on slight differences in the texture. In order to extend this work to larger areas, this ability to distinguish different textures was the starting point for an on-going work based on the recognition of textures with a semi-automatic approach.

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### References

- Adjahoun, E. 1964. Végétation des savanes et des rochers découverts en Côte d'Ivoire centrale. In *Mémoires ORSTOM*.
- Aubréville, A. 1966. Les lisières forêt-savane des régions tropicales. *Adansonia* 175–187.
- Barret, J., Blancaneaux, P., Caillé, O., Charron, C., Gaucherel, C., Granville, J.-J. de, Grenand, P., Guiral, D., Lointier, M., & Mérona, B. de. 2001. *Atlas illustré de la Guyane*.
- Beerling, D.J., & Osborne, C.P. 2006. The origin of the savanna biome. *Global Change Biology* 12: 2023–2031.
- Behling, H., Pillar, V.D., & Bauermann, S.G. 2005. Late Quaternary grassland (Campos), gallery forest, fire and climate dynamics, studied by pollen, charcoal and multivariate analysis of the São Francisco de Assis core in western Rio Grande do Sul (southern Brazil). *Review of Palaeobotany and Palynology* 133: 235–248.
- Bond, W.J., Woodward, F.I., & Midgley, G.F. 2005. The global distribution of ecosystems in a world without fire. *New Phytologist* 165: 525–538.
- Bowman, D.M., Balch, J.K., Artaxo, P., Bond, W.J., Carlson, J.M., Cochrane, M.A., D'Antonio, C.M., DeFries, R.S., Doyle, J.C., & Harrison, S.P. 2009. Fire in the Earth system. *science* 324: 481–484.
- Brook, B.W., & Bowman, D.M. 2006. Postcards from the past: charting the landscape-scale conversion of tropical Australian savanna to closed forest during the 20th century. *Landscape Ecology* 21: 1253–1266.
- Chaix, M. 2002. *Connaissance et conservation des savanes de Guyane*. IRD-WWF Guyane.
- Chave, J. 2000. Dynamique spatio-temporelle de la forêt tropicale. In *Annales de Physique*.
- Congalton, R.G., (1991). *A review of assessing the accuracy of classification of remotely sensed data*. *Remote Sensing of Environment*, 37, 35-46.
- Coster, M., & Chermant, J.L. 1989. *Précis d'analyse d'images*. Paris.
- Eden, M.J., & McGregor, D.F.M. 1992. Dynamics of the forest-savanna boundary in the Rio Branco-Rupunumi region of northern Amazonia. In *Nature and Dynamics of Forest Savanna Boundaries*, pp. 77–89. Chapman & Hall, London.
- Fölster, H., & Dezzio, N. 1994. Ecología de la altiplanicie de la Gran Sabana (Guayana Venezolana). Investigaciones sobre la dinámica bosque-sabana en el sector SE: subcuencas de los ríos Yuruaní, vol. 4 *Arabopó y Alto Kukenán*.
- Foody, G. M. 2002. *Status of land cover classification accuracy assessment*. *Remote Sensing of Environment*, 80, 185-201.
- De Foresta, H. 1990. Origine et evolution des savanes intramayombiennes. In *Paysages quaternaires de l'Afrique centrale atlantique*, pp. 326–335. Bondy.
- Gautier, L. 1989. Contact forêt-savane en Côte d'Ivoire centrale: évolution de la surface forestière de la réserve de Lamto (sud du V-Baoulé). *Bull. Soc. Bot. France, Actual. Bot* 85–92.
- Granville, J.-J. de. 1990. Recherche sur la flore et la végétation guyanaise.
- Hills, T.L., & Randall, R.E. 1968. *The Ecology of the Forest/savanna Boundary (proceedings of the Igu Humid Tropics Commission Symposium, Venezuela, 1964)*. DTIC Document.
- Hoff, M., & Brisse, H. 1990. Diversité et répartition des formations végétales en Guyane française à partir d'une base de données sur l'environnement. In p. 20.
- Hoffmann, W.A., Orthen, B., & Franco, A.C. 2004. Constraints to seedling success of savanna and forest trees across the savanna-forest boundary. *Oecologia* 140: 252–260.
- Hoffmann, W.A., Orthen, B., & Nascimento, P.K.V. do. 2003. Comparative fire ecology of tropical savanna and forest trees. *Functional Ecology* 17: 720–726.
- Hoock, J. 1971. *Les Savanes guyanaises: Kourou, essai de phytoécologie numérique*. IRD Editions.
- Hudak, A.T., & Wessman, C.A. 1998. Textural analysis of historical aerial photography to characterize woody plant encroachment in South African savanna. *Remote Sensing of Environment* 66: 317–330.
- Ibanez, T., Borgniet, L., Mangeas, M., Gaucherel, C., Geraux, H., & Hely, C. 2012. Rainforest and savanna landscape dynamics in New Caledonia: Towards a mosaic of stable rainforest and savanna states? *Austral*

*Ecology.*

- Iriarte, J., Power, M.J., Rostain, S., Mayle, F.E., Jones, H., Watling, J., Whitney, B.S., & McKey, D.B. 2012. Fire-free land use in pre-1492 Amazonian savannas. *Proceedings of the National Academy of Sciences* 109: 6473–6478.
- Krummel, J.R., Gardner, R.H., Sugihara, G., O'Neill, R.V., & Coleman, P.R. 1987. Landscape patterns in a disturbed environment. *Oikos* 48: 321–324.
- Louppe, D., Outtara, N., & Coulibaly, A. 1995. Effets des feux de brousse sur la végétation. *Bois et Forêts des Tropiques* 55–59.
- Lu, D., & Weng, Q., 2007. *A survey of image classification methods and techniques for improving classification performance*, International Journal of Remote Sensing, 28 :5, 823-870.
- McGarigal, K., & Marks, B.J. 1995. Spatial pattern analysis program for quantifying landscape structure. *Gen. Tech. Rep. PNW-GTR-351. US Department of Agriculture, Forest Service, Pacific Northwest Research Station.*
- McKey, D., Rostain, S., Iriarte, J., Glaser, B., Birk, J.J., Holst, I., & Renard, D. 2010. Pre-Columbian agricultural landscapes, ecosystem engineers, and self-organized patchiness in Amazonia. *Proceedings of the National Academy of Sciences* 107: 7823–7828.
- Puyravaud, J.-P., Dufour, C., & Aravajy, S. 2003. Rain forest expansion mediated by successional processes in vegetation thickets in the Western Ghats of India. *Journal of Biogeography* 30: 1067–1080.
- Ratnam, J., Bond, W.J., Fensham, R.J., Hoffmann, W.A., Archibald, S., Lehmann, C.E., Anderson, M.T., Higgins, S.I., & Sankaran, M. 2011. When is a “forest” a savanna, and why does it matter? *Global Ecology and Biogeography* 20: 653–660.
- Rossatto, D.R., Hoffmann, W.A., & Franco, A.C. 2009. Differences in growth patterns between co-occurring forest and savanna trees affect the forest–savanna boundary. *Functional Ecology* 23: 689–698.
- Rostain, S. 2008. Le littoral des guyanes, héritage de l'agriculture précolombienne. *Etudes rurales* 9–38.
- Russell-Smith, J., Stanton, P.J., Edwards, A.C., & Whitehead, P.J. 2004. Rain forest invasion of eucalypt-dominated woodland savanna, Iron Range, north-eastern Australia: II. Rates of landscape change. *Journal of Biogeography* 31: 1305–1316.
- Rutledge, D.T. 2003. Landscape indices as measures of the effects of fragmentation: can pattern reflect process ?
- Schoene, D., Killmann, W., von Lüpke, H., & Wilkie, M.L. 2007. *Definitional Issues Related to Reducing Emissions from Deforestation in Developing Countries*. Food and Agriculture Organization of the United Nations.
- Schwartz, D., De Foresta, H., Mariotti, A., Balesdent, J., Massimba, J.P., & Girardin, C. 1996. Present dynamics of the savanna-forest boundary in the Congolese Mayombe: a pedological, botanical and isotopic (<sup>13</sup>C and <sup>14</sup>C) study. *Oecologia* 106: 516–524.
- Silva, J.M.C.D., & Bates, J.M. 2002. Biogeographic Patterns and Conservation in the South American Cerrado: A Tropical Savanna Hotspot The Cerrado, which includes both forest and savanna habitats, is the second largest South American biome, and among the most threatened on the continent. *BioScience* 52: 225–234.
- Da Silva, J.M.C., & Bates, J.M. 2002. Biogeographic Patterns and Conservation in the South American Cerrado: A Tropical Savanna Hotspot The Cerrado, which includes both forest and savanna habitats, is the second largest South American biome, and among the most threatened on the continent. *BioScience* 52: 225–234.
- Silva, L.C., Sternberg, L., Haridasan, M., Hoffmann, W.A., MIRALLES-WILHELM, F., & Franco, A.C. 2008. Expansion of gallery forests into central Brazilian savannas. *Global Change Biology* 14: 2108–2118.
- Smits, P.C., Dellepiane, S.G., & Schowengerdt, R.A. (1999). *Quality assessment of image classification algorithms for land-cover mapping: a review and proposal for a cost-based approach*. International Journal of Remote Sensing, 20, 1461-1486.
- Soledad, G.-G., & Santiago, S. 2005. Forest fragmentation estimated from remotely sensed data: is comparison across scales possible? *Forest Science* 51: 51–63.
- Thomlinson, J.R., Bolstad, P.V., & Cohen, W.B. (1999). *Coordinating methodologies for scaling landcover classifications from site-specific to global: steps toward validating global map products*. Remote Sensing of environment, 70, 16-28.
- Visilog software documentation, Copyright ©Noesis, 1991.
- Vrabel, J. 1996. Multispectral imagery band sharpening study. *Photogrammetric Engineering and Remote Sensing* 62: 1075–1084.
- Youta Happy, J. 1998. Arbres contre graminées: la lente invasion de la savane par la forêt au Centre-Cameroun.