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Multi-criteria analysis of the environmental vulnerability of the cotton zone of Mali: Case of the northeast subsidiary of Koutiala

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***Abstract*— *The northeast subsidiary of Koutiala is a very ancient and important cotton production zone in Mali. Commonly called old cotton basin of Mali, this subsidiary counting ten sectors divided between two divisions, is today finds confronted to environmental problems. However, it is difficult to locate the essential reasons of this problem so much the factors are numerous. To assess the impact of different factors on environment, this study devoted itself as objective to analyze the spatiotemporal dynamics of the environmental vulnerability of the northeast subsidiary of Koutiala between 2003 and 2017. It used several types of data for this purpose (climatic, satellite, socioeconomic and demographic, geographical). The used methodology was based on the Principal Component Analysis (PCA) and the Agglomerative Hierarchical Clustering (AHC), after standardizing the data using the empirical normalization method. The study reveals that the main factors of environmental vulnerability are mainly composed of indicators of occupation of the soil (NDVI and Occupancy rate of the soil by cultures which are present in 100.0% of the factors), socioeconomic (in 83.3%), climatic (in 66.7%) and socio-demographic (in 58.3%). It also reveals that the sector of Konséguéla in the southwest (division of Koutiala) is the least vulnerable contrary to that from Kimparana to the north (division of San) which is the most vulnerable. Globally between 2003 and 2017, there is a downward trend of the environmental vulnerability of the northeast subsidiary of Koutiala.*

Keywords— ***Multicriteria analysis, environmental vulnerability, cotton zone, Mali.***

I. INTRODUCTION

Mali is a big cotton-producing country in Africa. During countryside 2017/2018 and 2021/2022, the country ranked first African producer with a record production of 725 000 tons of cotton seed (Maïga, 2019 ; Westerberg et *al*., 2020 ; WTO, 2021). The cotton is a strategical product for Mali (Soumaré et *al*., 2020) for reasons which follow: 1. the cotton is the main cash crop and export crop of the country contributing to about 15% in its Gross Domestic Product (GDP), but especially in 40% incomes of the rural population; 2. The cotton cultivation occupies nearly 70% of the active population in the areas of its production (cotton zones) and gives direct and indirect incomes to more than 15 million persons; 3. finally the cotton zones are areas of production of dry cereals (millet, corn and sorghum) par excellence with a production of more than 2.1 million tons in 2017/2018 (Maïga, 2019), in particular thanks to the access to inputs and agricultural equipment facilitated by cotton cultivation, which contribute substantially to the food security of the small producers. This activity is therefore very important in Mali as well in economic terms as in security food.

The Malian cotton is produced on hundreds of thousand hectares (703 652 hectares in 2017/2018) in the cotton zone, or on about 6% of the national territories (Cissé, 2016). It extends over the southern and central regions of the country, and has five (05) subsidiaries including the northeast subsidiary of Koutiala.

However, the increasingly growing production of cotton in Mali raises questions about its environmental impacts. Indeed, since the 1980s, we have seen more and more land clearing to increase the areas cultivated with cotton and cereals, more pollution of soil and water due to the abusive use of pesticides, land degradation, climate change, etc. (Bidou et *al*., 2013 ; Camara, 2015 ; Ballo et *al*., 2016). Yet, this constitutes a major constraint for the achievement of certain strategic objectives which Mali aims to achieve in the short term (MEF/CSLP, 2019), in touch with the Objectives 1, 2, 3 and 12 of the Sustainable Development (OSD). So, the environmental vulnerability of the cotton zone of Mali is multi factor.

Studies showed that the northeast subsidiary of Koutiala of the cotton zone of Mali is confronted with several environmental problems because of the enhancement of agriculture and of population growth (Soumaré, 2008). To clear tracks of alleviation of the effect combined by the different factors of this vulnerability, it is therefore primordial to identify them and to classify them objectively in order of importance. That is why this research settles as main objective to analyze the spatiotemporal dynamics of the environmental vulnerability of the northeast cotton subsidiary zone of Koutiala from 2003 till 2017.

To achieve this objective, three essential tasks will be carried out: (1) evaluate the indicators of environmental vulnerability, (2) identify and classify the most determining vulnerability factors and finally, (3) analyze the spatial-temporal evolution of environmental vulnerability factors of the study area.

II. PRESENTATION OF THE SITE

The study area is the northeastern subsidiary of the Malian Textile Development Company (CMDT), commonly called old cotton basin of Mali. It stretches over the southeast and the center of Mali (Soumaré et *al*., 2020), between 6°08′ and 4°46′ of west degree of longitude and, 12°16′ and 12°88′ of north degree of latitude, including the regions of Sikasso and of Ségou (Fig. 1). The northeast subsidiary counts ten (10) sectors divided between two (2) divisions, divisions of Koutiala and of San. The zone counts 841 villages retorted between 77 municipalities and covers a complete area of 20585 km². It shelters a complete population of 1 429 746 inhabitants, that is a density of 56 hbts/km².

The agriculture is the main activity of the population, which is grouped into 2 122 peasant organizations. The cotton is the dominant speculation in the area. However, cereal cultivation (corn, millet, sorghum) and livestock also occupy a significant place.

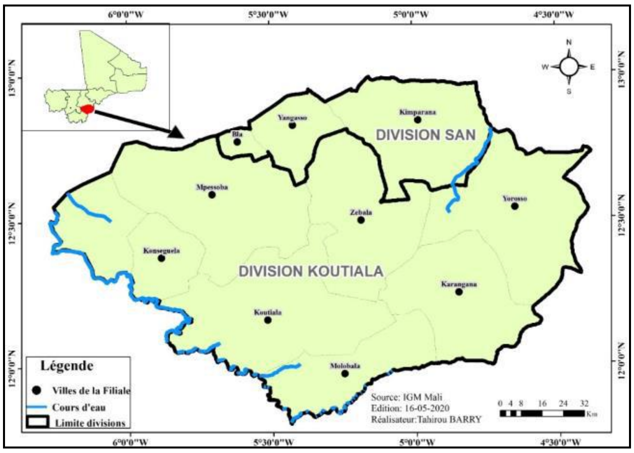

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Fig.1: Location map of the study area.

The climate of the area is dry tropical characterized by the alternation of two seasons (rainy season and dry season). The annual cumulative rainfall decreases from south to north with a zonal average of up to 900 mm. For the temperature, it evolves in a bimodal regime with the maximums in April-May (main) and September-October (secondary).

The relief is not very rugged and the soils are of tropical ferruginous types. The vegetation is mainly composed of Shea “*Vitellaria paradoxa*” and Néré “*Parkia biglobosa*” (Soumaré, 2008). The area is crossed by the permanent river the « Banifing » and seasonal rivers including the « Kifa » and the « Kimparana ».

III. MATERIALS AND METHODS

3.1. Data and processing tools

Several types of data were used in this research. The characteristics of these are detailed in the Table 1.

Table 1: Characteristics of the used data

№	Types	Variables	Spatial-temporal scales	Descriptions	Sources
1	Climatic	Rain	Sector 2003, 2007, 2012, 2017	Monthly data gathered on 8 stations in the zone	CMDT
		Temperature			
2	Satellite	NDVI image	Sector 2003, 2007, 2012, 2017	Low resolution of 250 m, MODIS Terra sensor, taken every 16 days	USGS Appears-NDVI - Modis
		Landsat 7 (ETM+) and 8 (OLI) images	Division November 2000 and October 2017	- High resolution of 30m by 30m. ETM+ and TM sensor, panchromatic band covers an area of 185 km by 185 km. - 2 sensors, Operational Land Imager (OLI) and thermal infrared. It covers an area of 170 km by 185 km.	USGS, Earth Explorer
3	Socio-economic and demographic	Population	Sector 1998 and 2009	The enrolments of the population of the different sectors	CMDT
		Agricultural statistics	Sector **2003, 2007, 2012,** 2017	Areas, production and average yields of crops (cotton, corn, millet and sorghum)	INSTAT-Mali
4	Geographical	Limits and attributes	-	These are geographical boundaries and elements (watercourses, roads and villages) in .shp format elements (watercourses, roads and villages) in .shp format	IER/CRRA

The main tools used are ENVI 4.7 for processing satellite images (Landsat 7 and 8) in order to obtain the land occupation rate, the XLSTAT software which is an extension of Microsoft Excel, for carrying out the Analysis in Principal Component Analysis (PCA) and Agglomerative Hierarchical Clustering (AHC), and finally ArcGIS 10.3 for producing thematic maps.

3.2. Methods of data analysis

The analysis of the collected data was carried out in three successive stages.

3.2.1. Preliminary processing (or aggregation) of data and evaluation of indicators

The climatic data (rain and temperature) were processed according to practical climatological standards (WMO, 2018) in order to extract climatic indices, in this case the annual cumulative rainfall (Pan) and the average annual temperatures (Tan), which will then be used in the development of environmental vulnerability indicators.

The satellite images allowed, thanks to the methods of treatment of Remote sensing (Elhadj, 2016), for every geographical unit (sector) and study year, to assess first from the images of the sensor MODIS Terra minimal, medium and maximum values of the Normalized Difference Vegetation Index (NDVI). Then the rate of the cultivated complete areas of cereals and of cotton, and the rate of annual occupation of cultures by sector were estimated (Formula 1).

$$T_o = \frac{A_a}{A_t} \times 100 \quad , \tag{1}$$

where T_o, Aa and A_t are respectively the occupancy rate of the soil by cultures, the agricultural complete area in the sector and the complete area of the sector.

Disposing only data of the population by sector of 1998 and of 2009 (years of the two last general censuses of the population and habitat (GCPH)), it was undertaken the extrapolation of these for the study years (2003, 2007, 2012 and 2017). For this, the following population projection equation (Blanchet and Le Gallo, 2008) was used:

$$P_i = (P_o + t)^n \quad , \qquad (2)$$

where P_i – population for year i ; P_o – population for the reference year (1998 or 2009); t – average annual natural increase rate of the population (the rate of regional natural increase is taken as reference rate) and n – the number of years between the years of projection and of reference.

Then, the density of the population (D_P), that is to say the report of the population by the area for every sector, was calculated for different years.

Concerning the agricultural data, from the areas and yields per speculation (cotton, corn, millet and sorghum), the average agricultural yield (ton/ha) was evaluated in a weighted manner using Formula 3.

$$R_{moy} = \frac{\sum(As_i \times Rs_i)}{\sum As_i} \quad , \qquad (3)$$

where R_{moy} is the average agricultural yield, As_i and Rs_i are the area and yield of speculation i.

Finally, agricultural production per capita (P_{hbt}) by sector was also evaluated as the ratio of the total quantity of agricultural production (P_t) in the sector by its population (P_{op}) for each year of the study.

3.2.2. Training of vulnerability components and standardization of indicators

To form the components of environmental vulnerability by sector of the study area, the climatic, environmental, economic and social indices previously assessed, summarized in Table 2, were crossed.

Table 2: Summary of the vulnerability indicators

№	Components	Indicators	Units
1	Climate (Cl)	Annual accumulation of the rain (P_{an})	mm
		Average of annual temperature (T_{an})	°C
2	Environment (En)	$NDVI_{Min}$, $NDVI_{Moy}$, $NDVI_{Max}$	-
		Soil occupation rate by crops (T_o)	%
3	Society (So)	Population for year i (P_i)	hbts
		Population density (D_P)	hbts/km²
4	Economy (Ec)	Agricultural production (P_t)	ton
		Average agricultural yield (R_{moy})	ton/ha
		Agricultural production per capita (P_{hbt})	kg/hbt

The indicators of vulnerability above in the Table 2 are of natures and very different units, that is why before passing to their classification and organization into a hierarchy, all data were standardized (normalized) and aggregated. In order to bring these multivariate indicators to the same unit of magnitude and maintain an acceptable gap between them, the empirical normalization method was applied (Boulanger et *al*., 2004). The principle of this method is presented in formula 4 below.

$$y_i = \frac{(x_i - x_{min})}{(x_{max} - x_{min})} \quad , \qquad (4)$$

where y_i are the normalized indices, x_i are the modalities of the variable X, x_{max} and x_{min} are the minimum and maximum values of the data series.

3.2.3. Principal Component Analysis (PCA) and Agglomerative Hierarchical Clustering (AHC)

To the normalized and aggregated data, the PCA algorithm was applied, in order to obtain the best possible combination of variables (climatic, environmental and socio-economic/demographic). This made it possible to determine the factor axes to be retained, where each component constitutes a vulnerability criterion.

A AHC was applied to the factorial axes obtained through the PCA, using the Ward method (Von Storch and Zwiers, 1999). This made it possible to classify the sectors according to their degree of vulnerability, according to the years (2003, 2007, 2012 and 2017), and to produce vulnerability maps.

3.2.4. Spatial-temporal evolution of environmental vulnerability factors in the study area

At the end of the AHC, the degree of vulnerability of the different sectors of the subsidiary was assessed, for the years 2003, 2007, 2012 and 2017. It varies strongly from a sector to other one, from one year to other one and according to the elements. The classification of sectors by level of vulnerability was made according to the weight of the variables of every indicator, varying between 0 and 3. This is how the three levels of vulnerability were defined (Low, Medium and High), with the weight intervals [0; 1],]1 ; 2] and]2; 3] respectively.

IV. RESULTS AND DISCUSSION

Three main results were obtained at the end of this study, namely the estimates of vulnerability indicators, the classes of vulnerability factors, and the spatial-temporal dynamics of the environmental vulnerability factors of the study area.

4.1. Vulnerability indicators of the study area

The normalized and aggregated estimates, at the scale of the northeast Koutiala subsidiary, of vulnerability indicators are summarized in the Table 3 below.

Table 3: Standardized estimates of vulnerability indicators at the subsidiary level

№	Components	Standardized indicators	Year			
			2003	2007	2012	2017
1	Climate (Cl)	P_{an}	0.53	0.57	0.62	0.48
		T_{an}	0.41	0.39	0.45	0.45
2	Environment (En)	$NDVI_{Min}$	0.55	0.54	0.56	0.63
		$NDVI_{Moy}$	0.47	0.52	0.43	0.47
		$NDVI_{Max}$	0.34	0.47	0.49	0.58
		T_o	0.37	0.37	0.34	0.47
3	Society (So)	P_i	0.24	0.22	0.23	0.23
		D_P	0.52	0.50	0.44	0.44
4	Economy (Ec)	P_t	0.25	0.50	0.44	0.52
		R_{moy}	0.55	0.48	0.20	0.56
		P_{hbt}	0.18	0.24	0.27	0.24
Total			4,41	4,80	4.47	5.07

Individually taken, normalized estimates by some indicators of vulnerability on the scale of the subsidiary vary considerably from one year to other one. The most unstable indicator is the average return (Rmoy) with an amplitude of 0.36. Its lowest value was obtained for the year 2012 despite a clear increase in rain that year. As for the accumulation of the values of all the indicators at the scale of the study area, it evolves in sawtooth from 2003 to 2017.

4.2. Classes of vulnerability factors of the study area

The characteristics of the three main factors of vulnerability, got for the zone of study at the end of the PCA, are introduced in the Table 4, for every considered year. The second column of the table contains the factors or component, the third contains the coefficients of indications (their factorial contribution), the fourth contains the variance explained by each of the elements and, finally the last contains the increasing combined variance of the three factors.

Table 4: Characteristics of the three main vulnerability factors of the study area

Year	Factor	Own value	Variability (%)	Cumulative (%)
2003	F1	4.51	37.57	37.57
	F2	2.45	20.46	58.03
	F3	1.87	15.54	73.57

Year	Factor	Own value	Variability (%)	Cumulative (%)
2007	F1	3.99	33.22	33.22
	F2	2.77	23.08	56.30
	F3	2.36	19.68	75.97
2012	F1	4.30	35.81	35.81
	F2	2.45	20.44	56.24
	F3	1.91	15.91	72.16
2017	F1	4.17	34.74	34.74
	F2	3.15	26.21	60.94
	F3	2.06	17.18	78.12

Across these results, the official report is that the three main factors (elements) have an individual weight representing more than 30% for the first, between 20 and 30% for the second, and between 15 and 20% for the third. Their combined weight is more than 70% for every year. What is sufficient to analyze environmental vulnerability across these (Guerrien, 2003).

The details on the composition of the three vulnerability factors, based on climatic (Cl), environmental (En), social (So) and economic (Ec) indicators are given in the Table 5.

Table 5: Summary of the factors explaining vulnerability over the four years

Factors	Year							
	2003		2007		2012		2017	
	Composition	Rate (%)	Composition	Rate (%)	Composition	Rate (%)	Composition	Rate (%)
F1	So-Ec-En	37.57	So-En-Ec	33.22	En-So-Ec	35.81	So-En-Ec	34.74
F2	En-Cl-So	20.46	En-Ec-Cl	23.08	En-Cl-Ec-So	20.44	En-Cl-So	26.21
F3	En-Ec-Cl	15.54	En-Cl-Ec	16.68	En-Cl-Ec	15.91	En-Ec-Cl	17.18
Total	-	73.57	-	75.97	-	72.16	-	78.12

It is visible that the all factors of every year are made up of three indicators, except for the factor F2 of 2012 who in count four. The environmental indicators (En), namely NDVI are present in all factors (100.0%). The other indicators Ec, Cl and So are respectively present in 83.3%, 66.7% and 58.3% of the factors.

Thus, in this study, the different factors So-Ec-En, En-Cl-So and En-Ec-Cl were objectively established on the basis of the PCA, when the variance rate is high. This same principle was used by Mara (2010) in his thesis work on the vulnerability of populations in the Sirba valley in Burkina Faso.

4.3. Spatial-temporal dynamics of environmental vulnerability factors in the study area

In order to understand the spatial-temporal dynamics of the vulnerability factors, maps of the study area composed of sectors were developed for the years of the study on the basis of the factors So-Ec-En, En-Cl- So and En-Ec-Cl (Fig. 2 to 5).

By observing the maps in the Fig. 2, there is an overall increase in environmental vulnerability in the subsidiary from 2003 to 2017, according to the So-En-Ec factor. Indeed, the number of sectors with a low level of vulnerability in 2003 decreased in 2017, unlike the number of sectors with medium and high levels of vulnerability.

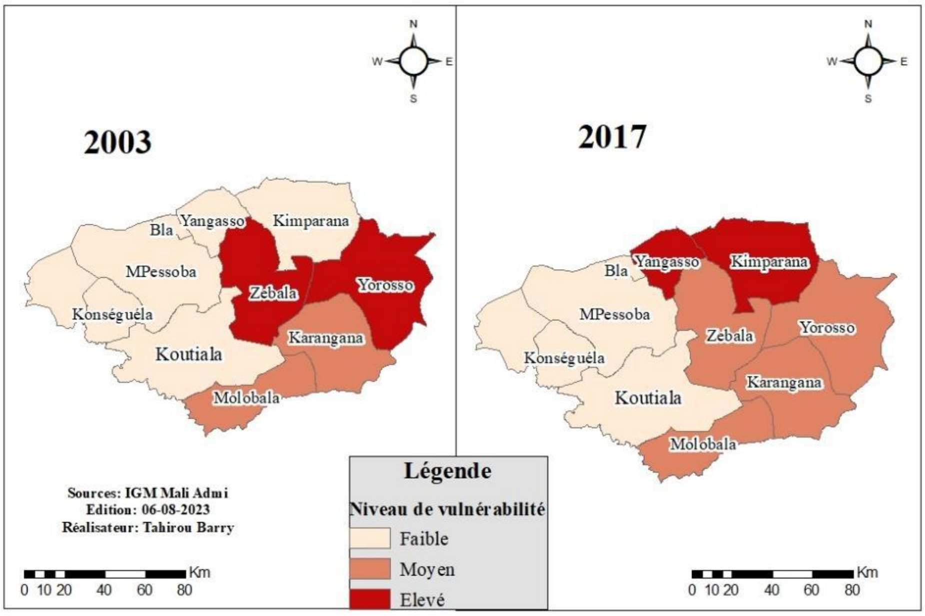

Fig.2: Spatial-temporal distribution of vulnerability according to the So-En-Ec factor.

All sectors with a medium and high level of vulnerability over the entire study period are located in the eastern half of the subsidiary. The Yangasso and Kimparana sectors saw their level of vulnerability go from low to high, while that of the Zébala and Yorosso sectors declined from high to medium.

According to the En-Cl-So factor, the situation has on the contrary improved a lot between 2003 and 2017. In fact, there were four sectors with a high level of vulnerability and as many with an average level, which respectively moved to the numbers of one and three. Thus, the overall level of vulnerability in the subsidiary has fallen significantly (Fig. 3) because, with the exception of the Bla sector, all other sectors with a medium and high level of vulnerability have fallen by a notch.

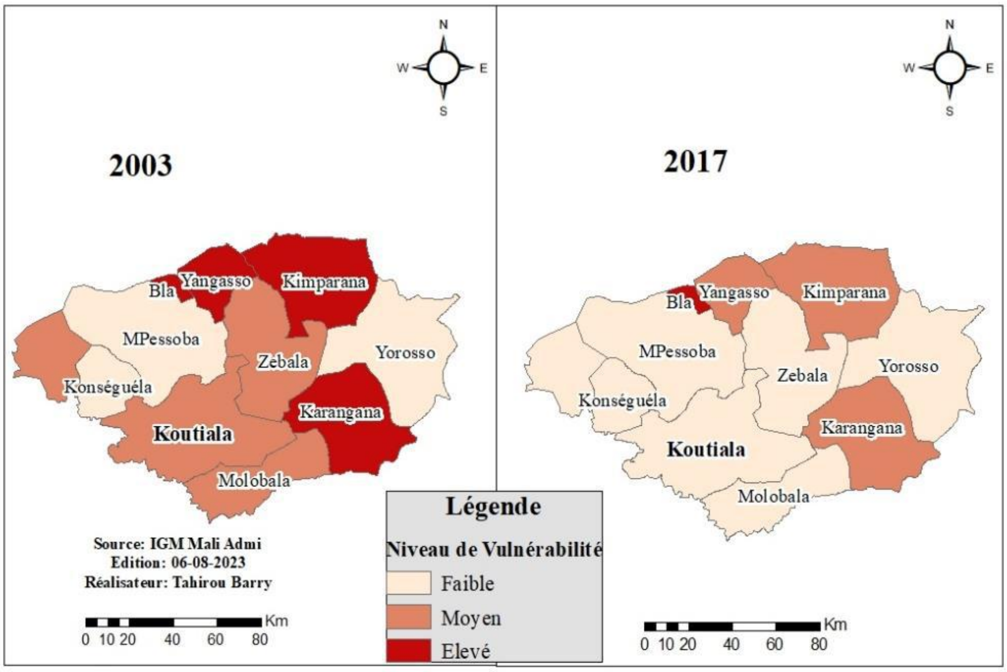

Fig.3: Spatial-temporal distribution of vulnerability according to the En-Cl-So factor.

Finally, the spatial-temporal dynamics of the vulnerability in the subsidiary, according to the En-Ec-Cl factor, shows a trend towards the average level because the numbers of low and high level sectors decreased at the profile of the average level (Fig. 4). In particular, the Zébala sector went from high level in 2003 to low level in 2017. The only sectors of the subsidiary which became more vulnerable in 2017 compared to 2003, are that of M'Péssoba (from medium level to high level) and that of Karangana (from low level to high level).

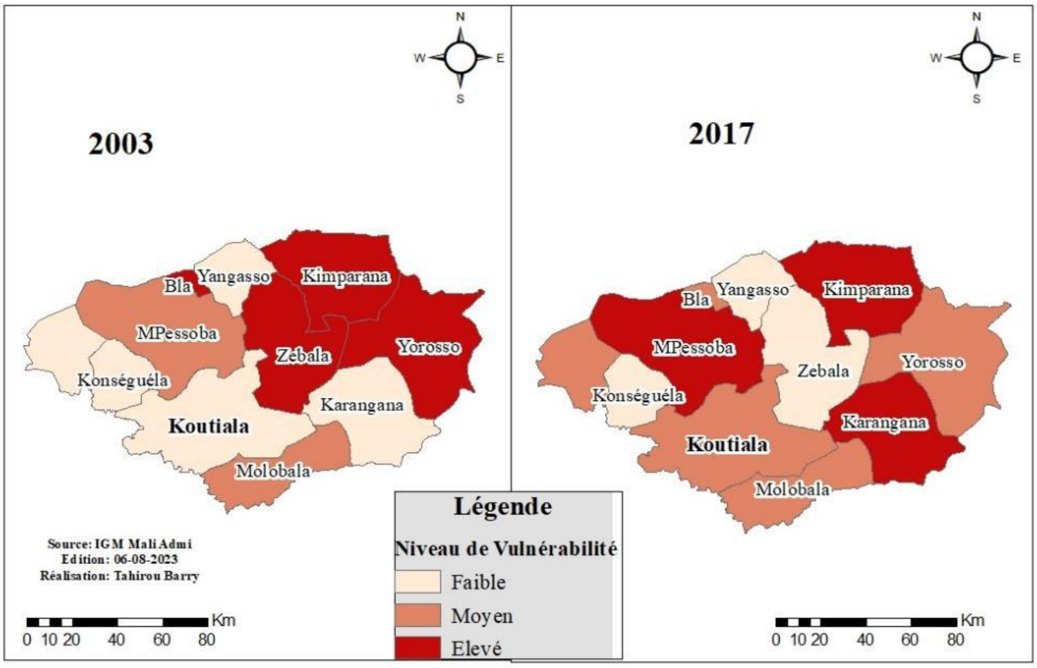

Fig. 4: Spatial-temporal distribution of vulnerability according to the En-Ec-Cl factor.

The crossing of the three vulnerability factors (Fig. 5) shows an increase in the general level of vulnerability in the subsidiary until 2007, with only two low level sectors (in 2017) compared to four (in 2003). In 2012, all sectors except Konséguéla had a medium level of vulnerability. Finally, in 2017, heterogeneity is again observable in the spatial distribution of the level of vulnerability in the subsidiary, but with a downward trend except for the Kimparana sector which increased.

The evolution of the proportions of surface areas according to the level of vulnerability, between 2003 and 2017 is presented in Fig. 6.

It shows that the dominant level of vulnerability in terms of surface area is the average level with almost 50% of the total surface area of the subsidiary in 2003, and up to 94.9% in 2012. The high level of vulnerability is as it is the least representative level with 0 to 9.4% of the surface area of the subsidiary, depending on the year.

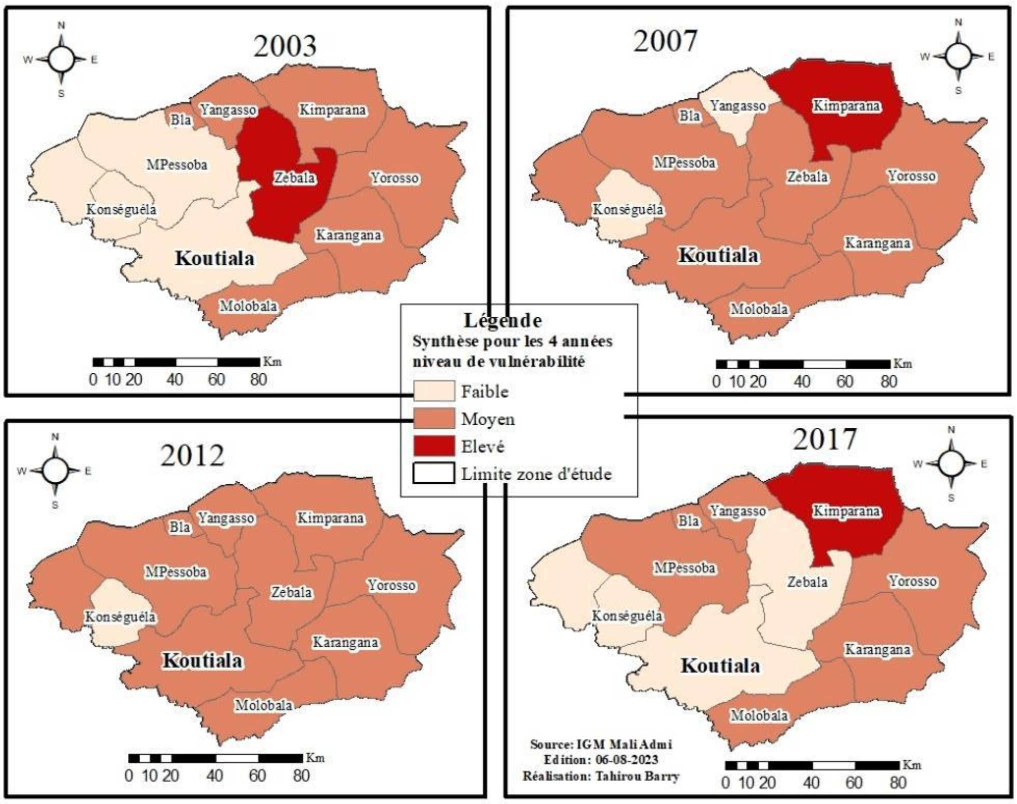

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Fig. 5: Spatial-temporal distribution of the vulnerability according to the intersection of the three factors.

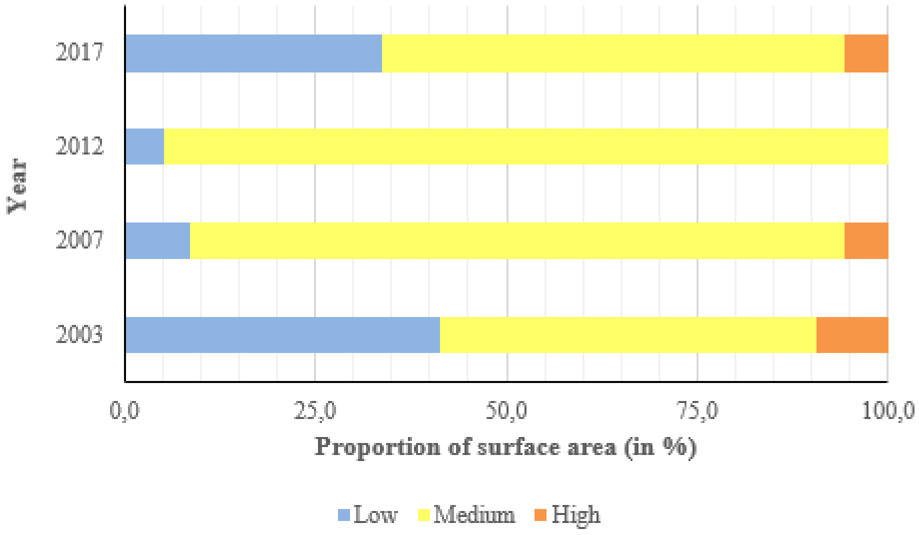

Fig. 6: Evolution of the proportions of surface areas according to the level of vulnerability.

Thus, contrary to what was observed by Mara (2010), it can be assumed that the increase in rain in Sahelian West Africa (Nouaceur, 2020) and in Mali in particular from 2010 (Diawara et *al*., 2021) probably led to a reduction in the environmental vulnerability of the study area. Indeed, on the maps, it is visible that in 2012 all sectors of the subsidiary, except Konséguéla, had an average vulnerability and that the downward trend continued until 2017 except for the Kimparana sector.

V. CONCLUSION

At the end of this work, the application of multicriteria analysis first made it possible to develop indicators representative of the environmental vulnerability of the cotton zone (northeast subsidiary of Koutiala), and to identify the determining factors of this vulnerability. Then, these environmental vulnerability factors were spatialized and analyzed for the years 2003, 2007, 2012 and 2017. As a result, it turns out that it is the Konséguéla (Koutiala) sector which is the least vulnerable while that of Kimparana (San) is the most vulnerable of the subsidiary.

The study also made it possible to classify the factors influencing environmental vulnerability, namely from the most influential to the least influential: the Environment, the Economy, the Climate and finally the Social factors.

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