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Dynamics of Land Salinization in the Commune of Fimela (Fatick, Senegal) from 1973 to 2020

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Abstract

In Senegal, the agricultural sector remains a major component of the economy and national growth. As the main subsistence activity for 60% of the population, agricultural activity is essential to reduce poverty and ensure food security for the population. In this context, land degradation is a major constraint. In the Fatick region, in the commune of Fimela, land salinization is a worrying environmental problem. The purpose of this study is to understand the dynamics of soil salinization in Fimela in the context of climate change that tends to modify the evolution of landscapes. It required direct observations in the field, socio-economic surveys based on a questionnaire administered in six (6) villages. The processing of the data from these surveys was carried out with Sphinx software for the extraction of data in numerical form and SPSS to carry out the correlations between the collected variables. Excel was also used to perform calculations and make tables and graphs. In addition, the acquisition and processing of Landsat multi-spectral satellite images from 1973, 1988 and 2020 allowed us to observe the evolution of landscape units according to determining climatic events such as drought. The areas of tans have experienced a positive evolution during the period 1973-2020 with an increase of 163.11 hectares or an evolution rate of 7.47%. The localities most affected are Ndangane, Fimela, Djilor, Simal and the villages of the Mar Islands. The overall dynamics of cultivable land are marked by a decline with a rate of change of −18%. Despite the multiple reforestation campaigns, the mangrove has recorded a continuous decrease of 54.58% or a loss estimated at 5335.59 ha during the period 1973-2020. Finally, the analysis of the results of our study shows that land salinization is a determining element of the dynamics of land use and deteriorates the already precarious living conditions of rural populations and compromises the future of the agropastoral production system.

Keywords

Dynamics, Land Salinization, Fimela, Senegal

1. Introduction

The West African coasts are very susceptible to marine water penetration due to their low altitude and highly sandy nature. [1] estimates that in these low-lying areas, a rise in sea level of 50 cm would result in deep inland water penetration.

Consequently, climate change poses a threat to the economy of Sahelian countries.

This vulnerability to climate fluctuations is all the greater because these countries depend heavily on rain-fed crops. According to [2], the world loses an average of 10 hectares of cultivable land per minute due to soil salinization. Thus, the area of land affected by salinization in Senegal is estimated by INP to be 996,950 ha [3].

Indeed, Senegal is facing an invasion, of rivers, water tables and soils by marine waters. It is the rainfall deficit recorded since the early 1970s that accelerated the first processes leading to the over-salting and acidification of the soils of these estuarine environments.

This chemical degradation of the soils has made it impossible to develop land that was previously used for rice production. At the same time, salt extraction activities are developing in the northern Saloum estuary [4]. Thus, the phenomenon of land salinization has taken on the appearance of a real ecological disaster with a strong extension of bare, over-salted spaces, and unfit for agriculture [5]. Indeed, the Commune of Fimela because of its geographical position suffers from this phenomenon. Thus, under the effect of climate change, the sea level is rising, which means that the sea water tends to advance on the continent [6]. This situation leads to a progression of the salty tongue at the level of the soil.

2. Presentation of the Study Area

The Commune of Fimela is located in the district that bears the same name, in the Department of Fatick. Located between 14˚0' and 14˚10' North latitude and between 16˚30' and 16˚45' West longitude, it is bordered to the North by the commune of Djilasse, to the East by the commune of Djirnda, to the West by the commune of Ngueniene and to the South by the communes of Palmarin and Dionewar (**Figure 1**).

It covers an area of 369 km^2 or 33.09% of the total area of the arrondissement which is 1115 km^2 [7]. The commune is polarized by sixteen villages.

2.1. Rainfall

The analysis of annual rainfall totals for the period 1991-2020 shows strong interannual variability. Indeed, **Figure 2** illustrates a temporal irregularity that is characterized by deviations from the 1961-1990 normal of 566.74 mm. However, the 1991-2020 series records an average of 604.69 mm, *i.e.*, an increase of 37.95 mm compared to the previous normal despite the strong interannual variability. The maximum rainfall was reached in 2012 with 922.5 mm, *i.e.* a surplus of

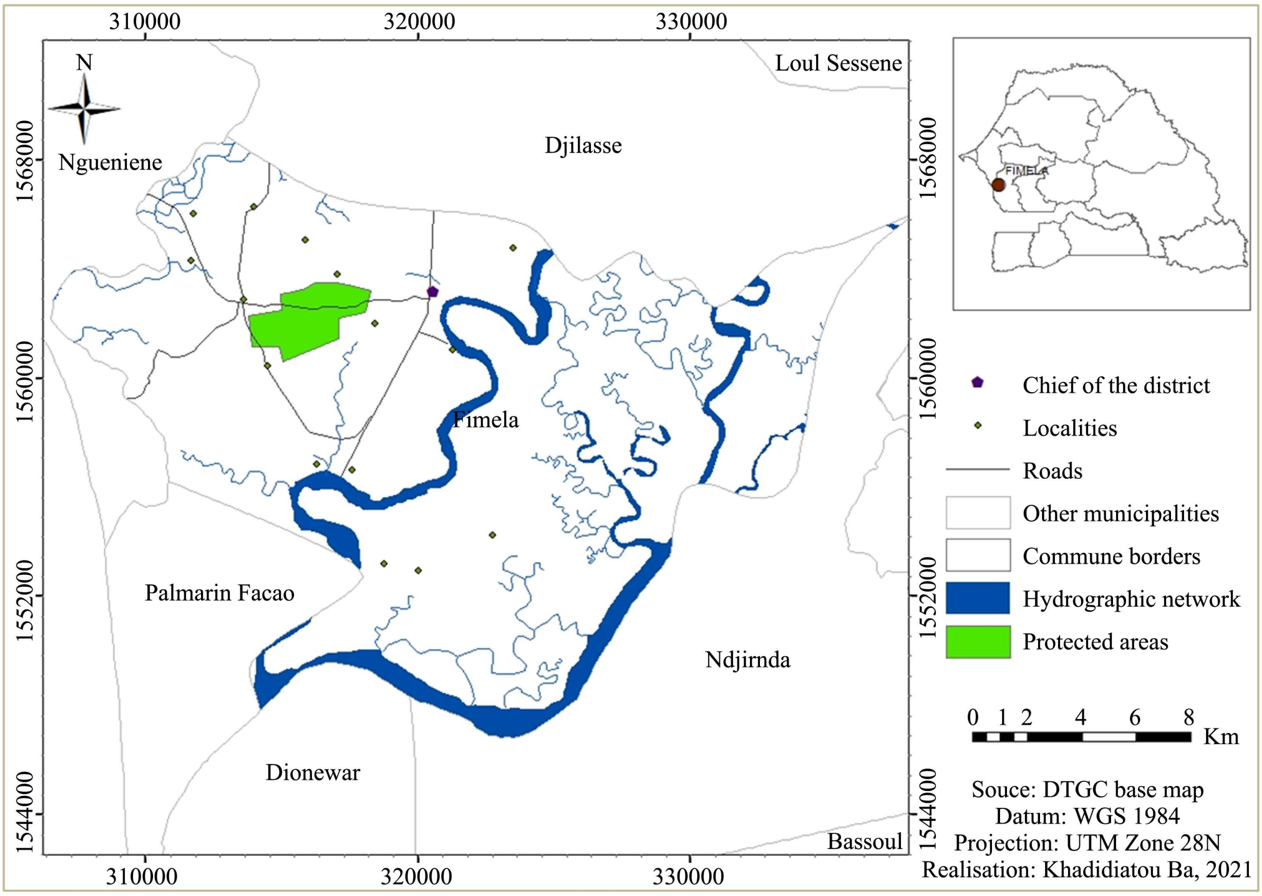

Figure 1. Location of the commune of Fimela.

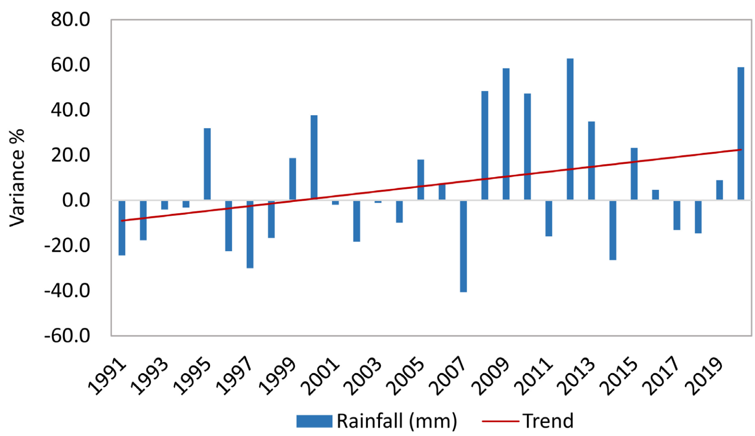

Figure 2. Rainfall trend compared to the 1960-1990 normal.

62.8%, while the lowest rainfall was recorded in 2007 with 336.6 mm, *i.e.* a difference of −40.6%. Thus, an initial sequence of generally dry years was observed from 1991 to 1998. This period was followed by two wet years (1999-2000) with surpluses of 18.7% and 37.6% respectively.

In addition, a second sequence of deficits is noted between 2001 and 2007. On the other hand, a predominantly surplus period that marks the return to normal rainfall is observed from 2008 to 2016. This series of rainy years was followed by two deficit years, 2017 and 2018, which recorded 492 and 484.3 mm in succession (**Figure 2**). Finally, the last two years are marked by good rainfall. This is particularly true of 2020, which recorded 901 mm, *i.e.* an excess of 59%.

2.2. Pedology

The study of the soil typology of the commune has made it possible to highlight several pedological units. Tropical ferruginous soils with little or no leaching are the most widespread in the commune.

These are deep, well-drained, permeable soils with low clay content. They have a great agricultural importance but are mostly degraded because of overexploitation and bad cultivation practices. They are spread over the continental part from Mbissel to Djilor and from Ndangane to Mar Soulou (**Figure 3**).

Hydromorphic soils located in the northwest, precisely in the villages of Kobongoye 1 and 2, on the banks of the river. These are soils whose evolution is dominated by the presence of excess water in the profile, which may come from a permanent water table (hydromorphic soils with gley) or from temporary waterlogging (hydromorphic soils with pseudo-gley). In addition to the marine

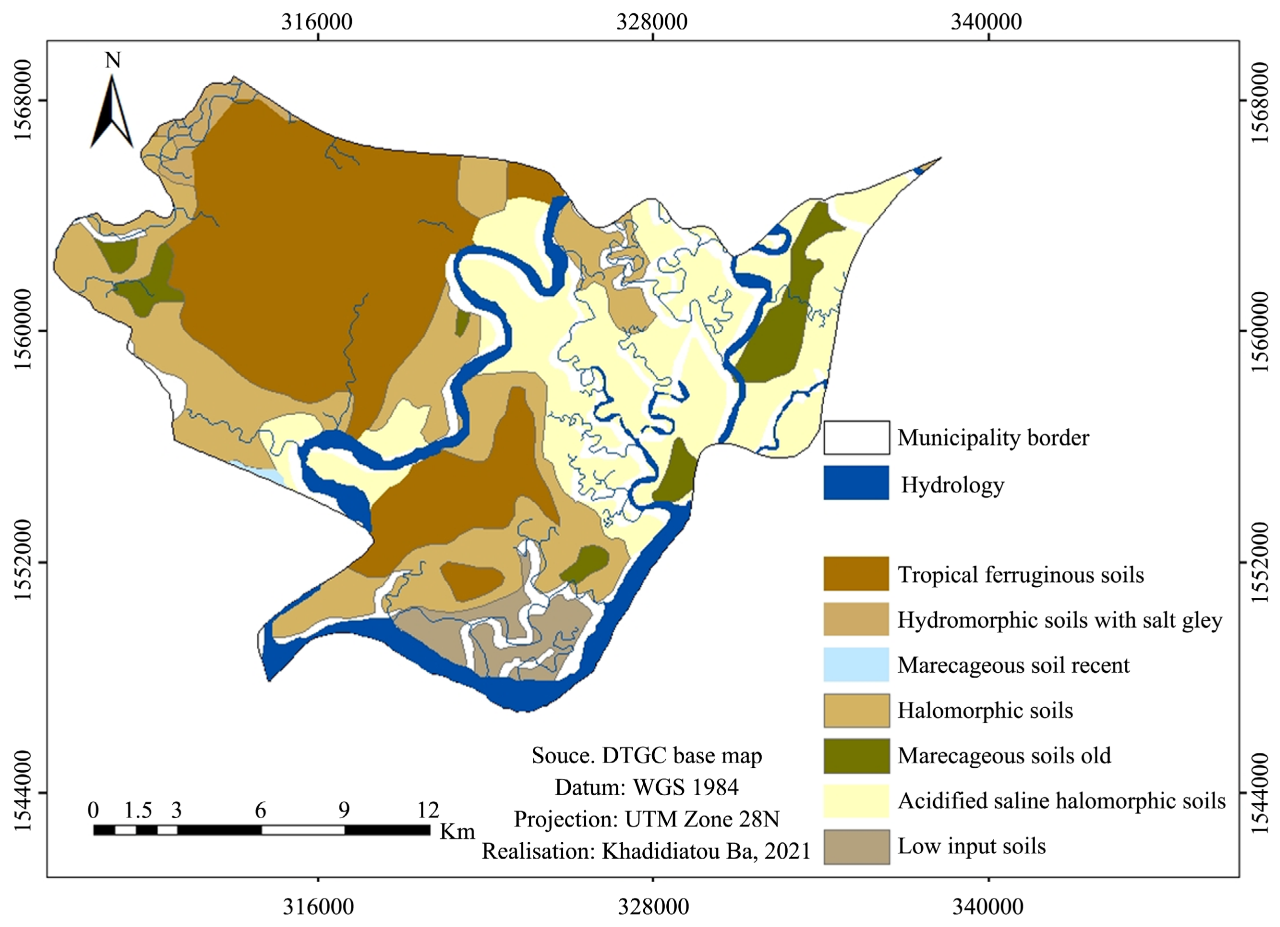

Figure 3. Soil of Fimela municipality.

dynamics which has a strong influence on the pedology. The acidified saline halomorphic soils are located along the sea arm, towards Mar Lodj, in Simal, south of the islands and in the western part of the commune. These saline soils are characterized by high contents of soluble salts of marine or continental origin. Because of their salinity and hydromorphy, these soils are very limited from an agricultural point of view. However, some halophytes develop there.

3. Methodology

The approach used is both analytical and diachronic. The data used are composed of satellite images, technical material and software. The Landsat multiband images are from the 205-050 scene. They are Landsat MSS of February 21, 1973, Landsat 5 TM (Thematic Mapper) of March 10, 1988 and Landsat 8 OLI+ (Operational Land Imager Plus) of March 26, 2020 downloaded from the following site: http://earthexplorer.usgs.gov. The technical equipment consists of a GPS (Global Positioning System), to record the geographical coordinates of the control plots. The software used: ENVI 5.3, for digital image processing; ARCGIS 10.8 for GIS (Geographic Information Systems) applications and cartographic and dynamic realizations. The perception of climate change by the population and the consequences of land salinization on agricultural activities were analyzed from questionnaires.

3.1. Data Collection

This is information that is collected through fieldwork including documentation, observation and socio-economic surveys. The documentation consisted of using books, reports, articles, theses, etc. to obtain information related to the field of study. The direct observation allowed identifying on the field surfaces affected by salinization, notably the saline inflorescences and the tans.

To obtain quantitative and qualitative data, a questionnaire was designed based on information that took into account the specific objectives of the study and was administered to concession managers.

Individual semi-structured interviews were also conducted. To this end, interview guides were used to gather the opinions of resource persons on the phenomenon under study. More specifically, interviews were conducted with the municipal authorities, the Production Organizations (POs), the Women's Promotion Group (GPF), the Union of Village Development Associations (UAVD), NGOs and structures involved in agriculture and salinization.

3.2. Data Analysis and Processing

For the processing of the data from the surveys, Sphinx and SPSS software were used. Sphinx was used to extract the data in numerical form in order to make them more easily usable, and SPSS was used to carry out correlations between the different data collected. For the qualitative data, a content analysis was performed. Excel was also used to create tables and graphs.

4. Collection and Processing of Spatial Data

4.1. Acquisition of Satellite Images and Auxiliary Data

The Landsat multi-spectral satellite images of 1973, 1988 and 2020 respectively from MSS, TM (30 m spatial resolution) and OLI (30 m spatial resolution) sensors were selected to analyze and understand the dynamics of land use in the commune of Fimela.

These dates were chosen in order to compare the state of the commune before and after the great drought of the 1970s. These dates were chosen in order to compare the state of the Niayes before and after the great drought of the 1970s, although the time interval between 1973 and 1988 is shorter than that of 1988-2020. Thus, the 1973 image illustrates the period of the great drought of the 1970s. The year 1988 is marked by a gradual return to better rainfall. Finally, the year 2020 provides a representation of the recent land use situation.

4.2. Spatial Data Processing

Preliminary work on image pre-processing was carried out before classification. The pre-processing consisted in enhancing the images to facilitate their exploitation. The resulting scenes were subjected to geometric corrections in order to enhance the quality of the images and to make the spatial features present on the images close to the real world [8] [9].

In addition, the satellite images have undergone a number of treatments that have made it possible to map the changes that have occurred in the municipality between 1973 and 2020). They were calibrated using a reference image of the area already georeferenced. Fourteen (14) landmarks (homologous points between the reference image and those acquired (MSS, TM and OLI) were selected. The resampling method is the nearest neighbor and the geometric correction was performed using a first order polynomial transformation. The validity was checked by estimating the standard error, RMSE (Root Mean Square Error). The RMSE being only an indicator, the validation of the geometrical corrections was completed by a visual control carried out by the superposition of the images. The threshold of spatial precision retained was an error of less than one pixel. They were then enhanced by dynamic range spreading and false color compositions (4-3-2), (5-4-3) and (6-5-4) respectively for the 1973, 1988 and 2020 image were created for a better interpretation of the image themes. The choice of channels was based on near-infrared (channel 4) because vegetation reflects better in this channel, and the two visible channels red (channel 3) and green (channel 2).

4.3. Determination of the Different Classes

The scientific literature offers various classification systems suitable [10] [11] [12] for different ecosystem types. Among these are the Land Cover Classification Systems (LCCS), and the Land Cover Macro Language (LCML). To remain consistent with the system jointly promoted by FAO and UNEP to meet the requirements of a globally standardized system in terms of land cover unit classification [10], the LCCS system was selected for this study. Previous research and work [11] [13] [14] has successfully used it in their work in Madagascar and along the coast of Senegal, Gambia, and Guinea-Bissau. It is a classification system that is characterized by its flexibility, consistency, and integrity in classifying land-use units. The nomenclature of the different land covers types based on the Land Cover Classification System (LCCS) model [12].

4.4. Classification of Multi-Spectral Images

The determination and understanding of the different thematic classes of the commune of Fimela on satellite images was made possible by field observations associated with those derived from Spot 5 images. These observations made it possible to distinguish the different spectral signatures that characterize the land use units when defining the training plots. Complementary data, mainly from Google Earth images, were used for visual interpretation. A supervised classification was applied to the Landsat images. Among all the existing supervised classification algorithms, the maximum likelihood algorithm was used to classify the images. This algorithm has the ability to classify pixels on a probabilistic basis [15] [16] by highlighting the standard error margin between pixel values and those of different training sites [17].

4.5. Field Verification and Image Classification Validation Data

To further refine the image classification results, existing spatial and cartographic data such as the 2005 land use map produced under the Senegal Land Use Cover project led by the Centre de Suivi Ecologique du Senegal in collaboration with USGS were used.

Field missions were then organized to validate the boundaries of the different land use units resulting from the interpretation and to improve the accuracy of the interpretation by comparing the cartographic results with the reality on the ground. This stage of processing also made it possible to verify uncertain sites and rectify interpretation errors, in order to validate the cartographic work carried out.

In addition, three hundred and sixty points (360) evenly distributed over all the occupation units resulting from the classification of the 2020 image were verified during a field campaign. The validation of the field data allowed a visual and qualitative appreciation of the physiognomic characteristics of the different types of land use. This information on the state of occupation and land use coupled with the results obtained from previous land use results were used to validate the classification and then to deduce the issues of the spatio-temporal dynamics of the saline areas.

The confusion matrices obtained from the processed images were used to validate the supervised classification. This matrix is obtained by comparing the data from the classification with the data from the field verification (reference data), which must be different from those used to perform the classification. The estimation of the quality of the classification is indicated by the kappa coefficient which varies from 0 to 1.

Finally, the processing and classification of the images were done using ENVI 5.3 software and the layout and area calculations were done using ArcMap 10.8.

5. Results and Discussion

5.1. Results

5.1.1. Land Use Dynamics of the Fimela Commune

At the end of the different satellite image data processing, the land use maps of 1973, 1988 and 2020 are obtained with an accuracy of 94% for 1973, 98% for 1988 and 99% for the 2020 image. This shows that the classification carried out on the different satellite images is very satisfactory, which translates into a correspondence of the samples carried out with the spatial reality (**Figure 4**).

5.1.2. Diachronic Analysis of Landscape Units

The analysis of the land use allows us to highlight the changes that occurred between 1973, 1988 and 2020.

Thus, the land use units identified by the supervised classification are waterways, mudflats, mangroves, tannins, agricultural land, dry land vegetation and finally built-up areas. Indeed, the built-up area, although existing before the 1970s, does not appear in the 1973 Landsat image. This is due to the low spatial resolution of the image (60 meters of resolution).

However, buildings are represented in the 1988 and 2020 images. It appears in (**Table 1**) that the mudflat, water, built-up and tannish strata are characterized by a progressive increase in their areas between 1973 and 2020. Agricultural land has experienced a regressive evolution of −4.23% from 1973 to 2020. The same situation is observed at the level of terrestrial vegetation, which has experienced a downward trend. It is the same for the mangrove whose area went from 9774.44 ha in 1973 to 7409.10 ha in 1988 and 4438.85 ha in 2020.

Table 1. Area of land use classes in the commune of Fimela.

Years	1973		1988		2020	
Classes	Area (ha)	Percentage (%)	Area (ha)	Percentage (%)	Area (ha)	Percentage (%)
Vegetation	4234.37	12.15	3612.93	10.37	3722.26	10.68
Marecageous soil	8405.87	24.12	9619.22	27.60	11809.23	33.88
Agricultural lands	8174.02	23.45	8630.10	24.76	6697.64	19.22
Tans	2183.79	6.27	2323.14	6.67	2346.90	6.73
Mangrove	9774.44	28.04	7409.10	21.26	4438.85	12.74
Water	2080.59	5.97	2925.87	8.39	5220.45	14.98
Habitat			332.73	0.95	617.75	1.77

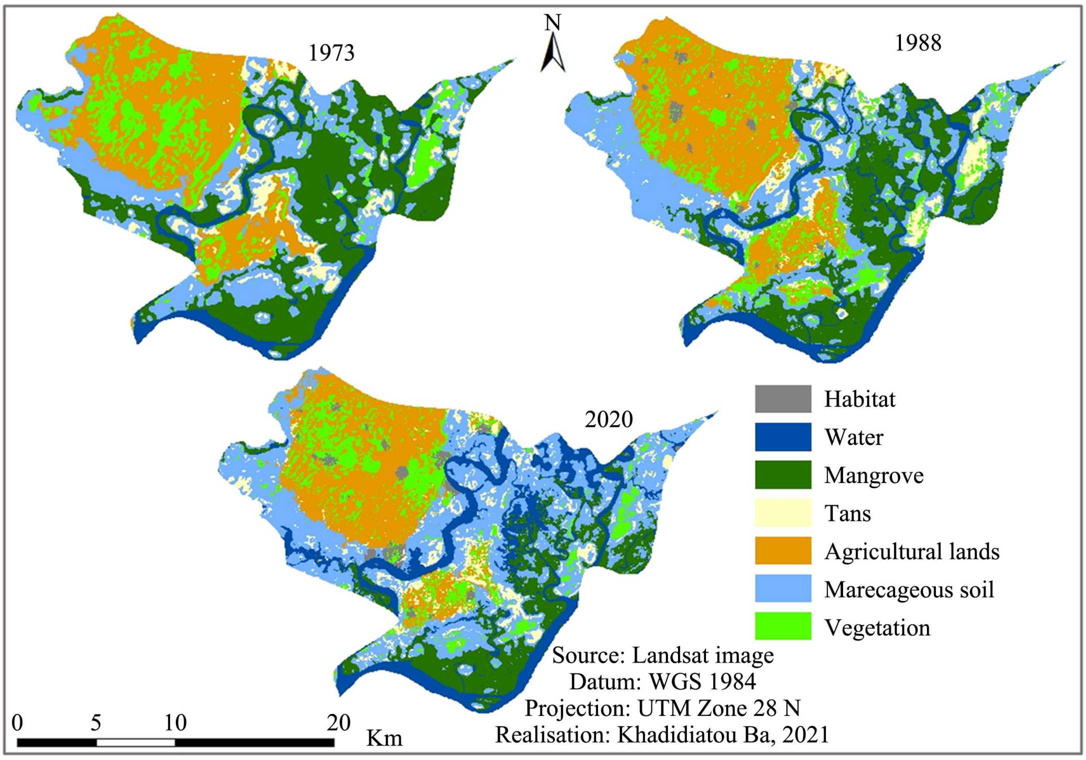

Figure 4. Land use in the municipality of Fimela in 1973, 1988 and 2020.

5.1.3. Dynamics of Soil Salinization from 1973 to 2020

This study focuses especially on the dynamics of tans, mangroves and croplands because of their strong interrelation.

Thus, **Figure 5** illustrates the evolution of these different strata during the period studied.

5.1.4. Evolution of Land Use from 1973 to 1988

The surface area of the tans showed a positive evolution during the period 1973-1988 with a variation of 139.35 hectares, that is to say a rate of evolution of 6.38%.

In addition, the mangrove is marked by a regression of its surface which passed from 9774.4 ha in 1973 to 7409.1 ha in 1988 with a rate of evolution of −24.2%.

As for agricultural land, it increased during the period 1973 to 1988 with an increase of 456.1 ha, a rate of 5.58% (**Figure 6**).

5.1.5. Evolution of Land Use from 1988 to 2020

The rate of increase of the tans has slowed down between the period 1988 and 2020 with an evolution rate of 1.02%. This corresponds to a gain of 23.77 ha, contrary to the period 1973-2020 which recorded an increase of 139.35 ha.

Regarding the evolution of the mangrove, it has resulted in a decrease of 2970.25 ha.

In addition, the agricultural areas are also marked by a regressive trend between 1988 and 2020 with a negative evolution of 1932.46 ha (**Figure 7**).

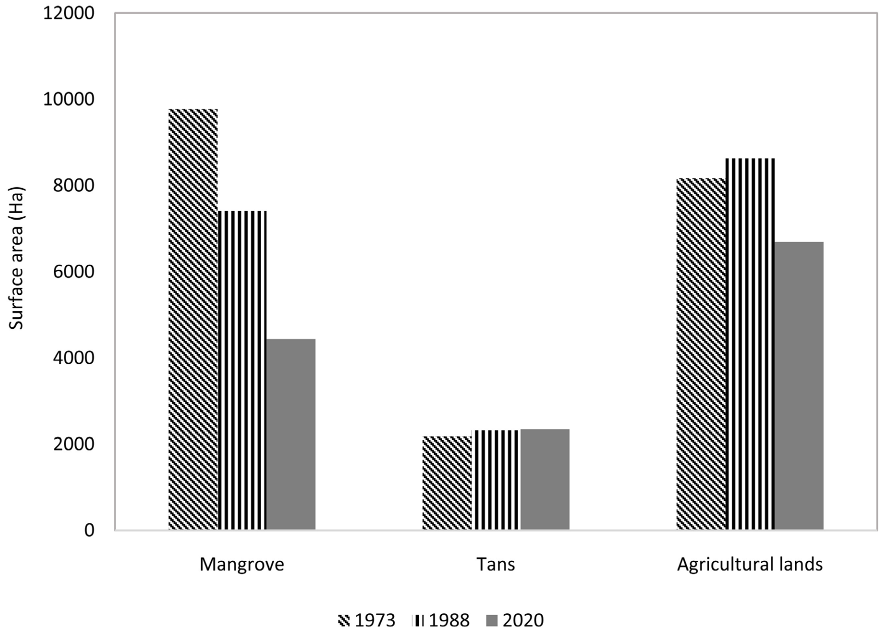

Figure 5. Evolution of mangrove, tans and agricultural land from 1973 to 2020.

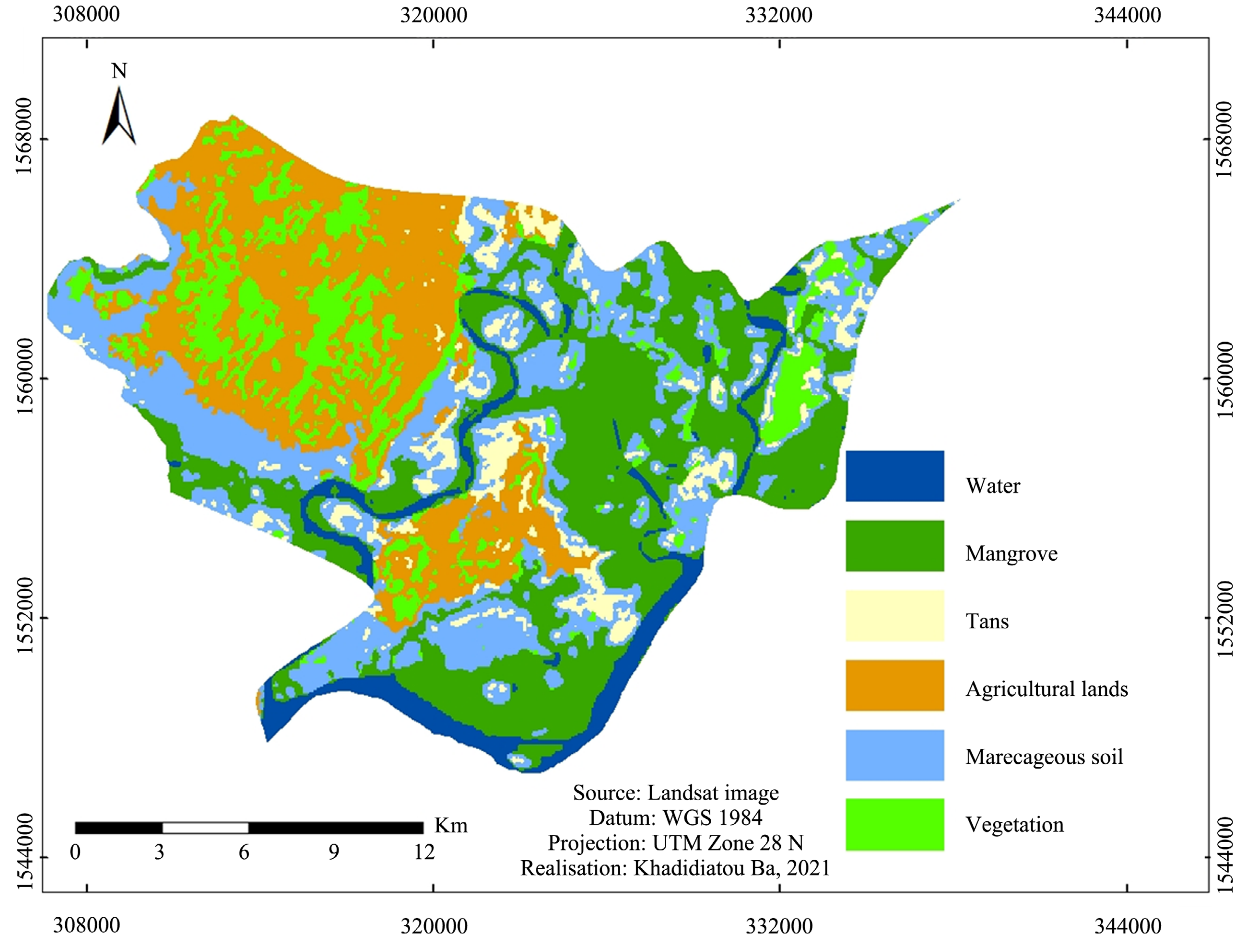

Figure 6. Land use in the commune of Fimela in 1973.

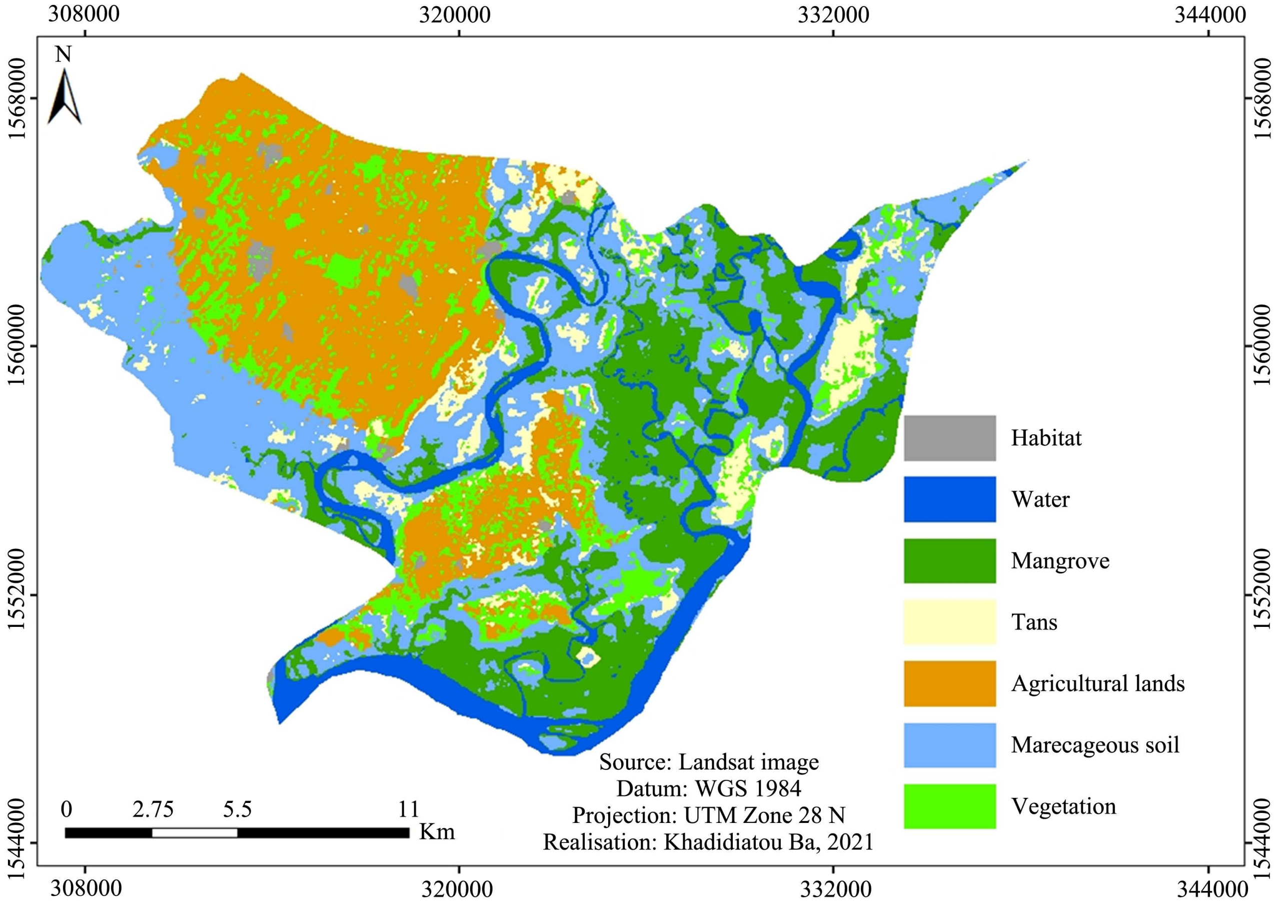

Figure 7. Land use in the commune of Fimela in 1988.

5.1.6. Evolution of Land Use from 1973 to 2020

The dynamics of the tans is characterized by a progression of 7.47% in the period 1973-2020, that is to say an increase of 163.11 ha.

The most affected localities are Ndangane, Fimela, Djilor, Simal and Iles Mar. They are located in the insular and estuarine parts of the Commune of Fimela, which makes them more vulnerable.

As a result, the overall dynamics of crop land is marked by a decline with an evolution rate of −18% (Figure 8).

The mangrove recorded a continuous decrease during the period studied despite the multiple reforestation campaigns. This regression corresponds to 54.58% or an estimated loss of 5335.59 ha. Thus, the areas gained by the tannins combined with those lost by the mangrove represent 5498 ha in terms of degraded land (Figure 9).

6. Discussion

The analysis of the results obtained shows a general trend of strong growth in the area occupied by tans between 1973 and 1988. This is followed by a slow progression from 1988 to 2020. Indeed, this dynamic could be explained by its correlation with climatic variability, which was characterized by a drastic

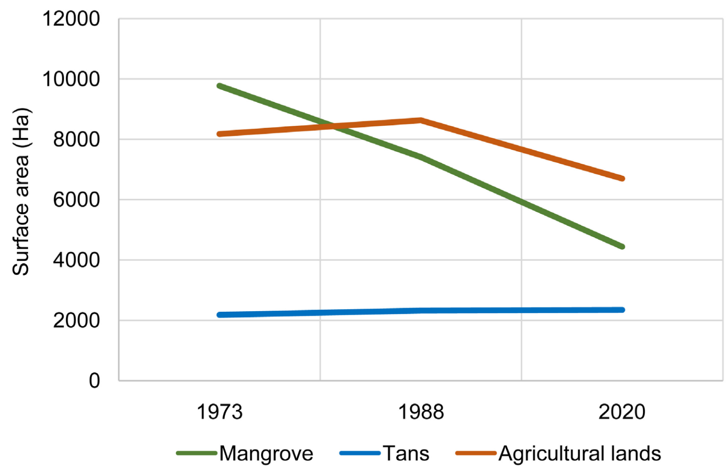

Figure 8. Dynamics of land salinization in the commune of Fimela between 1973, 1988 and 2020.

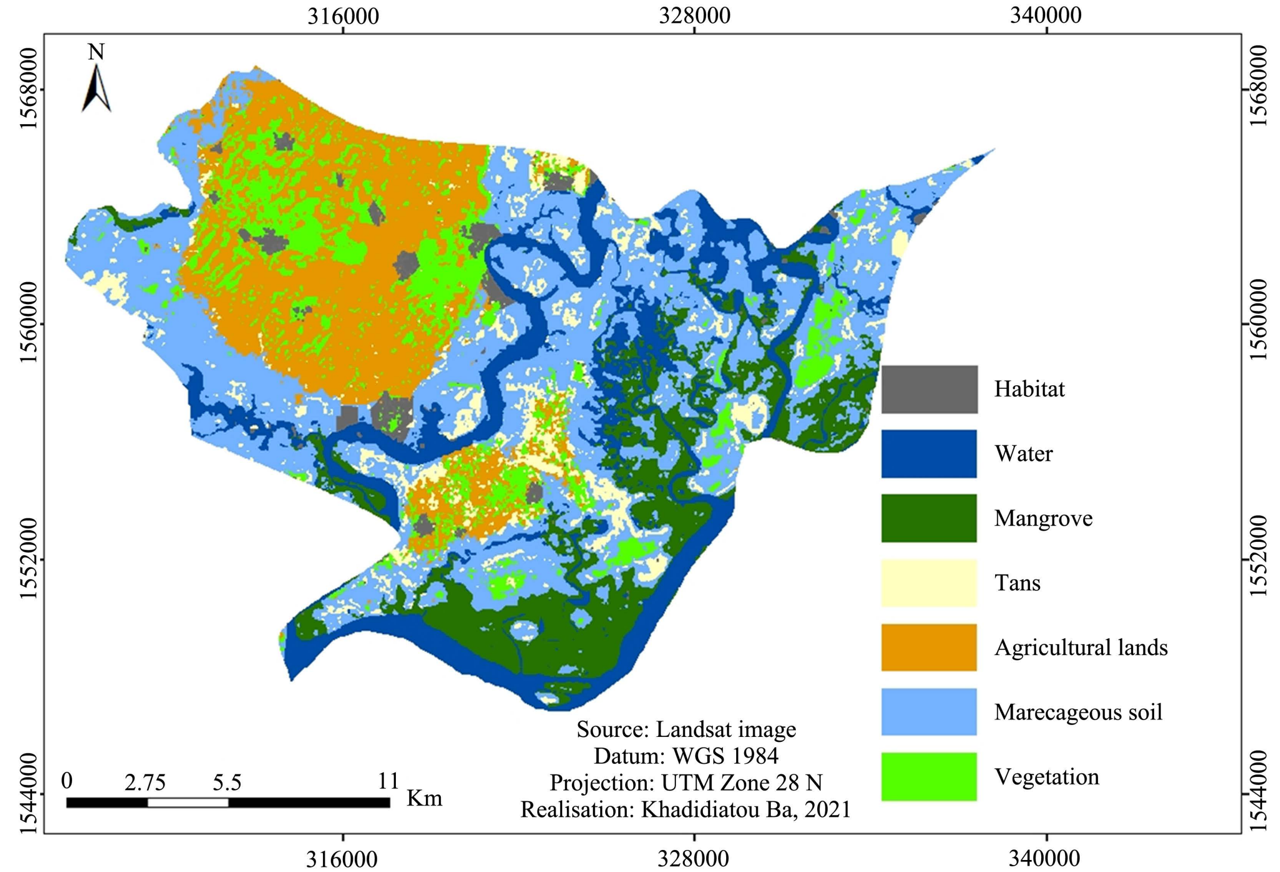

Figure 9. Land use in the commune of Fimela in 2020.

decrease in rainfall in the 1970s, 1980s and 1990s, before beginning a return to normal towards the end of the 1990s. These results corroborate those of [18], who show that the extension of tannas increased during the period 1979-2011 with more than 7197.31 ha of agricultural area being colonized by tannas in the Department of Foundiougne region of Fatick. In addition, [19] agree that saline lands have increased at the expense of cultivable areas in the Senegal River delta. [20] highlights the same trend in the Senghor Valley with an increase of 79 ha of tans between 1990 and 2005.

Furthermore, the findings of [4] show a regression of salt-covered areas in the northern Saloum estuary between 1973 and 1994 and an increase since 1994.

The study conducted by [21] showed that the area of land affected by salt in the Fatick region is equal to a minimum of 33% of the region and that it is highly saline land. At the agricultural level, the degree of salinity constitutes a major constraint to the development of these soils.

In addition, the dynamics of cultivable areas that are manifested by an increasing trend during the first period could be justified by the increase in population. The increase in population has led to the expansion of agricultural land, as some studies have pointed out, with land being cleared to meet the high demand for fertile soil. However, the decrease in the area of cultivated land between 1988 and 2020 is linked to the increase in land abandoned due to salinity, as evidenced by the people interviewed. While for [22], cultivated land recorded the highest gain (17%) during the period 1984-2017 at the level of the coastal zone of Senegal.

Remote sensing does not pose difficulties for the mapping of very saline soils, but soils with a sodic horizon, soils with low salinity or in the process of salinization without specific surface manifestations, are poorly identified and the surfaces underestimated [23] [24] [25] [26]. In this way, low-salinity soils that do not show a change in surface condition identifiable by remote sensing are not shown on the three maps. However, on land not affected by salinization on the maps, one must not overlook the existence of a certain percentage of potentially saline soils that could not be detected in this study because of the absence of specific surface manifestations.

We would like to document this study by analyzing soil samples to quantify salt concentrations in the commune, which has not been done. We consider this to be a limitation of our study.

7. Conclusion

The study of the dynamics of soil salinization in the commune of Fimela reveals an increase of 7.47% of saline land during the period 1973-2020. It is characterized by a rapid evolution between 1973 and 1988, before slowing down from 1988 to 2020. However, the area of tans remains in an evolutionary trend. In addition, the overall dynamics of cropland are marked by a regression of 18% during the period studied. On the other hand, the mangrove recorded a continuous decrease during the period studied, that is to say, a rate of evolution of −54.58%, in spite of the annual campaigns of reforestation. The geographic location of the commune, particularly its proximity to the ocean and the Saloum River, exposes it to salinity. Thus, the socio-economic and biophysical characteristics of the Commune of Fimela exacerbate its vulnerability. The climatic variability marked by a drastic decrease in rainfall contributes largely to soil degradation. Indeed, soil salinization considerably limits production and consequently hinders the development of the locality. However, most soils are affected by both salinity and acidity. Only interpolation and geostatistical methods can take into account potentially salty and acid soils. However, these complex methods require significant resources (technical, financial and temporal) that could not be gathered in the framework of this study. Nevertheless, this is an avenue for future work.

Acknowledgements

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Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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