Short Research Article

Impact of climatic and anthropogenic factors on the spatio-temporal dynamics of mangroves in the Grand-Bassam wetland, Côte d'Ivoire

UNDER PEER REVIEW

ABSTRACT

Background: Mangroves in Côte d'Ivoire, particularly in the Grand-Bassam Ramsar Wetland (ZHGB), are seriously threatened by human activities and climate change. Since 1989, these pressures have considerably reduced their area, increasing the risk of coastal erosion and flooding.
Aim: This thesis examines the spatio-temporal evolution of Ivorian mangroves under the effect of climate change, focusing on the changes that occurred between 1989 and 2024.
Methodology: The study relies on remote sensing techniques, such as Landsat satellite image classification and the Land Cover Modeler (LCM) module to analyze the spatio-temporal dynamics of mangroves. In addition, socio-economic surveys were conducted among local populations, making it possible to identify the causes and consequences of these transformations. Finally, the collection of physicochemical data on mangrove waters to assess their state under the effect of climate change.
Results: The results obtained show a 65.55% decrease in mangrovy cover between 1989 and 2024. Climate factors, such as sea level rise (estimated at +18 cm by 2050), play a major role in this degradation. At the same time, the demand for firewood and urbanization have contributed to unsustainable exploitation of mangrove resources.
Conclusion: Despite conservation efforts, the lack of concrete restoration projects has slowed down attempts at resilience.

Keywords: Grand-Bassam, Ramsar, Spatio-temporal dynamics, Mangroves, Climate change

1. INTRODUCTION

Mangroves are ecosystems that provide many ecosystem and socio-economic services. They contribute to the protection and stabilization of coastlines by controlling erosion in coastal areas and flooding [1], [2]. They help in the filtration and retention of pollutants contributing to water regulation and carbon sequestration [3], [4]. They also provide habitat and food for many of the terrestrial and aquatic species they host [5]. They also provide wood for the smoking of fishery products, the cooking of food, the construction of habitats for the local populations, the design of fishing instruments, medicinal plants and the development of ecotourism activity [6].

According to the 2015 World Forest Resources Assessment [7], the area of mangroves in Côte d'Ivoire was obtained by linear extrapolation from 2000 and 2005 data and was estimated at 10,000 ha compared to 20,000 ha in 1990. Today, the area of mangrove forests in Côte d'Ivoire is estimated at less than 3000 ha, a disappearance of more than 95% in less than 50 years [8].

Despite all these services rendered, mangroves are considered marginal environments in Côte d'Ivoire and are therefore subject to many anthropogenic pressures, including industrial and domestic pollution [9]. Anarchic urbanization, the spread of tourist establishments instead of mangroves and the practice of agriculture are other causes [10]. In addition to these disruptions, Mangroves are also subject to illegal logging.

In addition, the coastline is constantly threatened by the hassles of climate change that affect the dynamics of mangroves through the incessant rise of the sea, the modification of rainfall patterns and the increase in temperatures [11]. Seawater is one of the greatest threats to mangrove ecosystems because of their sensitivity to the increase in salinity that affects species specific to these ecosystems that can lead to their extinction [11]. According to the IPCC (Intergovernmental Panel on Climate Change), West African countries, particularly Côte d'Ivoire, could reach the mark of 100 to 250 lethal heat days/year over the next 40 years, with maximum temperatures observed in coastal areas [12].

In view of all these threats, several organizations invested in the cause of the environment, such as the ACB-CI (Action for the Conservation of Biodiversity) and the NGO SOS-Forêts, are hastening to reverse the trend by organizing awareness-raising and training sessions for coastal populations, mangrove reforestation activities, and the organization of conferences and workshops [6]. UNEP, for its part, has been trying to add its stone to the building through its Coastal Fisheries Initiative program since 2019 in Gbôklé. Since July 26, 2015, it has been delivered by the UNESCO conference, the JICEM (International Day for the Conservation of Mangrove Ecosystems) in order to remind every year the importance of this ecosystem throughout the world.

Since 1971, mangrove management has become a global priority due to their ecological importance. The emergence of remote sensing and spatial mapping of land use has improved strategies for sustainable mangrove management, despite persistent challenges related to their accurate identification. Studies have been carried out to develop specific indices adapted to the complexity of mangrove ecosystems.

To synchronize the efforts already made, it is necessary to understand the spatio-temporal dynamics of Ivorian mangroves, particularly those of Grand-Bassam. The main objective of this research is to contribute to the sustainable management of the mangrove ecosystems of Grand-Bassam by studying the impacts of climate change on their spatio-temporal dynamics. Specifically, this study will consist of assessing the perceptions of local populations on climate change, assessing floristic richness, assessing the physico-chemical quality of the surrounding waters and mapping the dynamics of these mangroves in order to make recommendations for the conservation, rehabilitation and sustainable management of the mangroves of the Grand-Bassam area.

2. MATERIALS AND METHODS

2.1. Presentation of the Grand-Bassam wetland (ZHGB)

The ZHGB, the largest wetland in Côte d'Ivoire with an area of 40,210 ha, is located in the southeast of the country, between 5°21' north latitude and 3°46' west longitude. It has been listed as a Wetland of International Importance on the Ramsar List since 18 October 2005. A national Ramsar committee, created in 1996, brings together experts to assess the country's Ramsar sites. Several towns, such as Bingerville, Grand-Bassam, Bonoua and Oghlwapo, are in or near this area [13].

Ecologically, the flora is dominated by mangrove formations, mainly red (*Rhizophora racemosa*) and white (*Avicennia germinans*) mangroves, as well as tropical forests, swamps and grasslands. The wildlife is home to an exceptional diversity, including 78 species of birds, including several migratory, as well as endangered species such as the green turtle and the forest elephant. The humid tropical climate of the area is characterized by an average annual rainfall of 2,075 mm, temperatures ranging from 23°C to 31°C, and a regime of two rainy seasons and two dry seasons. The relief of the ZHGB is composed of low plains with altitudes ranging from 0 to 279 m, and its hydrography is dominated by lagoons and tributaries of the Comoé River.

On a human level, the ZHGB is densely populated, with a population that has almost tripled between 2014 and 2021. This population, mostly young, carries out various activities such as agriculture, fishing, trade and tourism. Listed as a UNESCO World Heritage Site since 2012, the area is a major tourist hub in Côte d'Ivoire, but is also subject to increasing anthropogenic pressures, including urbanization, the exploitation of natural resources, and the illegal cutting of mangroves. These pressures, combined with the impacts of climate change, make the conservation of the WZHB particularly urgent.

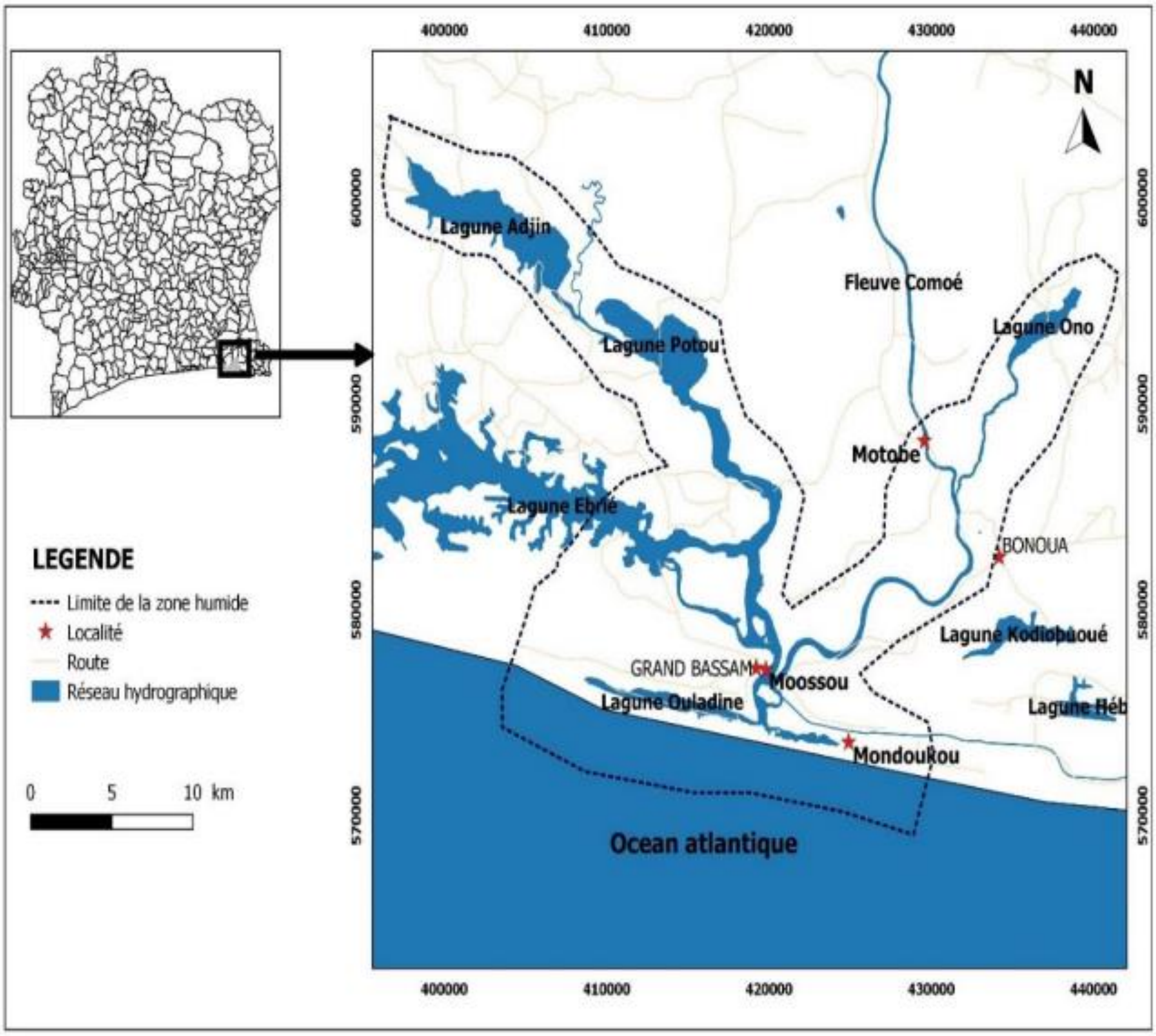

Fig. 1: Grand-Bassam wetland

2.2. Materials

This study on the spatio-temporal dynamics of the mangroves of the Grand-Bassam Wetland (ZHGB) mobilized various tools for field data collection and laboratory analysis. For the precise location of the sampling sites, a GPS was used. In addition, inventory sheets have made it possible to record the characteristics of the woody species identified. Regarding the physico-chemical analyses, a multi-parameter HI9829 was used to measure the pH, temperature, salinity and dissolved oxygen in mangrove water.

Socio-economic data was collected using questionnaires administered through KoboToolbox, facilitating the immediate digitization of the responses. Finally, Landsat satellite images from 1989 and 2024 were downloaded from the EarthExplorer platform to analyze spatio-temporal dynamics. These images were processed using ENVI, ArcGIS and TerrSet software.

2.3. Methods

In this study, the collection of floristic data followed a quadrat-based approach. Areas of 100 m² (10 m x 10 m) have been delineated along transects perpendicular to the coast or channel, as illustrated in Figure 2: Quadrat and transect diagram.

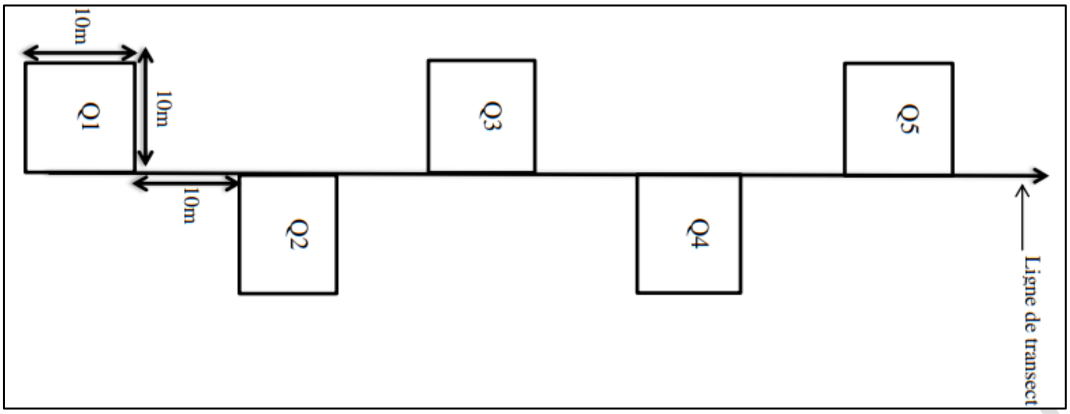

Fig. 2: Diagram of the Transect and quadrats

The woody species present in each quadrat were identified and listed according to standard botanical nomenclatures.

For the socio-economic surveys, a random sample was carried out, following equation 1, to interview 85 people in the localities of Ebrah, Eloka To and Eloka Te.

Equation 1 : Population Sampling Formula

$$n = \frac{t^2 pqN}{[e^2(N\text{-}1) + t^2 pq]}$$

These surveys focused on the perceptions of local populations on the uses of mangroves, the impacts of climate change and management methods.

Regarding the analysis of the satellite images, they were corrected for atmospheric imperfections using the *Dark Substruction* tool of the ENVI software. The study area was extracted by overlaying a vector file of the administrative boundaries using the *Region of Interest (ROI)* option. The supervised classifications were used to distinguish between different types of land use, including mangroves, agricultural land and urban areas. In addition, biophysical indices such as NDVI, BI (Soil Gloss Index) and WI (Surface Moisture Index) were calculated to refine the interpretation of the images, as shown in Equations 2, 3 and 4.

Equation 2 : Vegetation indices by normalized difference

$$NDVI \equiv \frac{PIR - R}{PIR + R}$$

Equation 3 : Soil gloss index

$$BI = (R^2 + PIR^2)^{\frac{1}{2}}$$

Equation 4 : Surface Moisture Index

$$WI \equiv \frac{PIR - MIR}{PIR + MIR}$$

These images thus obtained made it possible to evaluate the dynamics of the land cover classes of the ZZHGB by calculating the global rate of change (Tg) equation 5. This index is used to calculate the rate of increase or decrease in the surface area of a land cover class between two dates (t1 and t2) using the following formula:

Equation 5 : Rate of change

$$Tg = \frac{S_2 - S_1}{S_1} \times 100$$

Finally, the physico-chemical parameters were measured in the quadrats as well as at specific points, located at the intersection of the mangroves with the swamps and lagoons. These measurements made it possible to assess the conservation status of mangrove waters and the associated ecological risks. This integrated methodology, combining flora, physico-chemical and geospatial data, provided a comprehensive and detailed view of mangrove dynamics, paving the way for recommendations for sustainable management.

3. RESULTS AND DISCUSSION

3.1. Analysis of socio-economic data

3.1.1. Profile of the respondents

Table 1 shows the profile of the people surveyed. They are mostly adults ranging in age from 36 to 80. More than half of the respondents are men. They are mostly full-time fishermen (38.8%), followed by farmers (32.9%) and students (10.6%). Teachers are the least represented (2.4%).

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Table 1 : Profile of the respondents

Locality	Age range	Respondents			Proportion (%)	
		Woman	Man	Actual	Woman	Man
Ebrah	19 to 35	4	6	10	40	60
	36 to 80	1	7	8	13	87
Eloka Te	19 to 35	8	4	12	67	33
	36 to 80	7	18	25	28	72
Eloka To	19 to 35	3	4	7	43	57
	36 to 80	5	18	23	22	78
Total				**85**		

3.1.2. <u>Perception of local populations</u>

For more than 80% of those surveyed, climate change is a reality whose effects are perceptible in their localities.

More than half of the respondents, i.e. 60%, say that climate change is perceptible by the different trends in precipitation; sometimes irregular rainfall, sometimes heavy rains that cause crop losses or a drop in agricultural or fishing yields. Then we have the change in the growing seasons (11.8%) and the extremes observed throughout the year with a strong wave of coolness (11.8%) or heat (7.1%) and a long dry period (9.4%).

Nearly half of the respondents (49.5%) believe that these observed changes are attributable to the deforestation that the wetland localities have been suffering for several decades. Then we have 25.9% who think that the emission of greenhouse gases into the atmosphere is the major cause of these climatic disorders and 11.8% who believe that they should be attributed to bush fires. As for the rest, they attribute them to poaching and pollution.

When it comes to climate change impacts, we have categorized them into two types, namely direct impacts and indirect impacts.

Direct impacts, coastal erosion and flooding, cited by 41.2% and 25.9% of respondents respectively, are the most frequent direct consequences in the ZHB. They are followed by drought, which was mentioned by 23.5% of people, and finally the continuous rise of the sea, by 9.4% of respondents.

As for the indirect impacts, the majority (27.1%) are the reduction of arable land, the loss or disappearance of crops, animals or animal or plant species (18.8%) or the disappearance of mangroves (15.3%) and the appearance of insect pests (14.1%). For some, climate change is a vector for the emergence of new diseases and also for poverty.

The following Fig.3 presents the perceptions of local populations regarding climate change and its impacts on their daily activities.

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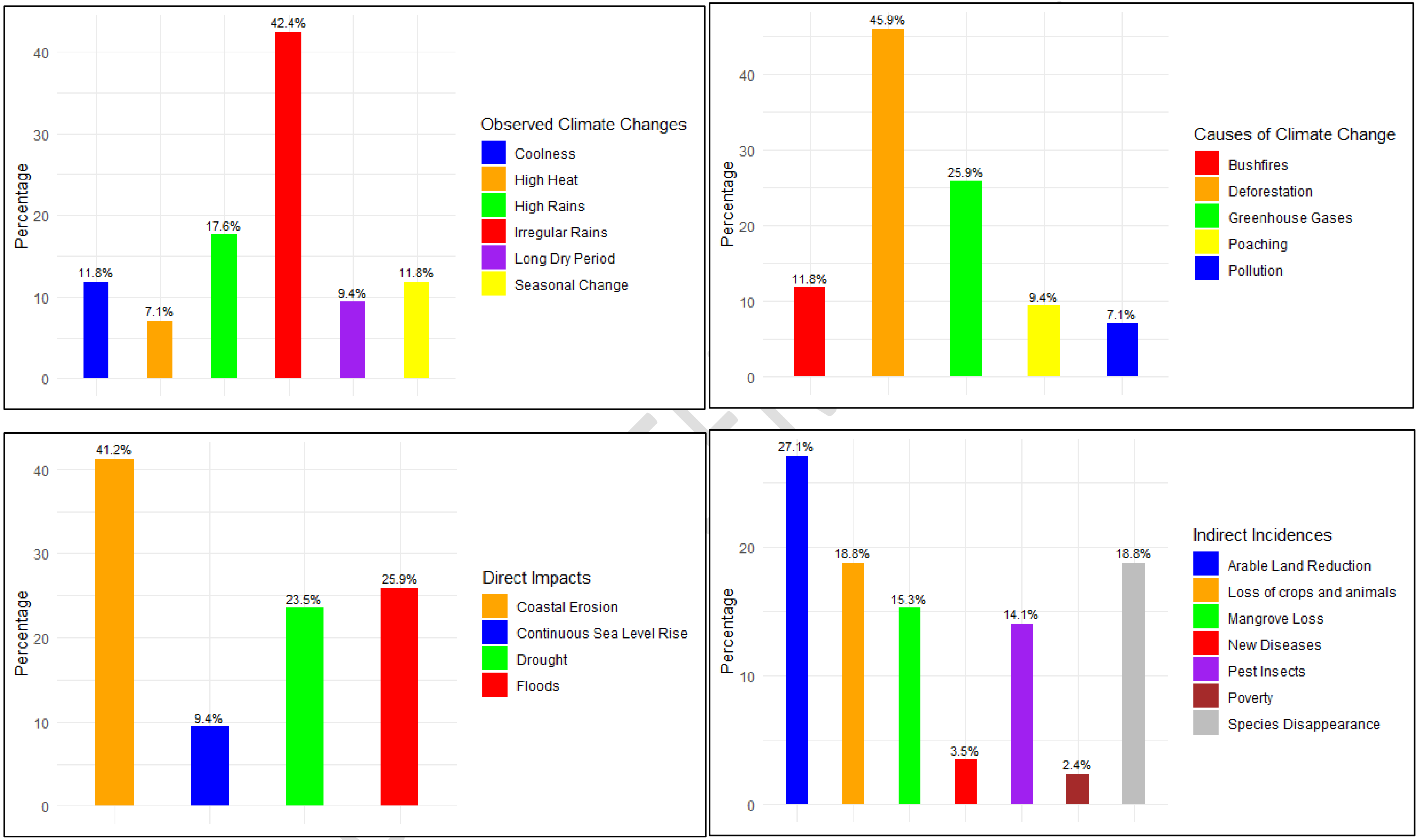

Fig 3: Perception of local populations

3.2. Analysis of floristic data

We were able to identify 18 species in 16 genera shared by 12 botanical families. The richest family is that of the Moraceae with 3 species including *Ficus congensis*, *Ficus ovata* and *Milicia excelsa* followed by the family of Rhizophoraceae, Moraceae and Fabaceae with 2 species each. The genus ficus is the most represented with 2 species *Ficus congensis* and *Ficus ovata;* however, *the Mitragyna ciliata* species is the most abundant, appearing 19 times in both the rainforest and the swamp forest. In the swamp forest, we have an abundance of *Raphia palm* (formerly *Raphia houkei*) which is the representative species of this biotope, while the mangrove forest is completely covered with red mangrove (*Rhizophora racemosa*) as well as other species that are poorly represented.

The results indicate that 17 of these species (94.44%) have a special conservation status, 15 of which are on the IUCN Red List (2024). These belong to 3 categories (10 species have the status of Least Concern (LC), 3 Vulnerable (VU) and 2 Near Threatened (NT)). According to the list of [14], the study identified 2 rare and endangered species. According to the list of [15], there is 1 species endemic to the West African Forest Block (WGC) (Table 2).

Table 2 : Plant species with special status inventoried

Scientific name	Family	IUCN (2024)	Ake Assi (1998)	Endemism
Anopyxis klaineana	Rhizophoraceae	VU		
Ceiba pentandra	Bombacaceae	LC		
This is the first time a man has been in the using the	Fabaceae	LC		
Dichapetalum filicaule Breteler	Dichapetalaceae			GCW
Diospyros tricolor	Ebenaceae	LC		
Entandrophragma candolle Harms	Meliaceae	VU		
Ficus congensis	Moraceae	LC		
Ficus ovata	Moraceae	LC		
Lepleae citron (Guarea cedrata (A.Chev.)Pellegrin)	Meliaceae	NT		
Sublime Militia	Moraceae	NT	R	
Mitragyna ciliata	Rubiaceae	VU		
Nauclea xanthoxylon	Rubiaceae		R	
Raphia palm	Arecaceae	LC		
Rhizophora racemosa	Rhizophoraceae	LC		
Symphonia globulifera	Clusiaceae	LC		
Monodora myristica	Annonaceae	LC		
Blighia Sapida	Sapindaceae	LC		

Seen: Vulnerable**; LC:** Least Concern**; NT:** Near threatened**; A**: Rare and Threatened**; GWC:** Endemic to the West African Forest Block

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3.3. Analysis of physicochemical data

Table 3 shows the results of analyses of the physicochemical parameters.

There is little variation in pH and temperature. Indeed, the average pH is 5.3 indicating an acidic environment, typical of wetlands such as mangroves. However, the standard deviation is 0.4, a variation of less than 10% from the mean. The same is true for the temperature, which averages 26°C, with a standard deviation of 1.1°C, which is very low compared to the average. While salinity and dissolved oxygen levels show the greatest variations. The average salinity is 0.5g/l. However, it has a standard deviation of 0.3 g/l, a variation of more than 50% compared to the average, revealing a high salinity at certain points in the collection. As far as the dissolved oxygen level is concerned, the average is low, 2.2mg/l. This observation is reflected in the standard deviation, which shows a value of 1.4 mg/l, a variation of nearly 70%.

Table 3 : Descriptive analysis of physico-chemical data

Parameters	*Ph*	*Temperature*	*Salinity*	*Dissolved oxygen*
Average	5,32133333	25,702	0,48066667	2,196666667
Standard deviation	0,42881676	1,14319852	0,26759422	1,427768822

3.4. Land cover dynamics from 1989 to 2024

3.4.1. Land use status of the Grand-Bassam area

In 1989, the wetland of the WZH was dominated by coastal forest, covering 13,882 ha (34% of the total area). Land clearing or fallow land occupied 8,020 ha (20%), while mangroves, limited to 987 ha (2%), were not very present. The watercourse represented 9,319 ha (23%), and bare soils or habitats extended over 5,474 ha (14%) (Fig. 4).

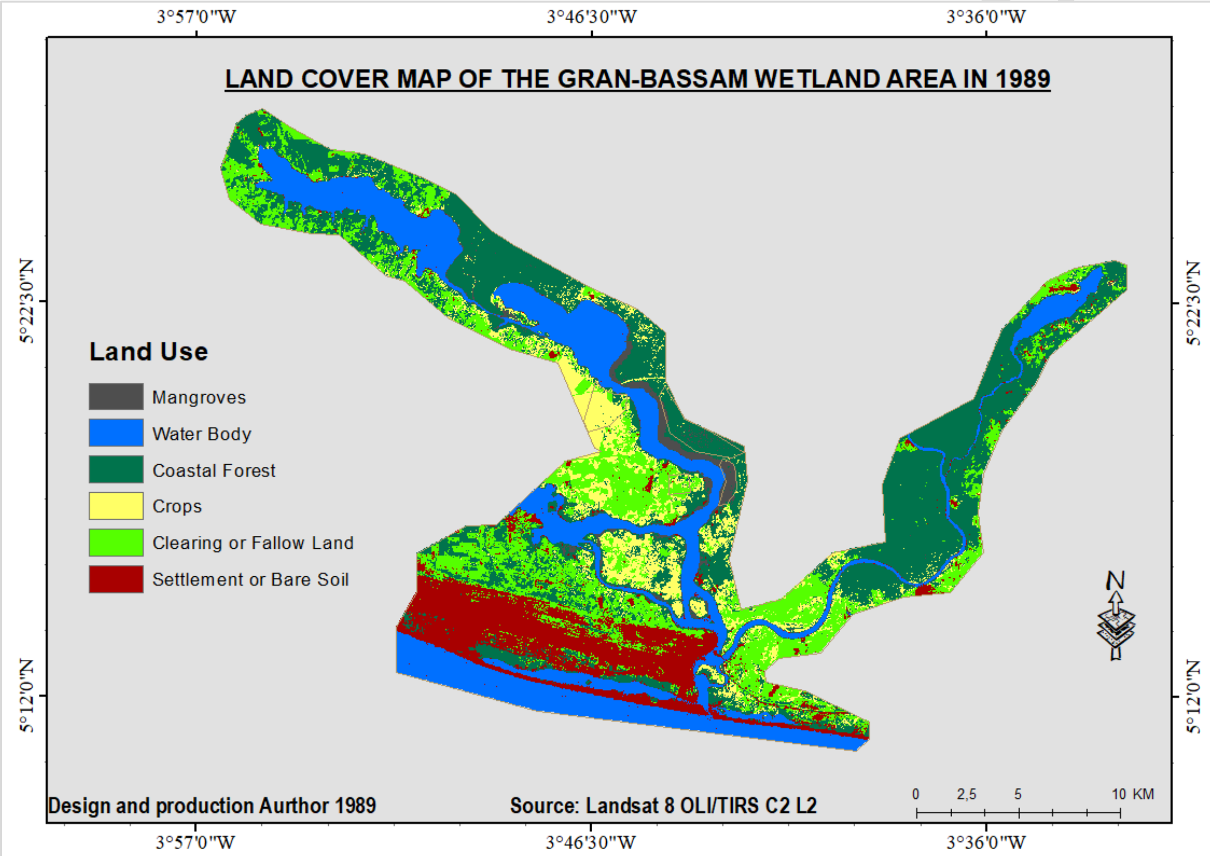

Fig. 4 : Land cover map in 1989

In 2024, the wetland shows a different spatial distribution, with a reduction to 11,367 ha (28% of the total area). The mangrove has declined sharply, covering only 340 ha (1%), located mainly along the banks of the river. Land clearing and fallow land remain predominant with 8,996 ha (22%), while oil palm and rubber plantations reach 6,141 ha (15%). The coastal forest covers 6,690 ha (17%), and the permanent and stable watercourse covers 7,741 ha (19%) (Fig. 5).

These developments illustrate a significant transformation of land use in the ZZHGB between 1989 and 2024, as presented in the associated figures (Fig.4 & 5).

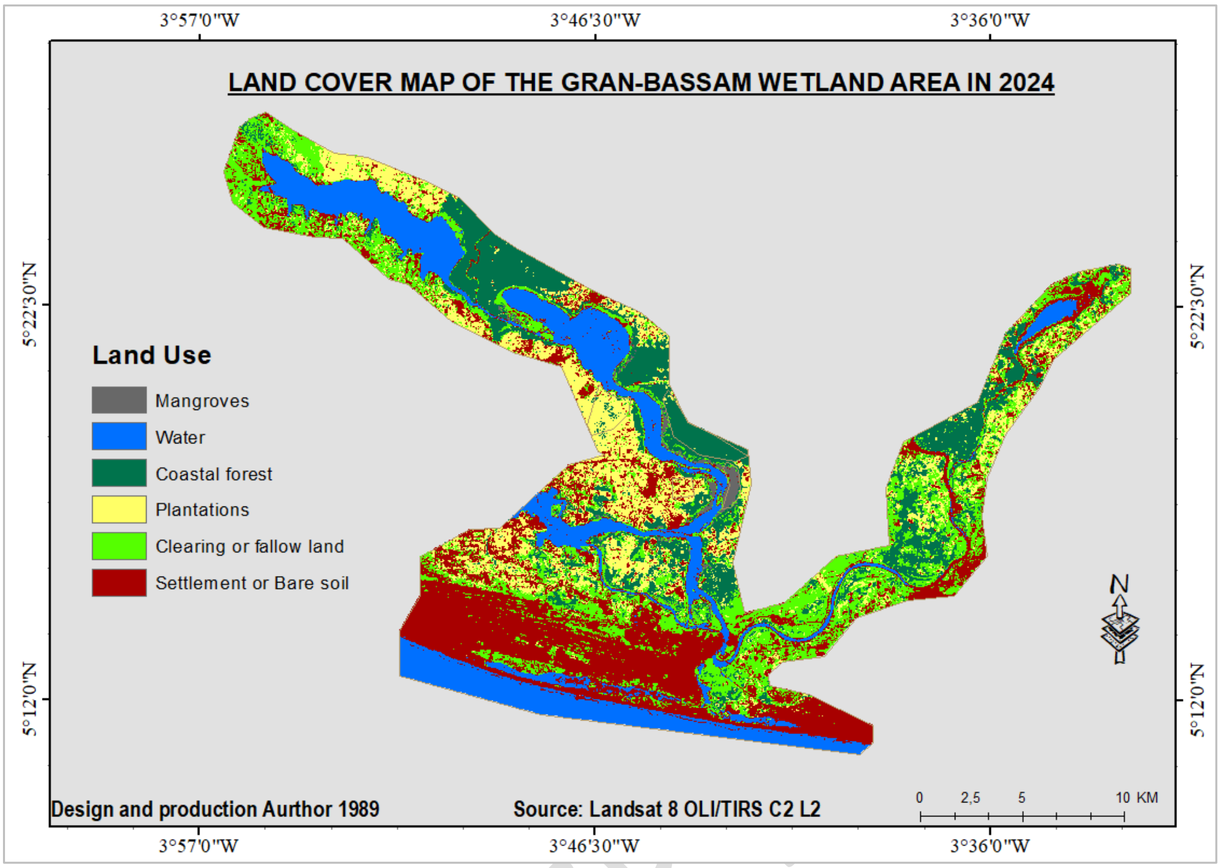

Fig. 5 : Land use map in 2024

3.4.2. Evolution of the mangrove over the period from 1989 to 2024

Table 4 illustrates the change in land cover between 1989 and 2024. The areas and percentages of the mangrove category reveal that over the past 35 years, the mangrove of the ZHGB has experienced a decrease in area. As shown in Table 4, the mangrove has lost 647 hectares of its area, i.e. 34% of its initial area in 1989. The reduction in its surface area has been in favour of housing and land clearing. Mangroves show a high percentage of net change (-65%) compared to the other categories. It is followed by the coastal forest, which shows a net change of (-51%) and water (-16%).

Table 4 : Land cover change between 1989 and 2024

Category	Land use in 1989	Land use in 2024	1989-2024	
			Surface	%
Mangroves	987	340	-647	-65,55
Water	9319	7741	-1578	-16,93
Coastal Forest	13882	6690	-7192	-51,81
Plantations	3593	6141	2548	70,92
Land clearing or fallow land	8020	8996	976	12,17
Dwelling or bare ground	5474	11367	5893	107,65

4. DISCUSSION

4.1. Socio-economic data

The results of the socio-economic survey reveal that the population of the Grand-Bassam area is mainly composed of fishermen and farmers, two sectors directly dependent on natural resources and vulnerable to the effects of climate change. The perception of climate change by the inhabitants, especially fishermen, is strongly influenced by erratic rainfall and seasonal variations. These observations are consistent with the studies of [16], which show that rural populations in sub-Saharan Africa, whose livelihoods depend on natural resources, are more sensitive to climate-related environmental disturbances.

The ageing of the labour force, as shown by the significant proportion of respondents aged 36 to 80, could be an obstacle to the adoption of modern adaptive practices. Indeed, this age group may be less receptive to innovation, as highlighted by studies conducted by De Janvry et al. (2015) on the adoption of green technologies in rural Africa. In addition, the lack of a strong female representation in certain sectors, such as fisheries, can also limit the inclusion and participation of women in conservation and adaptation initiatives, a finding confirmed by work on the gender dimension in climate policies in West Africa [18]. This low representation of women can also be attributed to their level of literacy. Indeed, in rural areas, women's education remains a relevant issue to explore because it is not a priority for their parents, who would prefer to see them take an interest in household management issues [19].

4.2. Floristic and physicochemical data

Floristic analysis shows a reduced diversity of species in the mangroves of the Grand-Bassam area, with a majority of species listed on the IUCN Red List. This situation reflects an advanced degradation of mangrove ecosystems, probably due to urbanization, the conversion of land for agriculture, as well as the overexploitation of natural resources [20]. The predominant presence of species such as *Rhizophora racemosa* and *Avicennia germinans* is typical of the mangroves of West Africa, but their low density and heterogeneous distribution indicate increasing habitat fragmentation [21].

Physicochemical data reveal significant anomalies in the parameters of salinity and dissolved oxygen in mangrove waters. These suboptimal conditions may be the result of saltwater intrusion due to sea level rise, a well-documented phenomenon in coastal regions facing rising global temperatures and melting polar ice [22]. The low concentration of dissolved oxygen could also result from organic pollution, caused by untreated sewage discharges, a recurring problem in many coastal urban areas of Africa [23].

This analysis shows notable variability in essential parameters such as temperature, pH, salinity and dissolved oxygen. These elements strongly influence the growth and health of the mangrove ecosystems studied. The water temperature, which is relatively stable, remains within a range compatible with the survival of the species, while the salinity regularly exceeds the maximum expected values, particularly in samples 2 to 4 and 12 to 15. This over-salinity can potentially negatively affect young plants, which would explain the virtual absence of mangrove saplings during the inventories carried out [24]. Therefore, it is necessary to employ measures to monitor and reduce this concentration.

The pH, on the other hand, shows a marked acidity in sample 13 with a pH of 4, which can create a hostile environment for some mangrove species sensitive to changes in acidity. Dissolved oxygen is below the minimum required at all sites, signaling a possible aeration problem due to pollution from human activities, including wastewater from factories discharged into the lagoon from factories along it[24]. This can lead to a decrease in aquatic and terrestrial biodiversity, which is essential for the natural regeneration of mangroves.

However, it is important to note that dissolved oxygen remains the parameter that has the greatest impact on mangrove dynamics. The management of these physicochemical parameters is crucial to maintain an environment conducive to the sustainability of mangroves.

4.3 1989 and 2024 land cover maps

The comparative analysis of land use maps between 1989 and 2024 reveals an alarming reduction in mangrove areas, from 987 ha in 1989 to 340 ha in 2024. This loss is mainly due to rapid urbanization, the expansion of palm oil and rubber plantations, and deforestation [25].

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The growth of infrastructure and housing in the Grand-Bassam region has strongly contributed to the fragmentation of mangrove ecosystems, reducing their ability to act as a barrier against coastal erosion and provide essential ecosystem services, such as flood regulation and carbon sequestration.

The decline in vegetation cover is a concern, as it compromises the region's resilience to the effects of climate change. The work of [26] on mangroves underline the importance of these ecosystems in mitigating the impacts of storms and in protecting coasts from rising sea levels. Without restoration measures, a continuation of this trend could lead to irreversible ecological damage.

5. CONCLUSION

The present study has highlighted the impact of climate change and anthropogenic activities on the spatio-temporal dynamics of mangroves in Côte d'Ivoire, particularly in the ZHB. The results show that the area of mangroves has decreased significantly in recent decades, due to climatic factors such as sea level rise and long dry periods, combined with anthropogenic pressures such as deforestation and urbanization. These changes pose serious threats to the ecological balance and resilience of coastal communities.

The spatio-temporal analysis confirmed the first hypothesis that mangroves are undergoing significant surface regression due to climate change and unsustainable human activities. In addition, the study also showed that the lack of concrete and sustainable restoration projects aggravates this degradation, thus validating the second hypothesis. To date, conservation and resilience efforts remain insufficient and unevenly distributed, leaving some areas without protection or management plans.

To meet these challenges, it is imperative to put in place ambitious conservation and restoration programmes, aligned with international targets, such as those set by the Aichi Targets and the Paris Agreement. Urgent action must be taken to protect these vital ecosystems and enable their resilience to the impacts of climate change, including through the reforestation of mangroves and the creation of buffer zones to reduce anthropogenic pressures.

However, it would be very nice to intensify studies at this level by encouraging research on the ZZHGB and Côte d'Ivoire in general.

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