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Spatio-temporal dynamics of the ecosystems of the Six Forages sylvopastoral reserve (Ferlo, North-Senegal)

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Abstract

Aim : This study focuses on the spatio-temporal dynamics of the ecosystems between 1965 to 2017.

Location : sylvopastoral reserve of the six Ferlo boreholes in Senegal

Methods : The methodological approach consists in delineating and mapping land cover in the reserve, in 1965 and 2017 and, analyzing changes during this period using remote sensing techniques and Geographic Information Systems (GIS).

Results : The results obtained show the identification of 10 land-use patterns in the reserve for the year 2017: savannah woodland, shrub savannah with tree, shrub savannah, shrub steppe with tree, shrub steppe, vegetable crop rainfall, village, pond, bare soil, tree plantation. In addition to savannah with tree, all these classes are present in 1965, except for the "tree plantation" class. The zones of shrub savannah and shrub steppe and shrub steppe with tree gradually changed between these dates, while the zones of shrub savannah with tree decreased. The areas occupied by savannah with tree disappeared completely. Analysis of changes between 1965 and 2017 showed that 19.71% of the reserve area remained in its original state, 70.58% was modified and 9.71% was converted.

Main conclusion : This study has been widened to the whole “sylvopastoral reserve” protected area, which will make possible to evaluate the effectiveness of the management plans for protected areas in the Ferlo.

Keywords: Dynamics, Ecosystem, Ferlo, GIS, Land cover, Senegal, Remote sensing

1. Introduction

The Sahel and West Africa is one of the regions of the world most affected by aridity, land degradation and desertification (1). Senegal, like many Sahelian countries, is affected by these degradation phenomena linked with the overexploitation of its resources, the most affected being identified in the sylvopastoral zone (2). These areas are parts of the State's forest heritage and are organised as sylvopastoral reserves. These reserves represent about twenty in Senegal and play a very important role in maintaining extensive livestock farming, the main activity in the area, which hosts more than two-thirds of Senegalese livestock (3). This activity exclusively depends on the availability of water and natural fodder (herbaceous and woody), which is the main source of protein and nutrients for livestock in the zone. Vegetation monitoring therefore appears necessary for the sustainability of such a production system, whose survival depends on vegetation that is subject to climatic hazards. In addition to the economic aspect, from an ecological point of view, ecosystems are constantly changing, both regionally and locally (4). This evolution may depend on several climatic and/or anthropogenic factors. Studies showed that these ecosystems have undergone significant stress due to very long drought episodes but to increasing anthropogenic pressure, as well [5-7]. The study has been carried out in the sylvopastoral reserve of the six boreholes. It was chosen because of its geographical position in the heart of the Sahelian zone (see figure 1) and the presence of numerous reforestation projects such as the Great Green Wall (GGW) and the installation of pastoral units, the Agricultural Development Support Programme and Rural

Entrepreneurship (ADSPRE), the Food Security Support Project (FSSP), the Agricultural Sector Support Project (ASSP), the Regional Project to Support Pastoralism in the Sahel (RPSPS) and the Sahel Integrated Ecosystem Management Project (SIEMP). This appears to be the ideal station to see whether the improvement of rainfall in the Sahel and environmental policies have had a positive impact on vegetation. Few vegetation monitoring studies have been carried out in the region. They mainly focused on the characterization of vegetation and flora according to soil types [8-10] its adaptation to climate change [11, 12], water resources [13-15]. Most of the studies on dynamics, having used the spatial approach, do not concern this area [16, 6, 5]. Following the "timid" improvement of rainfall conditions in Senegal (17) and the impact of various initiatives (Great Green Wall) in safeguarding natural resources. Studies of [18, 19, 9] have shown a regreening in the Sahel. This regreening observed could play an important role in improving the living conditions of rural populations. From this point of view, this study will not only make it possible to draw up an assessment of the evolution of vegetation, to evaluate the surface areas of the various plant formations, but also to provide some information on the resilience capacities of Sahelian ecosystems in order to improve the conservation conditions of protected areas.

Thus, this study focuses on the spatio-temporal dynamics of the ecosystems between 1965 to 2017.

2. Materials and Methods

2.1. Presentation of the study area

The sylvopastoral reserve of the six boreholes is almost entirely located in the sandy Ferlo (figure 1) and is the largest in the entire region with an area of 417720.34 ha. It was classified by the colonial authorities under decree 8110 of 04/11/1953. This classification policy mainly aimed at slowing down the northward progression of the groundnut front. Indeed, the decree specified that "all industrial crops are prohibited within a radius of 15 km around the boreholes, especially groundnuts. Only traditional food crops are allowed there (3). The sylvopastoral reserve of the six boreholes is in the private domain of the State and is under the supervision of the National Parks Department (NPD). Today, it fully and partially shelters twelve pastoral units set up within the framework of the FSSP (year 2000) and (LSP) (Livestock Support Project in 1993) projects.

The pastoral unit is a geographical space where populations with the same economic interests, the same pastoral routes, using the same water points (boreholes, ponds,...) and exploiting the same agricultural areas live (20). The objective is to group together all the settlements located in the area of influence of a borehole (about 15 km radius) and sharing the same agricultural and pastoral space, the same water points, with converging socio-economic interests, in order to encourage the inhabitants to pool their efforts for a sustainable management of their resources. These pastoral units are jointly managed by the State and local authorities.

The climate in the region is Sahelian, characterized by a short rainy season (three months from August to September) and a long dry season (nine months from November to July). There is great interannual variability in rainfall (figure 2), which increases from north to south. Between 1960 and 2018, rainfall varied between 180 mm and 782.9 mm in the southern part of the study area (Linguere) and between 57.3 and 431.4 mm in the northern part (Podor) (data were provided by the National Agency for Civil Aviation and Meteorology, NACAM).

The terrain is relatively flat with interdunal lows, oriented northeast, southwest, which break the monotony of the terrain (21). From a morphological and pedological standpoint, the study area belongs to the fertile sandy region and is characterized by a succession of dunes and shallows with little differentiation. Depending on whether one is at the top of a dune or on a downhill slope, the soil types differ (7). The main soil types encountered are sandy-clay soils of inter-dune corridors, clay-sand soils of fossil valleys and lateritic or armoured soils.

Vegetation is composed of a continuous herbaceous stratum in savannah areas and is present in places in the steppes (22). It reaches its optimum at the end of the rainy season (October). The woody stratum is composed of trees, shrubs and bushes (23). Overall, all forms of savannah and steppe are found in the study area and their spatial distribution roughly go the following pattern: savannah and steppe are found at the level of dunes, while the densest formations are found at the level of depressions (5).

The most abundant species (21) are: *Acacia raddiana, Balanites aegyptiaca, Zizyphus mauritiana, Calotropis procera, Adansonia digitata, Combretum glutinosum and Guiera senegalensis, Cenchrus biflorus, Schnoenefeldia gracilis, Dactyloctenium aegyptium, Zornia glochidiata*. Species that have become rare due to rainfall variability and anthropogenic actions are: *Terminalia avicennioides, Grevia bicolor, Piliostigma reticulatum, Dalbergia melanoxylon, Dicrostachys cinerea, Acacia senegal, Pentatropis spialis, Polycarpaea linearifolia, Andropogon pseudapricus.*

The main activity in the region is Agriculture and it is characterized by its extensive and transhumant aspect. It has developed considerably during the two years of the study. The livestock population has become more numerous and more diversified. The herd is composed of small ruminants (sheep, goats) and large ruminants (cattle, donkeys, horses) and the size differs from one pastoral unit to another. The Technical Breeding Agency (TBA) of Mbeuleukhe counted in 2015, 30043 heads in Labgar, 68487 in Amaly and 40397 in Widou Thiengoly.

2.2. Image and software used

A 2017 satellite image, taken in November and an aerial photograph taken in December 1965 were used for diachronic analysis. The image is from the Arcgis database and is of the earth sat 2017 type, with a resolution of more than 5m. It covers the entire sylvopastoral reserve of the six boreholes. The corona type aerial photograph with a resolution of 6.7 m comes from the American mission of 1965. This photograph is composed of several bands oriented North-South.

During image processing, these different bands were georeferenced (UTM zone 28N projection with WGS 84 reference ellipsoid).

Image processing tools such as ERDAS Imagine for geometric corrections and mapping software such as Arcgis for scanning and photo-interpretation were used for processing. To refine the classification, other media were used. For the 2017 layer, the 2017 sentinel image was used, for the 1965 layer, the google earth database for that date was used.

2.3. Image analysis and processing method

The methodological approach summarized in Figure 4 includes the following activities: geometric rectification, digitization and photo-interpretation, followed by validation of the classification and detection of changes between 1965 and 2017.

Using the arcgis software, the different bands were georeferenced and then mosaicked. Then, the digitization and interpretation of the different land-use themes were carried out on all media (image and photo). On-screen digitization was adopted because it does not distort the image and therefore allows the exact reproduction of the objects to be scanned. The objective is to delimit the outline of each identified unit. It is little [5, 6] because it is a difficult method to implement. The technique of visual photo-interpretation was used given the diversity of the themes to be mapped, the final objective of the study, the output scale (1/50000), etc.) According to (24), visual interpretation of images allows the most reliable analysis of the different landscape structures that make it up, which does not, however, hide the difficulties in accurately delineating the different land use patterns (25). The different land-use units were identified on the basis of their natural colour and vegetation types on the canopy density of each of them, as described in Yagambi's classification (Table 1). This nomenclature is to date the document that describes vegetation types in tropical Africa (different plant formations) (26).

Field checks were carried out in may 2017 with the aim of validating the photo-interpretation of the various plant formations obtained from the image of the platform and to further study the characteristics of the environment. A total of 100 points were distributed over the entire area (Figure 3) and validated.

To detect the dynamics of the landscape, the products from the interpretation of the two images were cross-referenced to obtain a resulting layer to locate the changes and a transition matrix to quantify them. This layer made it possible to identify the types of changes and to calculate the areas concerned.

Thus, a distinction was made between:

- conversions that correspond to the passage from one category to another, such as ponds that have been transformed into rainfed crops,

- modifications that concern changes within the same land-use category, such as the degradation of a shrub savannah into a shrub steppe,

- Unchanged fields, which designate classes that have not been affected by changes or conversions between the two study dates.

For each year, statistics for the different land use units are presented in relative area. This is calculated by dividing the area occupied by a land use class by the area of the reserve (417720.34 ha).

3. Results

3.1. Land use units

Visual interpretation of the images revealed the existence of eleven land use units. These are savannah woodland, savannah with tree(s), shrub savannah with tree(s), shrub savannah, shrub steppe with tree(s), shrub steppe, tree plantations, vegetable crop rainfall, bare soil, habitats and ponds.

In order to facilitate the analysis of these results, these different classes are grouped into five categories (Table 2):

Natural vegetation is vegetation that has formed spontaneously, i.e. wild plants as opposed to cultivated areas that correspond to artificial vegetation. Artificial areas are human settlements. The bare zone corresponds to almost non-existent vegetation cover, while the water surfaces refer to the surface water system of the area, which consists only of temporary pools.

3.2 Status of Land Use in 1965

The total area of the study area is 417720.34 ha. Table 3 and figure 5 show that the natural vegetation formation category covers most of the reserve with 93% of the area. This vegetation is organized in bands oriented northeast, northwest and southeast. These bands are essentially composed of shrub covered savannah with tree (50% of the area of the study zone) and covered savannah with tree 38% of the zone. The savannah woodland covers an area corresponding to 3% of the sylvopastoral reserve of the six boreholes. Most of it is located in the south-west. A small part is located in the north-western part of the study area. Shrub savannah covers 0.01% of the Study Area. It is mainly located in the northeastern part of the Study Area. Together with the steppes, it constitutes the least represented plant formations in the zone in 1965.

The "cultivation area" category occupied 7% of the sylvopastoral reserve in the six boreholes in 1965. These crops located in the north-eastern part of the area are also found in the depressions where the steppe with tree is concentrated. The category "cultivated area" includes only vegetable crop rainfall and fallow land.

The ponds, despite their low representativeness given the size of the study area, occupy an area of 23.72 ha and are concentrated in depressions where savannah with tree and cultivated areas are found.

The other categories: bare soil, artificial zone are poorly represented.

3.3 Land use situation in 2017

The landscape of the reserve in 2017 is still dominated by the category of natural vegetation formations. This category increased by 2.8%.

The savannah with tree present in the Six Forages Sylvipastoral Reserve in 1965 (38%) has completely disappeared in 2017. Some classes that were negligible in 1965, such as shrub savannah and shrub steppe with tree, occupy 26% and 22% of the study station respectively. They have increased considerably and are organized in longitudinal bands in the central-eastern part and in the north. They have colonized the lands lost by the covered savannah with tree. The shrub steppe also underwent a significant evolution ranging from 1 to 6% of the study area (figure 5).

The shrub savannah with tree has decreased, occupying 41% of the area of the reserve and is distributed in the southern part and at the level of some depressions (figure 5 and figure 6).

Despite their still negligible surface area, ponds have increased in importance in 2017 and occupy 411.07 ha of the reserve. They are still located at the level of depressions now colonized by shrub steppe with tree and shrub savannah with tree.

The cultivated areas have decreased and now occupy 4% of the reserve and are still located at the level of depressions. The tree plantation class, which did not exist in 1965, now occupies 3% of the sylvopastoral reserve of the six boreholes. The vegetation in 2017 appears more fragmented in its northern part, while the opposite is true in its southern part (figure 5 and figure 6). A homogenization of the shrub savannah with tree vegetation is observed in the south of the station, the presence of steppes in the eastern part of the study area and the appearance of tree plantations. The northern part of the study area seems to be more degraded than the southern part.

3.4. Assessment of changes

Analysis of the matrix and map of changes obtained from the 1965 and 2017 image overlay shows three types of changes (table 5 and figure 7):

- Modifications are changes in the formation of natural vegetation. They represent 70.58% of the reserve. These changes extend over most of the study area, with a preponderance in the southwest and northeast.

- The conversions represent 6.91% of the study area and mainly involve natural vegetation formations that have been transformed into cultivated areas. These changes are localized from the center to the south.

- Areas without change represent 20% of the reserve area and are organized in longitudinal strips running from northeast to northwest.

Table 5: Summary of changes in the sylvopastoral reserve from the six drill holes from 1965 to 2017

3.4. Summary of changes

A detailed analysis of the various changes has made it possible to distinguish between two types of modifications and two types of conversions.

3.4.1. Modifications

The analysis of figure 8 shows that changes in vegetation are of two types : those from a more stable state to a less stable state and vice versa.

- Balance modifications: these are in the minority compared to the changes in imbalance and concern**:** 25% of the shrub steppe in 1965 became shrub steppe with tree while 12% of the latter in 1965 became shrub savannah with tree. 6% of the land loss from shrub steppe is allocated to shrub savannah in 2017.

- Unbalance modifications: among these changes, the savannah with tree is the one that has undergone the most exchanges between 1965 and 2017. In fact, 51% of its area in 1965 became from shrub savannah with tree, 16% in shrub savannah, it receives a gain of 25% from savannah woodland while 60% of the savannah woodland in 1965 becomes from shrub savannah with tree in 2017 and 35% of the latter in 1965 becomes shrub savannah in 2017. The shrub covered steppe with tree is the formation that has received the most inputs during these 52 years with a gain of 26% of the share of the covered savannah with tree, 6% of the covered savannah woodland and 19% of the share of the srhub covered savannah with tree and also 26% of the shrub-covered savannah.

The steppe with tree and the shrub steppe had low exchanges, for 41% of the shrub savannah in 1965 which became shrub steppe.

3.4.2. Conversions

Exchanges between classes of different categories tend more towards the equilibrium state of the reserve (figure 9). The conversion of vegetable crop rainfall land to natural vegetation formation is the main reason for this. In fact, 23% and 29% of its surface area have become shrub savannah and shrub savannah with tree respectively, while 6% of the bare areas have become shrub savannah with tree, 12% have become village. Tree plantations are composed of 18% shrub savannah and 4% shrub savannah with tree. As with the modifications, the shrub steppe with tree had more gain with 31% of vegetable crop rainfall, 11% of village and 75% of bare soil, while 31% of its area in 1965 was used for ponds.

4. Discussion

Land use mapping of the Six Borehole Sylvipastoral Reserve in 1965 and 2017 shows that the landscape is mainly occupied by natural vegetation formations, over 90%, followed by cultivated and bare areas. Areas occupied by human settlements and surface water, represented by ponds, account for less than 1% of the area. The surface area of steppes has increased sharply to the detriment of that of savannahs. The studies carried out on the spatio-temporal dynamics of the Ferlo catchment area (6) present results consistent with those of our study. The same applies to the study carried out by (5) which concerned the commune of Tessékéré, an area entirely located in the sylvopastoral reserve of the six boreholes. On the other hand (16), which showed an advance of shrubby covered savannah with tree for the period 1990 to 2002 in the central watershed, does not corroborate with ours. It should be noted that these studies used the same methods (remote sensing and GIS), although the scales of digitization varied.

The analysis of the evolution of vegetation in the reserve showed that the vegetation cover has been degraded despite its protected status. This degradation is manifested by a decrease in savannah formations, with the exception of shrub savannah, and an increase in steppe formations. This result can be explained by an increase in populations, by very variable rainfall from one year to the next, but also by the spatial organisation of the different formations. Indeed, in 1965, only temporary habitats were authorized in the reserve, whereas today 1735 households live there all year round. From 1965 to 2017, the Podor station located in the North (P) recorded lower rainfall intensities than the Linguere station located in the South (L) (See the situation in the study area).

This result confirms the work of (27), on the dynamics of the Ferlo forests from 1955 to 2012, a wider interval than ours, and that of (6), in the Ferlo watershed in 52 years. This forest cover degradation seems to have spread throughout the Sahel, since the studies by (28), in Nigeria, (29), and (30), in Niger using the same method conclude that there has been a regression in forest cover, which they explain by two phenomena: anthropic action and irregular rainfall. On the other hand (31), attribute a large part of this degradation to strong anthropic activity.

Similarly, the results of this work confirm those of (32) in Burkina Faso and (8) in Ferlo who used farmers' perceptions to assess forest cover dynamics.

Our results contradict the re-greening thesis that has been supported by some authors in recent years. Indeed, following the "timid" improvement of rainfall conditions in the Sahel (17) and the impact of various initiatives (e.g. the Great Green Wall and assisted natural regeneration) in safeguarding natural resources, studies [9, 18, 19] have shown a regreening in the Sahel. This work using remote sensing techniques and comparing vegetation before and after droughts concluded that the Sahel, despite ever-increasing demographic pressure, has good resilience capacities. The legitimate question to be asked then is whether the degradation of woody vegetation in the Sahel is the result of high variability in rainfall?

However, this observed degradation within protected areas raises many concerns about the future of these ecosystems if the trend continues. It is the result of the combined action of human pressures and indirect pressures such as climatic hazards. This phenomenon has begun since the management of pastoral space has been modified. In fact, this space has been organized according to the availability of water, so that in the dry season, agro-pastoralists remained at the level of the valley to cultivate and feed the livestock. In the rainy season, the ponds in the Ferlo valley would fill up, allowing some pastoralists to stay there with their herds until they dried up. In this way, they exploited part of the surrounding ponds and pastures, leaving the ponds available for the fauna, which was highly developed in the area (33). With the hydro-agricultural developments in the valley in the early 1950s, the construction of the Keur Momar Sarr dam in 1956, and the policies of sedentarization, the agro-pastoralists who could no longer adapt became pastoralists and thus remained year-round at the Ferlo. As the boreholes are equidistant of 30 km (34), the pastoralists colonized the whole Ferlo, exploited all the ponds and thus hunted the once important fauna. Their needs for firewood and construction wood, the use of herbaceous and woody fodder for livestock and the diversification of activities (hunting and gathering) have put too much pressure on the environment.

In addition, the Sahel has experienced droughts, particularly in the 1970s. Indeed, during periods of drought, water still becomes a limiting factor for plant and animal species, forcing them to adapt or disappear.

The map analysis, using the transition matrix and land use maps, showed the processes of vegetation adaptation under the combined action of climatic factors and human pressures. Three phenomena were observed: the spatial reorganization of vegetation (the most degraded areas are located to the north of the study areas and the savannah areas are located to the south in isolated blocks), steppization materialized by the increase in the total area of steppes to the detriment of savannah, the increase in the number of ponds, etc.

The organization of the vegetation in large groups observed south of the sylvopastoral reserve of the six boreholes is an adaptation of the landscape to the hazards encountered. It is due to a combination of ecological, climatic and anthropogenic factors. Indeed, the distribution of vegetation is directly related to the chemical nature of the soil, the amount of rain it receives and the pressures it is subjected to over time. The north appears to be more degraded than the south, because with hydro-agricultural developments, populations have settled close to their land before gradually moving southwards and so far the north seems more inhabited than the south. The north has then suffered simultaneously from anthropogenic pressures and reduced rainfall. (11), whose study of climate variability in the Ferlo covers a very long series (1951-2005), has shown that the isohyets have gradually decreased from north to south over the decades. While the North was subject to these two phenomena, the South of the Ferlo was only subject to high variability in precipitation. This result confirms those of (8). Who noted an anthropogenic gradient at Ferlo by studying the dynamics of woody species. This finding also appears in the studies of (35), which indicate that more than climate change, it is anthropogenic activities that would be most responsible for biodiversity loss. Soil depletion after a long period of drought, overgrazing, high evaporation rates, and wind and water erosion could also influence the distribution of plant formations, confirming the study by (36), which showed that the distribution of woody species is linked to geographical position, average rainfall and soil type. This homogenization of plant formations at au Ferlo is mentioned for the first time in this study, however, recent studies by [8, 9, 37], have identified several extinct species and regeneration provided only by species (*Calotropis procera*, *Ziziphus mauritiana*, *Balanites aegyptiaca* ...) characteristic of degraded areas [8]. Similarly, [38] used the term "combretinization" in the Ferlo Biosphere Reserve to highlight the progressive colonization of the environment by the species *Combretum glutinosum* and *Guiera genagalensis*. The existence of a rainfall gradient decreasing from west to east (10), the rise of the agricultural front following the saturation of the groundnut basin (39), the sedentarization of pastoralists around water points, and the history of the wooded Ferlo (40) may also have favoured the evolution of the landscape. Further studies are needed to deepen the explanations.

The observed increase in steppe in the sylvipastoral reserve of the six boreholes could be due to the location of the boreholes. Indeed, the construction of the large boreholes has contributed to a massive increase in human and animal pressure on the ecosystems. Indeed, the north and east of the Ferlo are assimilated to the area of the large and first boreholes built from the 1950s onwards (41). For several authors [42, 43], these are the factors explaining the dynamics of pastoral activities and, by analogy, the dynamics of the landscape before the great droughts. New boreholes were added to existing boreholes in the early 1990s, so that the northern part of the Ferlo is covered by boreholes of various sizes, old and recent, sometimes 30 km or even less apart. These boreholes are the main access point to water for natives and transhumants in an area where rainfall barely exceeds 200 mm, and have largely contributed to the modification of the savannah landscape from 1965 to the steppe in 2017. On the other hand, (8) in his study of forest stand dynamics in Ferlo from 1970 to 2000 assimilates this environment to the dry sylvopastoral zone and shows the link between the disappearance of species with Sudanese affinity and the numerous droughts experienced in the region.

The steppes in 2017 are located further north than south of the study area. This could be due to the southward migration of 400 mm isohyets (11) and the existence of a north-south rainfall gradient (10). The North would therefore be more exposed to rainfall and anthropogenic risks.

The positive balance in terms of water surfaces is mainly due to the reopening of the Keur Momar Sarr dam in 1988 after 32 years of closure since its construction in 1956. They confirm those of for which this increase is due to "the development and creation of new basins to meet the high water demand of the area following the withdrawal of the State from borehole management". These authors also point out that farmers' perception of an increase in the availability of ponds is more closely linked to the presence of fossil valleys and better rainfall conditions.

Nevertheless, it would be prudent to qualify these results on the increase in ponds, as it was very difficult to distinguish them on the aerial photographs because they were in black and white.

Conclusion

The use of land use data in the sylvopastoral reserve of the six boreholes from 1965 and 2017 shows a predominance of natural plant formations, followed by cultivated areas and bare areas. Ponds and artificial areas occupy a smaller area in both years. These different categories would have been organized according to topography and soil type. Comparison of the different land-use units in 1965 and 2017 revealed changes in land use patterns that resulted in a very profound change in the landscape. It shows a spatial reorganization of the landscape, a homogenization of plant formations in 2017, a steppization materialized by the increase of steppes to the detriment of savannahs and an increase in ponds. Vegetation formations have been organized according to a North-South rainfall and an anthropogenic gradient. The steppes are to the north of the sylvopastoral reserve of the six boreholes. The analysis of the evolution of land use showed in the sylvopastoral reserve of the six boreholes that 19.71% of its surface remained in its initial state, 70.58% underwent modifications and 6.91% conversions. The results of this study raise other concerns related to the floristic composition of these formations and its evolution over the same period. It would also be useful to consider the impacts of anthropic factors in this degradation process with practices that are not in line with sustainable management of natural resources. These include excessive exploitation of the pastoral zone, irrational exploitation of forest resources, bush fires, etc. Despite the recent improvement in rainfall and the implementation of environmental policies, there is a continuous degradation of plant formations. This suggests that the vegetation of the Ferlo in particular and the Sahel in general has reached a point of irreversibility. To confirm this hypothesis, studies on the current state (risk of disappearance) of plant formations and on regeneration will have to be carried out.

Diachronic analysis through change mapping is an effective approach for assessing ecosystem change. Old and recent media (aerial photographs, satellite images, etc.), combined with Geographic Information Systems (GIS) tools, are very useful in this process.

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Figures and tables

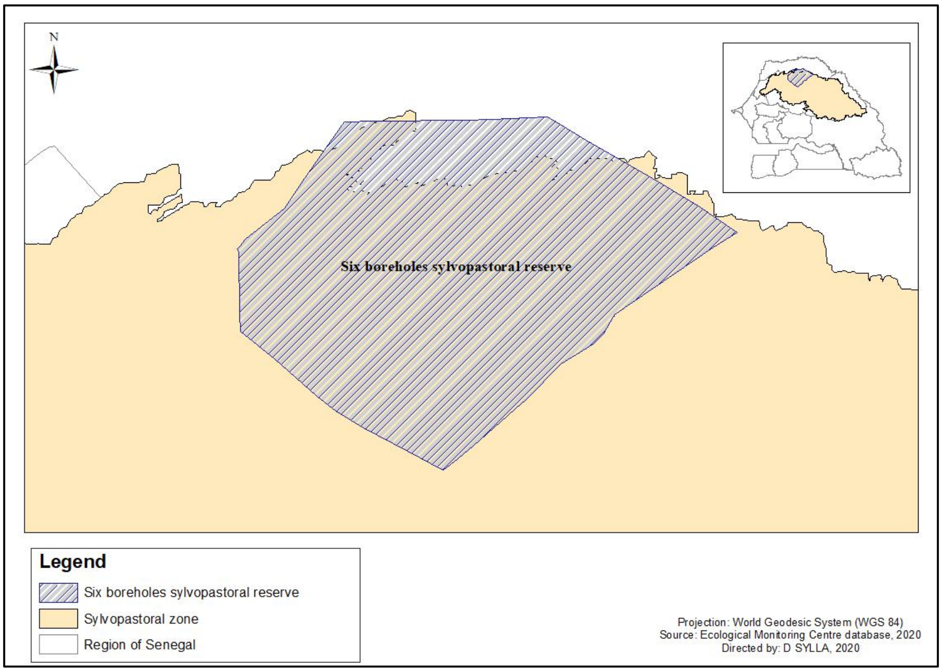

Figure 1: Location of the sylvopastoral reserve of the six boreholes

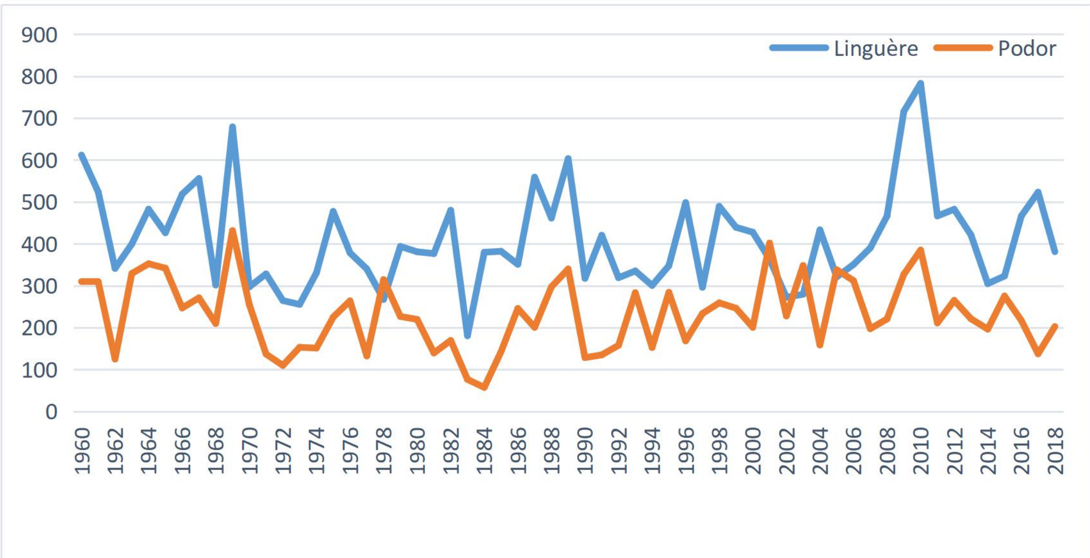

Figure 2: Evolution of annual rainfall at the Linguere (L) and Podor (P) stations from 1960 to 2018 (Source: National Agency for Civil Aviation and Meteorology, 2018)

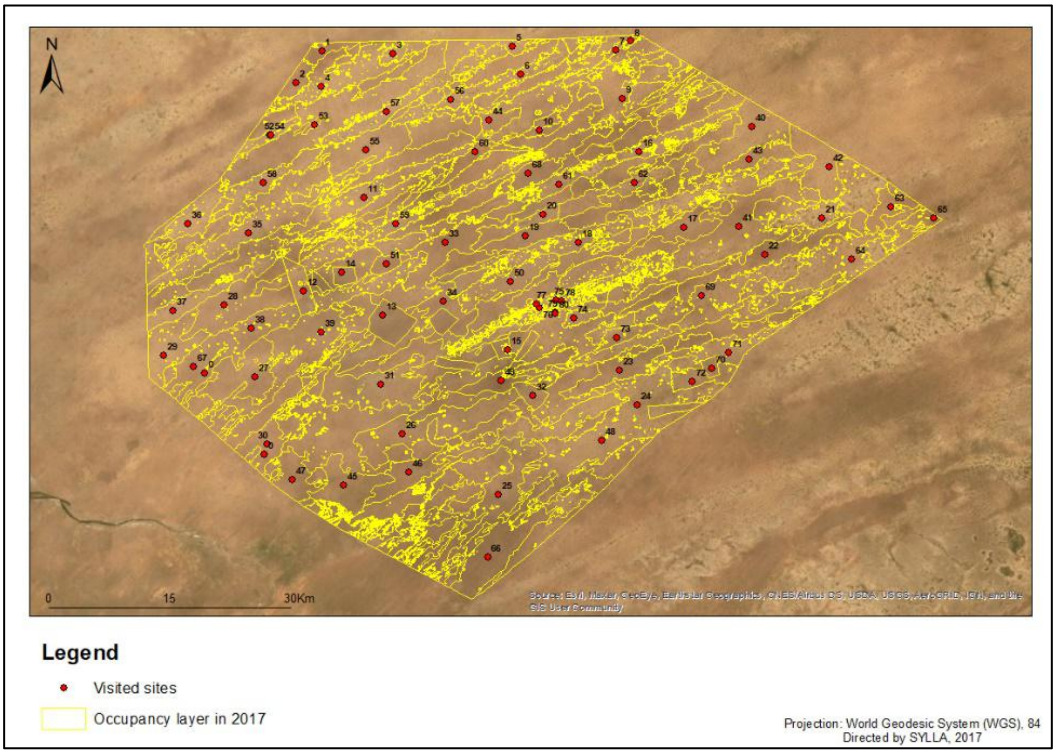

Figure 3: Sites visited during the validation process

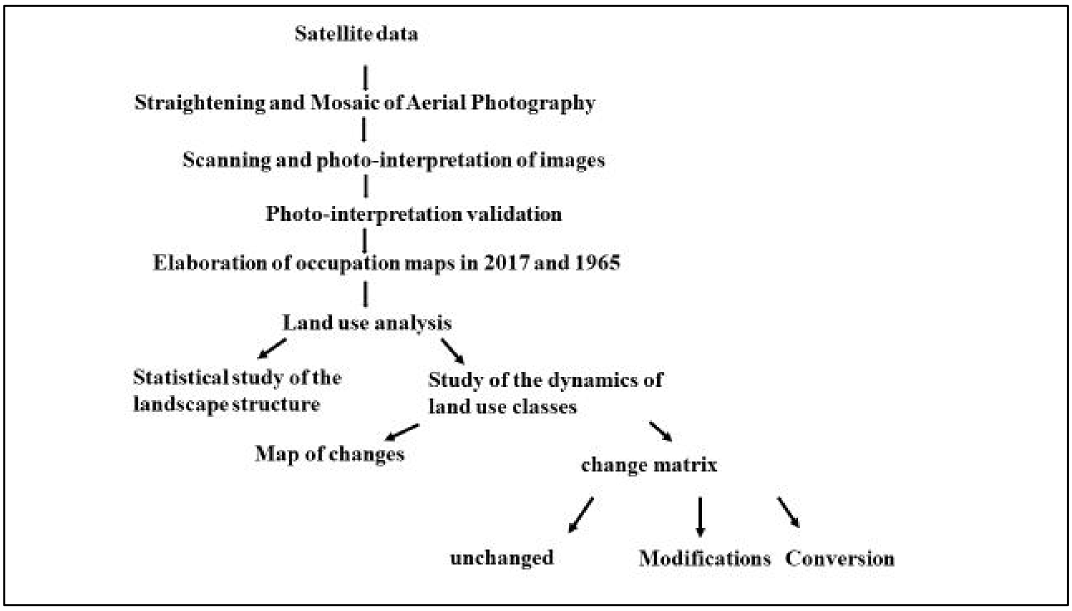

Figure 4: Methodological Approach

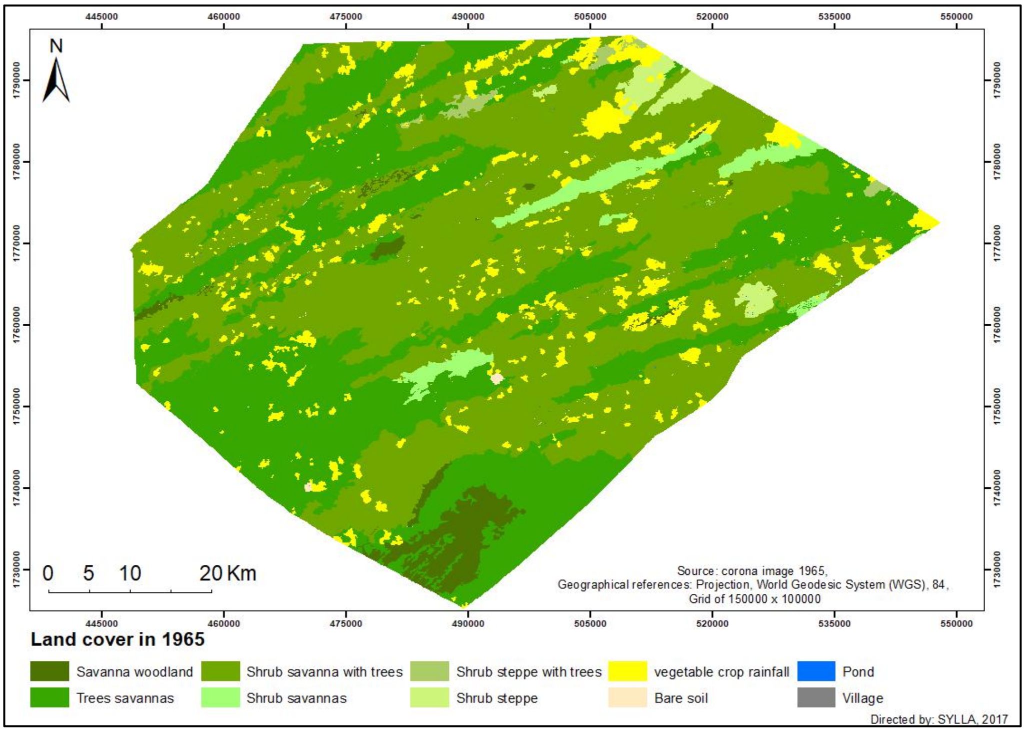

Figure 5: Land use map of the sylvipastoral reserve of the six boreholes in 1965

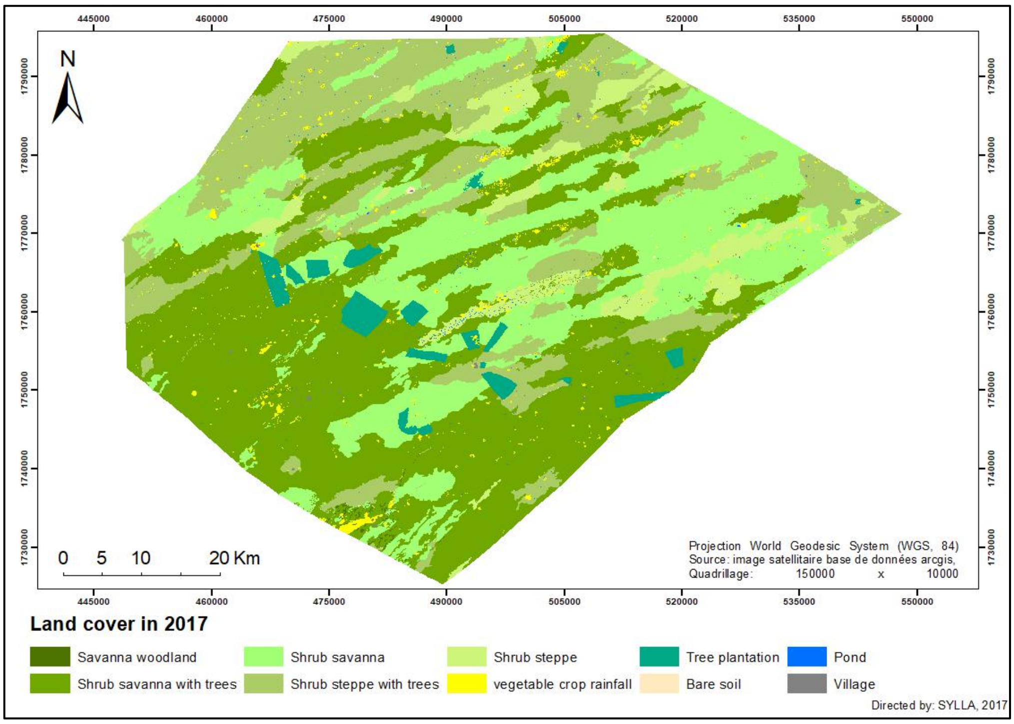

Figure 6: Sylvopastoral Reserve Land Use Map for the Six Drilling Sites in 2017

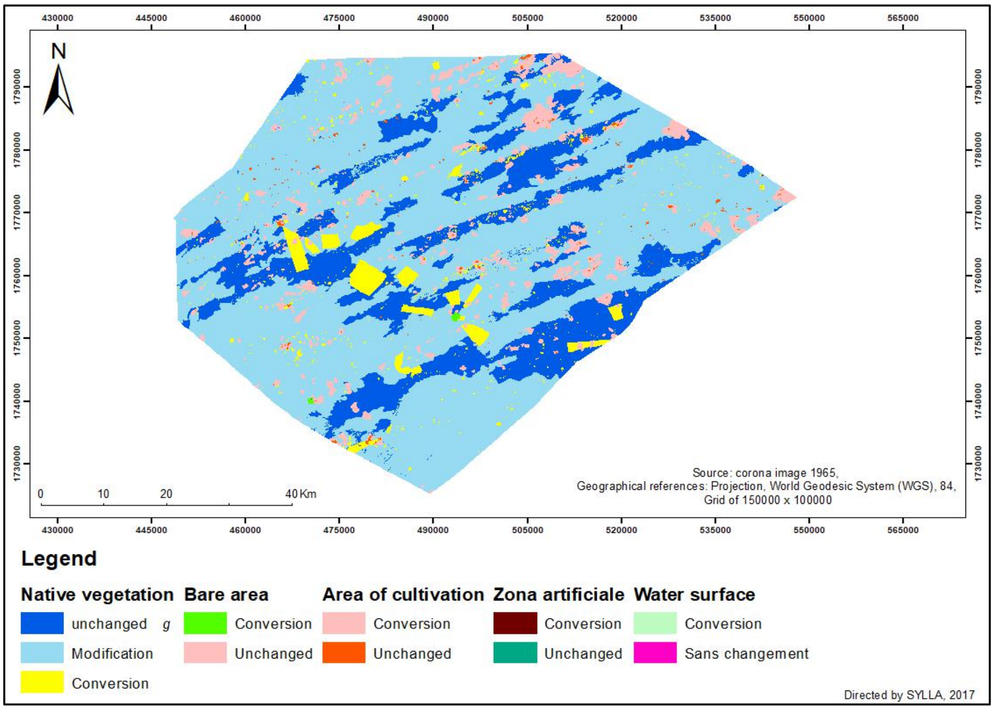

Figure 7: Map of the evolution of the sylvipastoral reserve of the six boreholes between 1965 and 2017

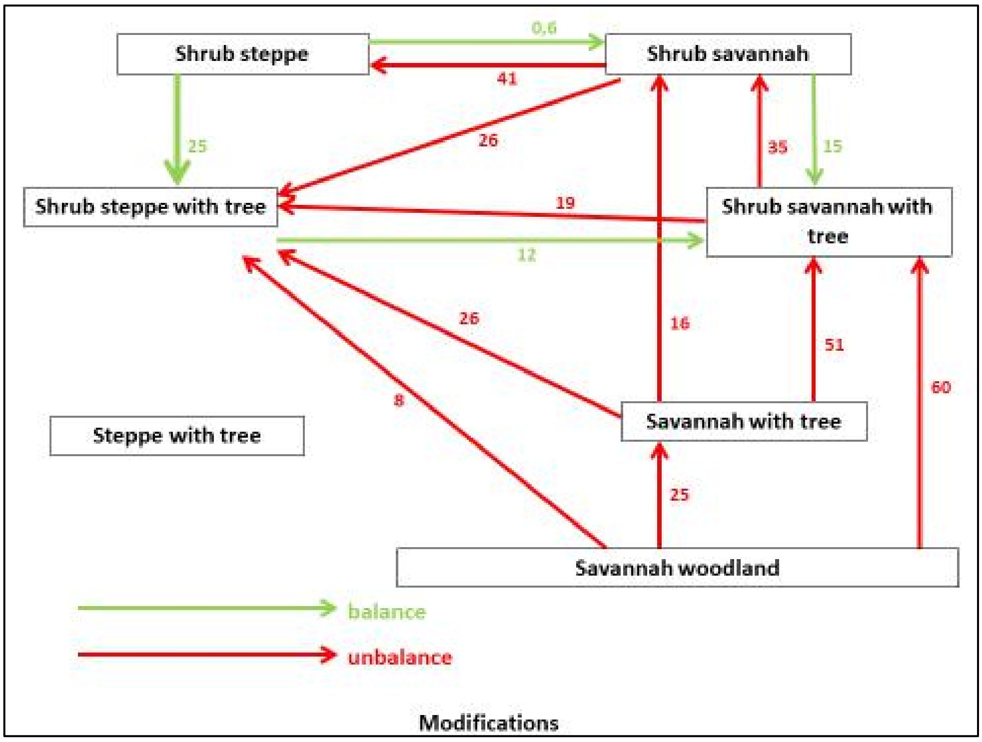

Figure 8: Summary of changes between 1965 and 2017 in the sylvopastoral reserve of the six boreholes

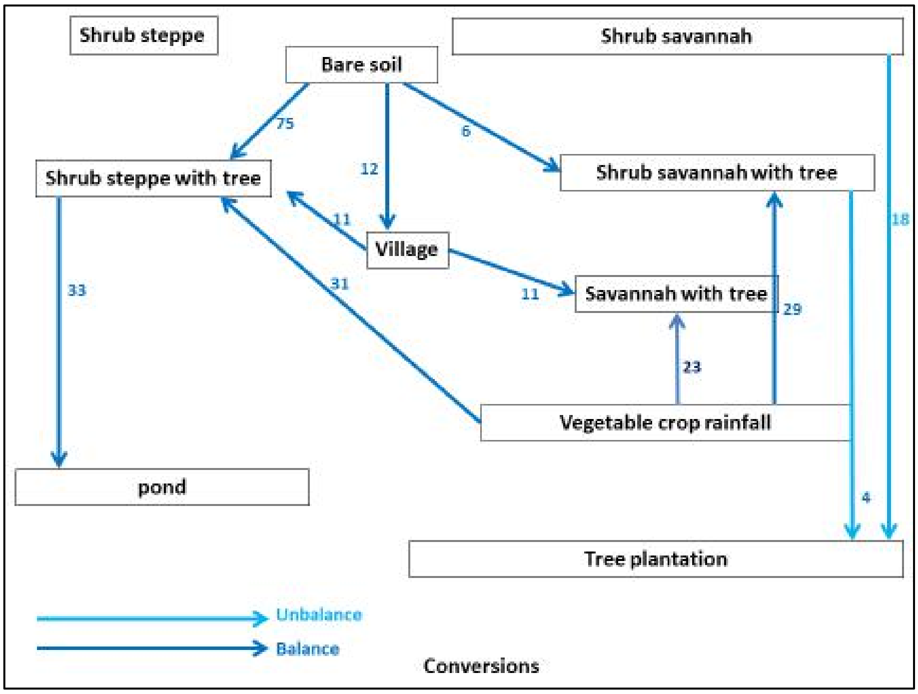

Figure 9: Balance of sylvopastoral reserve conversions for the six boreholes between 1965 and 2017

Table 1: Basis of identification of the different types of plant formations

Vegetation type	Canopy density (%)
Savannah woodland	30 – 45
Savannah with tree	25 – 35
Shrub savannah with tree	35 – 40
Shrub savannah	10 – 20
Steppe with tree	< 10
Shrub steppe with tree	5 – 10
Shrub steppe	2 – 5

Table 2: Sylvipastoral Reserve land use classes and categories for the six borehole sites

Category	Land use class
Natural vegetation	Savannah woodland Savannah with tree Shrub savannah with tree Shrub savannah Shrub steppe with tree Shrub steppe
Area of cultivation	Tree plantation Vegetable crop rainfall
Water surface	Pond
Bare area	Bare soil
Artificialized area	Village

Table 3: Statistics of land use classes in the Ferlo sylvipastoral Reserve in 1965

Land use class	Area (ha)	%
Savannah with tree	158460.38	38
Shrub savannah	3177.90	1
Shrub savannah with tree	207994.57	50
Savannah woodland	12640.47	3
Shrub steppe	5636.43	1
Shrub steppe with tree	2237.18	1
Vegetable crop rainfall	27225.62	7
Village	71.15	0
Pond	23.72	0
Bare soil	252.97	0

Table 4: Statistics on land use classes in the Sylvopastoral Reserve for the six boreholes in 1965 and 2017

Classe	Superficie (ha)	%
Shrub savannah	107843,18	26
Shrub savannah with tree	172855,81	41
Savannah woodland	450,60	0
Shrub steppe	25217,69	6
Shrub steppe with tree	93811,39	22
Tree Plantation	10553,49	3
Vegetable crop rainfall	5841,97	1
Village	671,94	0
Pond	411,07	0
Bare soil	63,24	0

Table 5: Summary of changes in the sylvopastoral reserve from the six drill holes from 1965 to 2017

Type of change	Area (ha)	Area (%)
Unchanged	82348,81	19,71
Modification	294817,74	70,58
Conversion	40553,84	9,71
Total	417720,34	100

References

[1] SSO. Sahel and Sahara Observatory. 2018. Sahel and West Africa - atlas of land use maps. Building Resilience through Innovation, Communication and Knowledge Services Project - BRICKS. 204 p. http://www.oss-online.org/sites/default/files/publications/OSS-BRICKS-Atlas_En.pdf

[2] EMC. Ecology Monitoring Centre. 2003. Land Degradation Assessment in Senegal: FAO Project. Land Degradation Assessment (LADA). Preliminary report. 59 p. http://www.fao.org/tempref/agl/agll/ladadocs/RapportLADASenegal.doc

[3] SNAPS Senegal's national protected areas strategy. 2011. Report from the Water and Forestry Directorate. 42 p. http://extwprlegs1.fao.org/docs/pdf/sen160732.pdf

[4] Tansley, G. A. 1935. The Use and abuse of vegetational concepts and terms. Ecology, vol. XVI, no 3. 284-307 p. https://www.researchgate.net/publication/249823757_Tansley_AG_1935_The_use_and_abuse_of_vegetational_concepts_and_terms_Ecology_16_284_307

[5] Sylla, D., Ba, T., et Guisse, A. 2019. Mapping changes in vegetation cover in the protected areas of Ferlo (Northern Senegal): the case of the biosphere reserve. Physio-Géo [Online], Volume 13 | 2019. 115-132. http://journals.openedition.org/physio-geo/8178

[6] Ba, T., Akpo L.E., Diouf, A.A. 2017. Spatial and temporal dynamics of ecosystems in the Ferlo watershed. Journal of Animal and Plant Sciences, 2017. Vol.33, Issue 1. 5255-5273 p. http://m.elewa.org/Journals/wp-content/uploads/2017/06/3.Taibou-3.pdf

[7] Diouf. M., Logbo. J., DO. F, C., Akpo. L, E. 2013. Determinism of the foliage of Acacia tortilis (Forsk.) in the sylvopastoral reserve of Sogobé, Ferlo, North-Senegal. International Journal Biology and Chemical Science 7(5). 2106-2116 p. https://www.ajol.info//index.php/ijbcs/article/view/102182

[8] Diouf, J. C. 2011. Dynamics of woody settlement in Ferlo (North Senegal), consequences and prospects for sustainable management. PhD thesis in plant biology: option Ecology, UCAD. 264 p. https://www.ppzs.org/FichiersComplementaires/Th%C3%A8se-Joseph-C-Diouf.pdf

[9] Bakhoum, A. 2013. Dynamics of fodder resources: indicators of resilience of community rangelands in Tessékéré au Ferlo, (Northern Senegal). PhD: Biology, pathology and

animal production: option: Pastoralism, UCAD. 118 p. https://afrique-ouest.cirad.fr/publications-et-ressources/theses-memoires/annees-anterieures/dynamiques-des-ressources-furrageres-indicateur-de-resilience-des-parcours-communautaires-de-tessekere-au-ferlo-nord-senegal

[10] Ndiaye, O., Diallo, A., Wood, S A., Guisse A. 2014. Structural Diversity of Woody Species in the Senegalese Semi-Arid Zone-Ferlo. American Journal of Plant Sciences, Vol 5. 416-426 p. http://www.columbia.edu/~saw2177/pubs/Ndiaye%20et%20al%20(Am%20J%20Plant%20Sci%202014).pdf

[11] Sarr, M A. 2009 (b). Recent evolution of climate and vegetation in Senegal (case of Ferlo). PhD thesis, Université Jean Moulin, Lyon3, LCRE UMR 5600 CNRS. 410 p. http://www.theses.fr/2009LYO31058

[12] Cissé, S., Eymard, L., Ottlé, C., Ndione, J.A., Gaye, A.T., Pinsard, F. 2016. Precipitation Intra-seasonal variability and vegetation growth in the Ferlo Basin (Senegal). Remote Sensing, 8. 66 p. https://doi.org/10.3390/rs8010066

[13] Ancey, V., Wane, A., Müller, A., André, D. and Leclerc, G. 2008. Paying the Ferlo for Water Pastoral Strategies for Community Water Management. Autrepart, 46(2). 51-66. https://doi.org/10.3917/autr.046.0051

[14] Diop, A.T., Diaw, O.T., Diémé, I., Touré, T., Sy, O, Diémé, G. 2004. Ponds in the area sylvopastoral of Senegal: evolutionary trends and role in production strategies pastoral people. Journal Breeding Veterinary Medicine Tropical countries 57 (1-2). 77-85 https://agritrop.cirad.fr/524015/1/ID524015.pdf

[15] Sy, O. 2009. Role of the waterhole in the management of the Sahelian pastoral systems of Ferlo (Senegal). Cybergeo: European Journal of Geography, Environment, Nature, Landscape, document 440. URL: http://journals.openedition.org/cybergeo/22057.

[16] Sarr, M A. 2009 (a). Mapping of land use changes between 1990 and 2002 in northern Senegal (Ferlo) using Landsat images. Cybergeo: European Journal of Geography, Environment, Nature, Landscape, document 472. url: http://cybergeo.revues.org/22707.

[17] Sarr, M A., Gachonb, P., Seidou, O., Bryant, C.R., Ndione, J.A., et Comby, J. 2015. Inconsistent linear trends in Senegalese rainfall indices from 1950 to 2007. Hydrological

Sciences Journal. Volume 60 n°9. 1-12 p. https://www.tandfonline.com/doi/full/10.1080/02626667.2014.926364

[18] Dardel, C. 2015. Chapter 6. Between desertification and regreening of the Sahel: What is really happening? In: is really happening? In: Rural Societies and Climate Change environmental issues in West Africa [online]. Marseille : IRD Éditions. https://books.openedition.org/irdeditions/12340

[19] Adey, S.A., Abdenbi, Z.E.A., Mahamat, A.M., Abdoulaye, M.O., Rabea, Z., Najiba, B., Saïd, L., et Najib, G. 2018. Analysis of the evolution of forest and pre-forest plant formations in the Sahel: the case of the Ouaddaï and Wadi-Fira regions in Chad. Physio-Géo, Volume 12 | -1 : 79-103 p. https://journals.openedition.org/physio-geo/5882

[20] Wane, A., Ancey V., Grosdidier B. 2006. The pastoral units of the Senegalese Sahel, tools for the management of livestock and pastoral spaces. Sustainable development and territories, dossier 8. URL: http://journals.openedition.org/developpementdurable/3292.

[21] Ndong, A.T., Ndiaye, O., Faye, M.N., Galop, D., Guissé. A. 2015. Woody species of Ferlo-Nord, Senegal: current status and use. Overseas Notebooks 271. 401-422. https://journals.openedition.org/com/7557

[22] Roberty G. 1952. The vegetation of the Ferlo. Extract from the Bulletin of the French Institute of Black Africa. Volume XlV, No. 3. 777-798 p. https://horizon.documentation.ird.fr/exl-doc/pleins_textes/pleins_textes_6/b_fdi_39-40/43297.pdf

[23] Fall, A. 2017. From Ferlo to the Groundnut Basin (Senegal): analysis of the floristic composition of the vegetation considered as a resource and as an indicator of socio-environmental changes. Physio-Géo, 11(1), 65-91 p. https://journals.openedition.org/physio-geo/5265

[24] Girard, M. C 1995. Visual interpretation of satellite images for spatial soil analysis: an example from the lodève region. Soil survey and management 2-1. 7-24 p. http://www.afes.fr/wp-content/uploads/2017/10/EGS_2_1_GIRARD.pdf

[25] Major, D.J., Baret, F., Guyot, J. 1990. A ratio vegetation index adjusted for soil brightness. International Journal of Remote Sensing, vol n° 5. DOI: 10.1080/01431169008955053. 727-740 p.

[26] Aubreville, A. 1957. Yangambi Agreement on the Nomenclature of African Types of Vegetation. Bois et Forêts des Tropiques, n°51, Janvier-Février. 23-27 p. http://bft.cirad.fr/cd/BFT_051_23-27.pdf

[27] Dendoncker, M., Ngom, D., et Vincke, C. 2015. Tree dynamics (1955-2012) and their uses in Senegal's Ferlo's région: insight from a historical vegetation database, local knowledge and field inventories. Bois et Forêts des tropiques, N° 326 (4). 25-41 p. https://www.researchgate.net/publication/294873014_Trees_dynamics_1955-2012_and_their_uses_in_the_Senegal%27s_Ferlo_region_insights_from_a_historical_vegetation_database_local_knowledge_and_field_inventories

[28] Hountoundji, Y.C., Nicolas, J., Sokpon, N., Ozer, P. 2005. Demonstrating the resilience of Sahelian vegetation by low-resolution remote sensing in Niger following drought episodes. Belgeo, 4, 499-516 p. https://journals.openedition.org/belgeo/12245

[29] Inoussa, M.M., Mahamane, A., Mbow, C., Bachmann Y. 2011. Spatial and Temporal Dynamics of Open Forests in the W National Park of Niger West Africa). Science and Planetary Changes - Drought Volume 22, Number 2. 108-116 p.. 108-116 p. https://www.jle.com/fr/revues/sec/edocs/dynamique_spatio_temporelle_des_forets_claires_dans_le_parc_national_du_w_du_niger_afrique_de_louest__288976/article.phtml

[30] Ouaba, A.P 2013. Climate change, vegetation dynamics and peasant perception in the Burkinabe Sahel. Single doctoral thesis in geography: Doctoral School of Letters, Human Sciences and Communications, Ouagadougou University. 305 p. http://hydrologie.org/THE/OUOBA_AP.pdf

[31] Touré, A.A., Guillon, R., Garba, Z., Rajot, J.L., Petit, C., Bichet, V., Durand, A., et Sebag, D. 2010. Evolution of the Sahelian landscapes over the last six decades in the Niamey region: from the disappearance of the tiger bush to the surface crusting of the soil. Géoscience et développement volume spécial impacts de l'homme et du climat sur les milieux sahéliens N° 47-48. 35-40 p. https://hal-insu.archives-ouvertes.fr/insu-00956999/document

[32] Ouaba, P., Da Dapola, E., et Paré, S. 2014. Local perception of the dynamics of woodland settlement over the last twenty years in the Burkinabe Sahel. Vertigo volume 14, number 2, September 2014.14(2). 13 p. https://journals.openedition.org/vertigo/15131

[33] Poulet, A. R. 1974. Ecological research on a northern Ferlo Sahelian savannah, Senegal: some effects of drought on mammalian settlement. Earth and life journal of Applied Ecology, vo1.1. 124-130 p.

[34] Barral, H. 1982. Le Ferlo des forages: old and current management of the space. ORSTOM. 85 p. https://horizon.documentation.ird.fr/exl-doc/pleins_textes/divers15-06/010004749.pdf

[35] Wezel, A. 2004. Local knowledge of vegetation changes in Sahelian Africa-implications for local resource management. In The Sahel Current politics in West Africa,the use of local knowledge in applied research-Participation in project planning and capacity building. Serein occasional paper 37-52 p. https://www.researchgate.net/publication/235660092_THE_SAHEL_Current_politics_in_West_Africa_The_use_of_local_knowledge_in_applied_research_Participation_in_project_planning_and_capacity_building

[36] Taugourdeau, S., Diouf, A., Mbaye, T., Dendoncker, M., Ndiaye, O., Hiernaux, P., Juanes, X., et Ickowitz, A. 2017. Ecological factors impacting woody and herbaceous plant communities in the Ferlo rangelands between 1970 and 1981. Pastoralism in the Current of Global Changes: Challenges, Issues, Perspectives (Dakar, Senegal, 20/11/2017 to 24/11/2017). In: Book of abstracts, 59-60 p. https://agritrop.cirad.fr/586083/1/166905_Taugourdeauetalp2cg2017.pdf

[37] Fecherolle, D. 2016. Characterization of natural woody regeneration in the Ferlo (Senegal). Dissertation of bio-engineer, Faculty of Bio-engineering, Catholic University of Leuven. 158. https://hal.archives-ouvertes.fr/hal-01326067/document

[38] Ngom, D., Fall, T., Sarr, O., Diatta, S., Akpo, L.E., 2013. Ecological characteristics of the woody stand of the Ferlo biosphere reserve (North Senegal). Journal of Applied Biosciences 65. 5008 – 5023p. https://www.ajol.info//index.php/jab/article/view/89644

[39] Ndiaye, M., Ndione., M.E., et Akpo, L E. 2010. Characteristics of woody plants in the pastoral terroirs of Ranérou. Journal des Sciences. 10 (3), 12–27 p. http://www.cadjds.org/assets/upload/media1/JDSV10N3/Article%20M.%20Ndiaye%20et%20al.pdf

[40] Ndong, A. 2016. Study of the history and the state of the vegetation of the Ferlo in the North of Senegal. PhD thesis, specialization Ecology and agroforestry, UCAD, Dakar. 161 p. https://bibnum.ucad.sn/viewer.php?c=ths&d=ths%5f2017%5f0034

[41] Ninot, O. 2008. Livestock and territory in the "Ferlo", a pastoral zone in northern Senegal. Mission report 22 November - 1 December 2007. 48 p. http://epe.cirad.fr/fr2/icare/docs/R_Mission_Senegal_Ferlo_22_11_01_12_07.pdf

[42] Santoir, C. 1994. Decadence and Resistance of Pastoralism The Fulani of the Senegal River Valley. Cahiers d'études africaines 133-135 XXXIV-1. 231-263 p. https://horizon.documentation.ird.fr/exldoc/pleins_textes/pleins_textes_5/pt5/travaux_d/16611.pdf

[43] Sy, O. 2010. Pastoral mobility in the Lower Ferlo Valley in the context of water resettlement. The Overseas Notebooks 249. 31-46 p. https://journals.openedition.org/com/5848