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Estimation of Aboveground Carbon Stock and Sequestration using Spatial Analysis and InVEST model: application to Benin's Ouémé-Supérieur Forest reserve

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Abstract: Deforestation and forest degradation compromise the capacity of ecosystems to store carbon, exacerbating climate change. This study analyses the dynamics of LULC change in the Ouémé-Supérieur Forest reserve (2003–2023) and assesses carbon sequestration relative to these dynamics using the InVEST model. Satellite image analysis was employed to map LULC changes, with a transition matrix quantifying conversions between LULC types. The InVEST model estimated variations in aboveground carbon stock. Results reveal a loss of 10,964.16 hectares of Dense Forest and the degradation of 17,947.47 hectares of Woodlands (WL). Gross deforestation amounted to 10,964.16 hectares, with an annual rate of 548.21 hectares (5.83%). Carbon stock decreased significantly by 13.7% (1,617,440.35 Mg) over two decades. Dense Forests' carbon stock dropped from 622,043.70 Mg to 407,227.51 Mg, while Dry Forests saw a slight increase, reaching 1,497,499.17 Mg in 2023. Trees and Shrubs Savannahs (TSS) experienced an increase in carbon stock, highlighting the need for a balance between conservation and development. ANOVA showed significant differences in carbon stock with LULC types (p-value < 0.001), with a high F-value (23.76). To reverse these trends, strengthened conservation policies, ecological restoration, remote sensing-based monitoring, and community participation are essential.

Keywords: forest degradation; remote sensing; ecological restoration

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1. Introduction

In a context of continuous environmental degradation and increasing greenhouse gas emissions, forest ecosystems serve as both a source and a sink of carbon dioxide (CO_2), thereby constituting one

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of the most reliable solutions for carbon sequestration (Meragiaw et al., 2021). They play an essential role in regulating the global carbon cycle (Salunkhe et al., 2018). However, global changes and particularly land cover changes are negatively affecting the capacity of these forest ecosystems to sequester carbon (Martin-Guay et al., 2020). In tropical regions, forest ecosystems are subject to constant pressures, including the harmful effects of agricultural practices, transhumance and unsustainable logging, all of which have a negative impact on biodiversity (Kadıoğulları, 2013; Hayes et al, 2023; Wong et al., 2024) but, above all, their carbon sequestration capacities, amounting to a loss of around 1 to 2 billion Mg each year (Brown et al., 1989; Albrecht and Kandji, 2003; Reynolds, 2012; Srinivas and Sundarapandian, 2019). Deforestation and forest degradation account for 17-20% of global greenhouse gas (GHG) emissions in developed countries (Albrechta and Kandji, 2003; Bhishma et al., 2010; Ngo et al., 2013), compared with a much higher proportion in developing countries, up to 70% in Africa (Gibbs et al., 2007; Nyawira et al., 2024). According to studies by Gibbs et al (2007), if deforestation continues at the current srate of 2%, around several billion Mg of stored carbon (C) will be released into the atmosphere in the next 50 years.

Indeed, the United Nations Convention on Biological Diversity, which aims to halt the loss of biodiversity and encourages the scientific community to focus on the conservation of forest ecosystems (Imorou et al., 2017), does not really seem to be bearing fruit. The IPBES report (2019) points out that biodiversity continues to decline rapidly, jeopardising the objectives of various international conventions (Bongaarts, 2019). This decline, amplified by changes in land cover, raises concerns about the capacity of these ecosystems to maintain their essential ecological functions. Land use and land cover have a direct influence on the capacity of forest ecosystems to store carbon dioxide (CO2) (Nyawira et al., 2024) and on soil erosion (Ahamefule et al., 2021). A study conducted in Ghana estimated that converting one hectare of tropical forest into farmland emits an average of 150 tonnes of CO2 (Asare et al., 2020). Similarly, in the Democratic Republic of Congo, commercial logging contributes to annual emissions of 40 million tonnes of CO2 (FAO, 2016). These figures clearly show the significant impact of land use on carbon emissions. The conservation and sustainable management of forest ecosystems, therefore, remain crucial to reducing greenhouse gas emissions in Africa and mitigating the effects of climate change.

In this context, local, national, and regional inventories of carbon sources and sinks are becoming essential for monitoring forest ecosystem health and its effectiveness in sequestering carbon and reducing the accumulation of atmospheric CO2 (Salunkhe et al., 2018) . These inventories are not only crucial for mitigating global warming, but they are also essential for the development of carbon markets and for the implementation of programmes such as REDD+, which aim to reduce emissions from deforestation and forest degradation in developing countries (Salunkhe et al., 2018). To this end, numerous studies have been carried out to estimate the rate of carbon sequestration of forest ecosystems. These rates have been determined using various methods and techniques, including detailed forest inventories and biomass stock tables, which allow carbon variations to be estimated with varying levels of accuracy (Salunkhe et al., 2018). Various methods are used to measure carbon biomass, including destructive (total sample harvesting), non-destructive (measurable parameters such as basal area, height, tree density and remote sensing methods) (Brown et al., 1989; Lu, 2006; Salunkhe et al., 2018). But these are controversial (Salunkhe et al., 2018), so choosing an appropriate method is an important issue (Sanquetta et al., 2015). Due to the costs associated with collecting field data and the adverse effects of studies requiring tree felling, many researchers have turned to the use of remote sensing to quantify the carbon sequestration capacity of forest ecosystems (Drake et al., 2003; Baccini et al., 2004; Anaya et al., 2009). In many cases, the Ordinary Least Squares (OLS) technique has been used to independently adjust biomass components and Total Aboveground Tree Biomass (TAGB) (Ganamé et al., 2021). Similarly, several scientific groups recommend the use of the InVEST model to assess the effectiveness of ecosystem services, particularly with regard to carbon sequestration capacity, taking into account disturbance factors such as land use dynamics (Pechanec et al., 2018). Although previous studies have established links between land use patterns and carbon storage, they have focused on cities, forested ecoregions, and floodplains (Gaglio et al., 2019). InVEST is rarely used to assess carbon sequestration in dry agro-urban environments and in sub-Saharan Africa (Zhou et al., 2020).

The aim of this study is to analyse the dynamics of land-use change in the Ouémé Supérieur Forest reserve between 2003 and 2023 on the one hand, and using the InVEST model to assess carbon sequestration in the same forest in relation to the dynamics of land-use change, on the other hand. A regression of forest area is expected due to the expansion of agricultural land and a significant difference between carbon storage within different land-use classes

2. Materials and Methods

2.1. Study area

The study was carried out in the Ouémé Supérieur Forest reserve, located in northern Benin between latitudes 9°11' and 9°47' north and longitudes 1°58' and 2°28' east (Figure 1). This forest lies in the Sudano-Guinean transition zone, in the South Borgou phytogeographical zone. The climate in this region is dry tropical, characterised by a near-melting of the two rainfall peaks of southern Benin and an annual rainfall of around 1,200 mm (Adomou, 2011). The zone is characterised by the absence of dense semi-deciduous rainforests and the enrichment of open forests and savannahs with Sudanian elements. The fauna of this zone is varied and diverse, but suffers from excessive poaching.

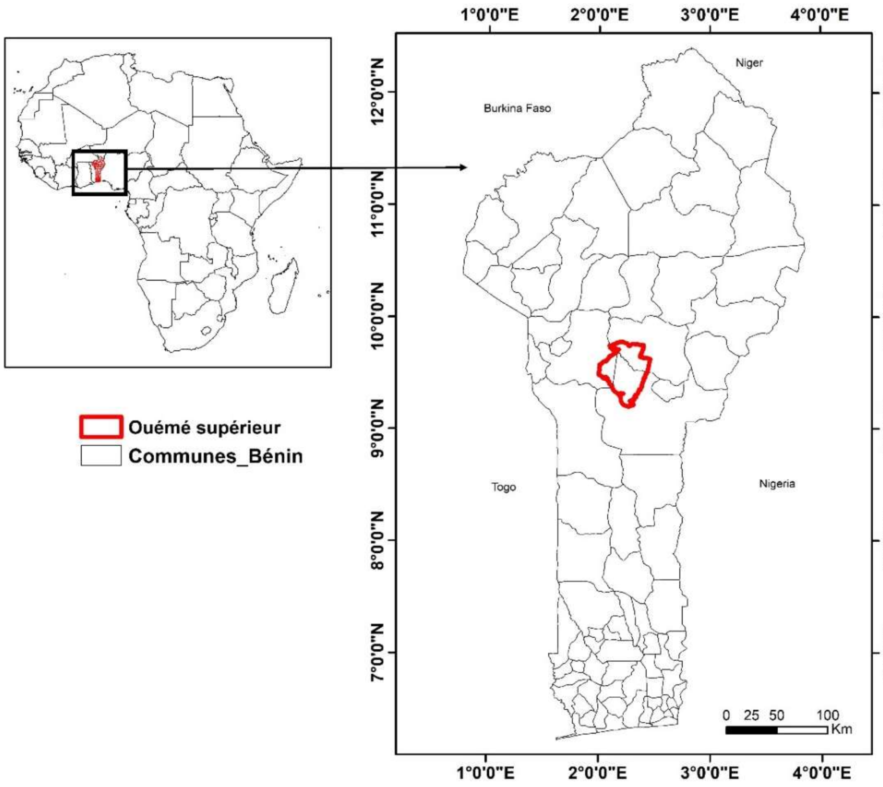

Figure 1: Geographical location of the Ouémé-Supérieur Forest reserve in Benin.

2.2. Data

In this study, only images from Landsat satellites were used to analyse the dynamics of land use and land cover (LULC). To meet the objectives of classification and dynamics analysis, Landsat 7 ETM+ (Enhanced Thematic Mapper Plus) images from 2003 and Landsat 8 OLI (Operational Land Imager) images from 2023 were used. These multispectral images offer a spatial resolution of 30m, which is suitable for mapping changes in land cover over a 20-year period. These data were chosen for their free availability and temporal consistency.

2.3. Modelling and validation of LULC maps

For image processing, a near-infrared false colour composite was performed with the three visible and infrared bands in order to highlight vegetated areas. These bands are the most commonly used to discriminate between different vegetation classes (Diouf et al., 2012; Rifai et al., 2018). After a supervised classification using the maximum likelihood ((ML) algorithm, the satellite images were visually interpreted to correct spectral confusions (Biaou et al., 2019; Kinnoumè et al., 2023).

2.4. Application of post-treatments

After classifying and correcting the images, the land cover (vector layers) for 2003 and 2023 were obtained separately. The features were then grouped together. The final step is to combine the occupations from different dates to obtain a vector layer containing information on the dynamics of the forest (Kinnoumè et al., 2023). Finally, the succession of land-use types was checked using the attribute table in order to correct any final errors.

2.5. Validation of classification result

Validation of the classification result is necessary to ensure the quality of the results obtained (Kinnoumè et al., 2023). Accuracy is assessed using the accuracies (global, producer, user) and the Kappa index (Short, 1982). Precision and the Kappa index were calculated using a confusion matrix. The classification results were then subjected to a field validation process. The field verification phase was carried out on the basis of 300 sample points distributed throughout the forest. These sample points were implemented in the Qfield programme under QGIS (Montagnetti, Guarino, 2021; Ostadabbas et al., 2020; Kinnoumè et al., 2023).

2.6. Analysis of land Use Land Cover dynamics

The spatial dynamics of the land-use units were evaluated by assessing changes in the various land-use units and comparing their surface areas. The rate of stability, regression or progression of land-use units was calculated from 2003 to 2023 using the formula (Bouko et al., 2016; Kinnoumè et al., 2023) :

$Tv = [\frac{S2}{S1} - 1] * 100$; With Tv the rate of change of the type; S1 the area of the land-use unit in year 1 and S2 the area of the land-use unit in year 2. Thus, if the difference (S2-S1) is negative, we conclude that there has been a regression in plant cover from year 1 to year 2. If the difference is positive, we speak of an increase in plant cover from year 1 to year 2, and if (S2-S1) is zero, we speak of stability in plant cover from year 1 to year 2.

2.7. Assessment of the quantity of carbon stock using the InVEST model

The InVEST model is a set of geographical information system models that predicts the provision and value of ecosystem services based on the land use/land cover map and biophysical data related to the amount of carbon stock in four carbon pools (aboveground biomass, belowground biomass, soil, dead organic matter) (Guo and Hettiarachchi, 2023; Li et al., 2023). It estimates the amount of carbon currently stored in a landscape or the amount of carbon sequestered over time. We used the InVEST model for this study. To cover the study area, land use rasters from 2003 and 2023 were considered. The amount of carbon stored in 2003 and 2023 was estimated. Next, we evaluated the carbon flux between the period 2003-2023. The default biomass data (Table 1) were obtained from the literature, based on the Intergovernmental Panel on Climate Change's (IPCC) carbon estimation document http://www.ipccnggip.iges.or.jp/public/2006gl/pdf/4_Volume4/V4_02_Ch2_Generic.pdf and the article by Grace et al, (2006, p. 389 and 394). The amount of biomass in each carbon sink was converted to carbon metric using conversion factors for climate zone and land use type (i.e. 0.49 for forests and 0.47 for other land uses) (IPCC, 2006). The value for belowground carbon was obtained by considering the value of the ratio of aboveground biomass to belowground biomass, which is 0.56 for tropical Africa (IPCC, 2006). The values used in this study for the tree and shrub savannah type are an average of the values for the two types taken separately. The carbon stock maps obtained after running the model were reclassified using QGIS version 3.22.

Table 1: Default biomass converted to metric carbon.

LULC	Metric tonnes of carbon per ha				Source
	AB	BB	Soil	DOM	
CFL	4.23	2.38	15.62	0.00	(Ipcc 2006 p.4.53)
WL	58.80	32.92	17.15	12.50	(IPCC 2006; Grace et al., 2006)
DF	58.80	32.92	17.15	12,50	Ipcc 2006)
GF	151.90	85.06	17.15	12.50	(Ipcc 2006)
PT	9.40	5.26	2.54	12.50	(Ipcc 2006)
TSS	3.00	24.44	2.54	0.98	(Grace et al., 2006; Gouwakinnou et al., 2018)
TSS	9.58	24.44	8.82	0.98	(Grace et al., 2006; Gouwakinnou et al., 2018)
ST	0.00	0.00	0.00	0.00	(Grace et al., 2006; Gouwakinnou et al., 2018)
WB	0.00	0.00	0.00	0.00	(Grace et al., 2006; Gouwakinnou et al., 2018)
RS	0.00	0.00	0.00	0.00	(Grace et al., 2006; Gouwakinnou et al., 2018)

Legend: *DF= Dense Forest; GF= Gallery Forest; WL= Woodlands; TSS= Trees and Shrubs Savannahs; PT= Plantations; CFL= Crops and fallow land; WB= Water body; ST= Settlements; RS= Rocky surface; AB= Above-ground biomass; BB= Below-ground biomass; Soil = Soil; DOM= Dead organic matter*.

2.8. Statistical analysis

To assess significant differences in carbon storage, an analysis of variance (ANOVA) was performed (Ferreiro-Domínguez et al., 2022; Li et al., 2023). The assumptions of normality and homogeneity of variances were checked before proceeding with the analysis. ANOVA was used to test the effects of year and land- class on stock. The results were interpreted at a significance level of 5% ($p < 0.05$).

3. Results

3.1. Validation of the classification

Following the mapping of LULC change, nine categories were identified (Table 2). These are represented at the level of natural forest formations by dense forest, gallery forest, woodland, riparian vegetation and tree and shrub savannah. Non-forest vegetations are composed of crops and fallow land, dwellings and rocky areas. The discrimination of these different types of LULC was significant despite some confusion for all the types identified (the pixels of some LULC units were confused with others); as was the case between plantations and trees and shrubs savannahs, and between open forests and savannahs. The result of the reliability analysis was an overall accuracy of 96.67% (K=0.96). This K value reflects the level of reliability of the image interpretation. Accuracy rates of the LULC classification were 85% (Table 2).

Table 2: confusion matrix.

Land reference	**Card**									**TOTAL**	**User details**	**Contamination (%)**
	DF	**GF**	**WL**	**TSS**	**PT**	**CFL**	**WB**	**ST**	**RS**			
Dense Forests	12	0	0	0	0	0	0	0	0	12	100.00%	0.00%
Gallery Forests	0	16	0	0	0	0	0	0	0	16	100.00%	0.00%
Woodlands	0	0	37	2	0	0	0	0	0	39	94.87%	5.13%
Trees and Shrubs Savannahs	0	0	5	56	1	0	0	0	0	62	90.32%	9.68%
Plantations	0	0	0	0	37	0	0	1	0	38	97.37%	2.63%
Crops and Fallow Landd	0	0	0	1	0	86	0	0	0	87	98.85%	1.15%
Water Bodies	0	0	0	0	0	0	8	0	0	8	100.00%	0.00%
Plantations	0	0	0	0	0	0	0	32	0	32	100.00%	0.00%
Rocky Surfaces	0	0	0	0	0	0	0	0	6	6	0.00%	100.00%
TOTAL	12	16	42	59	38	86	8	33	6	300		
Producer precision	100.00%	100.00%	88.10%	94.92%	97.37%	100.00%	100.00%	96.97%	0.00%			
Omission (%)	0.00%	0.00%	11.90%	5.08%	2.63%	0.00%	0.00%	3.03%	100.00%			
Overall accuracy:											96.67%	
Kappa index:											0.96	

***Legend**: DF= Dense Forest; GF= Gallery Forest; WL = Woodlands; TSS= Trees and Shrubs Savannahs; PT= Plantations; CFL= Crops and fallow land; WB= Water bodies; ST= Settlements; RS= Rocky surface*

3.2. Land Use Land Cover dynamics 2003-2023

Dense forests (DF) and woodlands recorded significant losses between 2003 and 2023 (Figure 2; Table 3). Dense forests decreased by 1,562.30 hectares, mainly changed to woodlands (1,306.06 hectares) and to Trees and Shrubs savannahs (245.87 hectares). Woodlands lost 16,974.14 hectares, most of which (16,395.54 hectares) changed to trees and Shrubs savannahs. Trees and shrubs savannahs had the biggest increase in area, rising from 131,926.66 hectares in 2003 to 148,568.20 hectares in 2023, an increase of 16,641.53 hectares. This represents a change from woodland to dense forest. Crops and fallow land (CFL) also increased significantly, with an increase of 10,962.11 hectares, largely due to land previously occupied by trees and Shrubs savannahs (10,348.15 hectares) and, to a lesser extent, by woodlands (573.83 hectares). Some categories, such as Plantations (PT), remained unchanged, with a constant surface area of 338.86 hectares over the period studied. Water bodies (WB), Settlements (ST), and Rocky surfaces (RS) also maintained their areas, with marginal variations.

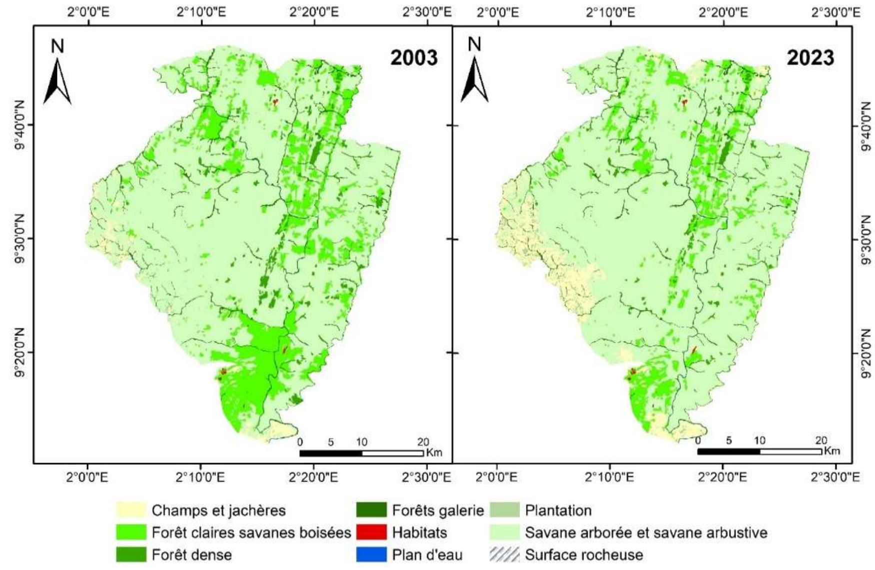

Figure 2: Maps of Land Use Land Cover dynamics between 2003 and 2023

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Table 3: Transition matrix of Land Use Land Cover units in the Tanguiéta area between 2003 and 2023

Land use 2003	**Land use 2023**									**TOTAL 2003**	**Loss**
	Dense Forest	**Gallery Forest**	**Woodlands**	**Trees and Shrubs Savannahs**	**Plantations**	**Crops and Fallow Land**	**Water Bodies**	**Settlements**	**Rocky Surfaces**		
Dense Forests	2828.50	0.00	1306.06	245.87	0.00	10.37	0.00	0.00	0.00	4390.80	1562.30
Gallery Forests	0.00	6109.24	0.00	0.00	0.00	29.76	0.14	0.00	0.00	6139.14	29.90
Woodlands	0.57	0.00	17634.00	16395.54	4.21	573.83	0.00	0.00	0.00	34608.13	16974.14
Trees and Shrubs Savannahs	0.00	0.00	62.34	131926.66	678.86	10348.15	1.56	0.36	0.00	143017.93	11091.27
Plantations	0.00	0.00	0.00	0.00	338.86	0.00	0.00	0.00	0.00	338.86	0.00
Crops and Fallow Land	0.00	0.00	0.00	0.13	372.19	3699.91	0.29	0.06	0.00	4072.59	372.67
Water Bodies	0.00	0.00	0.00	0.00	0.00	0.00	267.40	0.00	0.00	267.40	0.00
Settlements	0.00	0.00	0.00	0.00	0.00	0.00	0.00	137.47	0.00	137.47	0.00
Rocky Surfaces	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	20.18	20.18	0.00
TOTAL 2023	2829.07	6109.24	19002.40	148568.20	1394.12	14662.02	269.39	137.89	20.18	192992.50	
INCREASE	0.57	0.00	1368.40	16641.53	1055.26	10962.11	1.99	0.42	0.00		

3.3. Carbon stock in the Ouémé-Supérieur forest reserve between 2003 and 2023

LULC change impacted the amount of carbon stock and sequestration. Carbon stock in the Ouémé-Supérieur Forest reserve has been decreasing over time in correlation with the loss of natural vegetation. In 2003, carbon stock was 11,819,302.68 Mg. By 2023, it had fallen to 10,201,862.38 Mg of carbon (Table 4). Between 2003 and 2023, forest carbon stock decreased significantly. Dense forests lost nearly 214,816.2 Mg of carbon, falling from 622,043.7 Mg in 2003 to 407,227.5 Mg in 2023; while woodlands experienced an even greater decrease of 2,167,645.9 Mg, falling from 4,902,926.4 Mg to 2,735,280.5 Mg. These significant decreases are the result of the degradation of forest land, largely contributing to the loss of 1,617,440.35 Mg of carbon over the entire study area.

On the other hand, some categories experienced an increase in carbon stock. Shrubs savannahs on depleted soils recorded an increase of 257,003.5 Mg, rising from 4,632,050.7 Mg in 2003 to 4,889,054.2 Mg in 2023. Plantations also increased, with an increase of 60,131.6 Mg. These increases were not enough to offset the massive losses observed in forests. The loss of carbon sinks led to a release of 1617440.35 Mg between 2003 and 2023.

Table 4: Carbon stock per LULC unit.

LAND USE LAND COVER	2003			2023		
	Area	**%**	**Carbon**	**Area**	**%**	**Carbon**
Dense Forests	4390.8	2.28	622043.7	2829.07	1.47	407227.5
Gallery Forests	6139.14	3.18	1481054	6109.24	3.17	1497499
Woodlands	34608.13	17.93	4902926	19002.4	9.85	2735281
Trees and Shrubs Savannahs	143017.93	74.11	4632051	148568.2	76.98	4889054
Plantations	338.86	0.18	18908.17	1394.12	0.72	79039.75
Crops and Fallow Land	4072.59	2.11	162320.2	14662.02	7.6	593761.2
Water Bodies	267.4	0.14	0	269.39	0.14	0
Settlements	137.47	0.07	0	137.89	0.07	0
Rocky Surfaces	20.18	0.01	0	20.18	0.01	0
Total	192992.50		11819302.68	192992.50		10201862.38

The ANOVA results reveal a significant difference in carbon stock according to LULC type (p<0.001). However, there was no significant difference between year and LULC and carbon stock between the years 2003 and 2023 (p=0.84). In summary, the year has no significant influence on variations in carbon stock across all LULC types

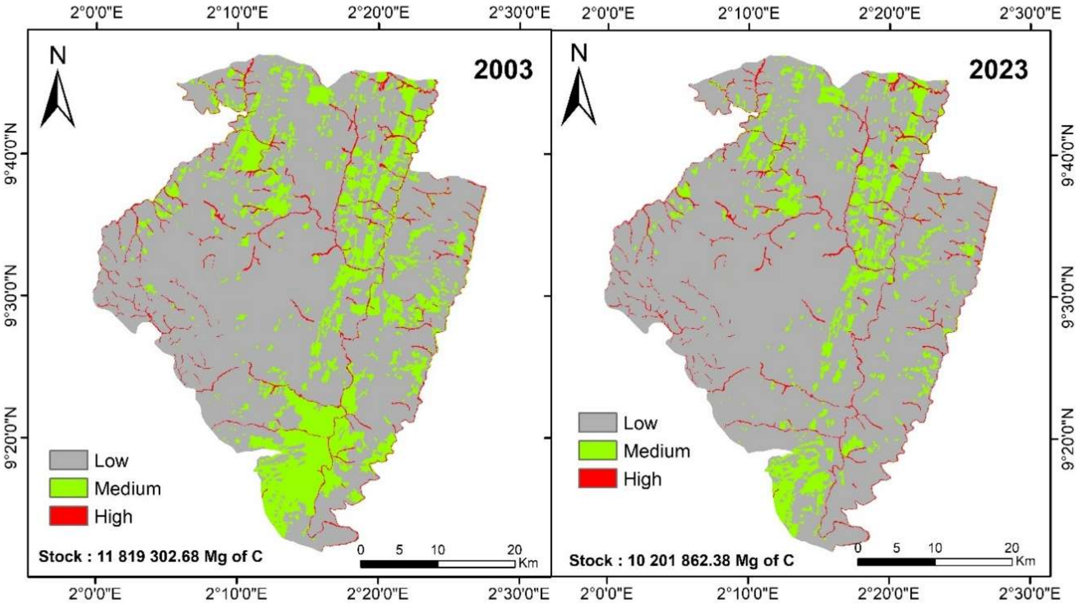

Figure 3: Map showing 2003 and 2023 carbon stock n.

4. Discussion

4.1. Study of dynamics and carbon stock

LULC change refers to spatio-temporal changes in vegetation structure. Changes in LULC in the Ouémé-Supérieur Forest reserve in Benin show a decline in forest ecosystems in favour of fields and fallow land and forest plantations. In 2003, LULC was dominated by forest formations (open forest, savannahs, etc.), but 20 years later they are dominated by fields and fallow land and a few settlements. There has been little degradation of gallery forests. This result could be explained by the uniqueness and diversity of this category (Natta, 2003) during the period from 2003 to 2023, forest formations gave way to anthropogenic formations. Our results show that, over a period of 20 years, the regression of forest ecosystems in the Ouémé-Supérieur Forest reserve is strongly linked to the expansion of agricultural land, largely driven by national policy aimed at increasing production of cotton and other cash crops such as maize and soya. According to data from the National Institute of Statistics and Economic Analysis (INSAE, 2020), the area sown with cotton in Benin increased by 60% between 2000 and 2020.

This decline is also exacerbated by widespread rapid population growth, which rose from 6.7 million in 1992 to around 13 million in 2023 (INSAE, 2023), and by urbanisation, which is leading to increased pressure on forest resources. Logging is another major cause. Woody species such as *Pterocarpus erinaceus* and *Khaya senegalensis* are particularly valued, not only for timber, but also for export, which exacerbates the degradation of forest cover. Although the Ouémé-Supérieur Forest reserve still contains individuals of these species, their density has decreased considerably due to over-exploitation. These dynamics affect not only the species richness of the woody flora, but also the provision of ecosystem services such as climate regulation and the availability of non-wood forest products. Our results corroborate those of Ousséni et al (2016) and Avakoudjo et al (2014) respectively in the Alibori-Supérieur basin and the W National Park in Benin, and are also similar to those of Mamane et al (2018) in the Tamou Total Reserve in Niger, who all showed that agriculture and logging are the main causes of the regression of our forest ecosystems. Similarly, it appears that the regression in forest cover is due to human activity. This might be preventing these ecosystems from providing the services and goods required by the populations (Oloukoi, 2013) and the balance of the environment. This regression might also be affecting the supply of ecosystem services to populations who depend on them and, at the same time, reduce the species richness of woody flora.

Furthermore, of the forest ecosystems in the Ouémé-Supérieur, dense forests, open forests and trees and shrubs savannahs were the most vulnerable between 2003 and 2023. This result could be explained by the clearing of land for new crops (Rifai et al., 2018). The vulnerability of these natural formations, which are teeming with a high diversity of species, constitutes a threat to the conservation of biodiversity and habitats (Ahononga, 2020).

Ecosystems behave like carbon sinks, if the outflows by heterotrophic respiration carbon sinks are less than the inflow through photosynthesis (Gitz and Ciais, 2003). In general, LULC change, through the increase in fields and the reduction in dense vegetations and savannah trees between 2003 and 2023, has contributed to a reduction in carbon sinks and, consequently, to a reduction in carbon stock in all carbon sinks. The same observation was made in many regions of Asia and tropical Africa with the shortening of fallow periods due to demographic growth (Uhlig et al., 1994) which leads to land scarcity. As fallow land increases, greater quantities of carbon are stored by regenerating vegetation, resulting in a net accumulation of carbon. This intensification causes shifting cultivation to become unsustainable (Houghton and Goodale, 2004). This increase is linked to the amplification of anthropogenic factors.

This finding could be due to the species used in these programmes, which are mainly fast-growing exogenous species such as Gmelina arborea and Tectona grandis, but which reduce emissions less, unlike the slow-growing endogenous species of tree found in woodlands and open forest, which changed most. Furthermore, the emission rates for the various periods considered were lower than the overall emission rates resulting from changes in LULC, which were estimated at 12% between 1990 and 2010 (Friedlingstein et al., 2010). But careless management can lead to significant degradation of vegetation and soil (Grace et al., 2006; Gouwakinnou et al., 2018) resulting in net losses of carbon to the atmosphere. However, these results show the importance of taking ecosystem services, particularly carbon sinks, into account when making LULC decisions and combating climate change.

4.2. Implications for the conservation of the Ouémé-Supérieur Forest reserve

The study and understanding of LULC change phenomena are a powerful tool for decision-making in terms of effective ecosystem management. This is one of the main reasons behind the many studies of LULC dynamics around the world (Maazou et al., 2017) and particularly in Benin s (Oloukoi, 2013; Issiaka et al., 2016). Almost all the studies carried out in the West African sub-region have shown a regressive dynamic of natural forest formations in favour of settlements, crops and fallow land and other types of anthropogenic categories. However, this study shows that all forest formations are most vulnerable, while fields and fallow land and settlements are increasingly vulnerable. Thus, the loss of the surface area of natural formations might be a real threat to the conservation of the habitats of this corridor and, therefore, to biodiversity. We, therefore, need to step up our protection efforts, especially in areas classified as State-owned, because despite the fact that our corridors are not located in agricultural areas as set out in the State's development plan, we are witnessing a worrying increase in fields and fallow land. Faced with this pressure on the corridor, now is the time to implement strategies to restore this degraded ecosystem. Restoring these ecosystems would be the most effective way of enabling them to continue to play their role, as deforestation is increasing in protected ecosystems, making them very vulnerable. This rate of deforestation is probably the result of non-compliance with current legislation on the protection of our watercourses in the Republic of Benin.

5. Conclusions

This study highlights the regressive dynamics of forest ecosystems in the Ouémé-Supérieur Forest reserve, followed by a significant decrease in carbon stock. Between 2003 and 2023, almost 11,000 hectares of forest were cleared, and more than 17,900 hectares were degraded, resulting in a net loss of 1,617,440.35 Mg of carbon. Dense forests and woodlands suffered the greatest carbon losses, while trees and shrubs savannahs and plantations had a slight increase in carbon stock, however without offsetting the overall loss. The ANOVA analysis confirms that changes in LULC have a significant impact on carbon stock, although the effect of year is negligible on this variation. These results underline the urgency to strengthen conservation measures and sustainable forest management to limit the loss of carbon sinks and mitigate the impacts of climate change. The intensification of agriculture and the expansion of cultivated land are putting increasing pressure on natural forests, accentuating the need to restore degraded ecosystems and promote sustainable LULC practices in order to preserve the carbon sequestration capacity of forests. Reforestation programmes, sustainable forest management policies and better regulation of agricultural practices could help to curb land conversion and mitigate the impacts of climate change. Further research should focus on the precise quantification of carbon emissions linked to deforestation and forest degradation, incorporating shorter time periods and local-scale analyses. In addition, studying the interactions between socioeconomic factors, LULC dynamics and carbon sequestration would provide a better understanding of the mechanisms underlying these transformations. Particular attention should be paid to assessing the effectiveness of conservation measures, particularly REDD+ programmes, in this region.

Author Contributions: AY was responsible for data collection, drafting the research protocol, and the complete writing of the manuscript. ÉSPA supervised the drafting of the protocol, corrected the manuscript, and guided the research topic's orientation. BMA contributed to the methodological aspects, the conceptualization of the InVEST model, the analysis of land-use and land-cover dynamics using satellite imagery, and the statistical analyses. SSHB supervised the entire work, from the initial idea of the manuscript to the methodological orientations and the correction of the final document.

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Data availability statement: All datasets used in this study are publicly available and freely accessible online. The data sources are clearly specified in the Methods section

Appendices

TableI5: Land Use Land Cover in 2003

LAND USE LAND COVER (LULC)	2003	
	Area	**Percentage**
Dense Forests	4,390.80	2.28
Gallery Forests	6,139.14	3.18
Woodlands	34,608.13	17.93
Trees and Shrubs Savannahs	143,017.93	74.11
Plantations	338.86	0.18
Crops and Fallow Land	4,072.59	2.11
Water Bodies	267.40	0.14
Settlements	137.47	0.07
Rocky Surfaces	20.18	0.01
Total	**192,992.50**	**100.00**

TableII6: Temporal land use in 2023

Land Use Land Cover (LULC)	2023	
	Area	**Percentage**
DF	2,829.07	1.47
GF	6,109.24	3.17
WL	19,002.40	9.85
TSS	148,568.20	76.98
PT	1,394.12	0.72
CFL	14,662.02	7.60
WB	269.39	0.14
ST	137.89	0.07
RS	20.18	0.01
Total	**192,992.50**	**100.00**

Legend: DF= Dense Forest; GF= Gallery Forest; WL= Woodlands; TSS= Trees and Shrubs Savannahs; PT= Plantations; CFL= Crops and fallow land; WB= Water Bodies; ST= Settlements; RS= Rocky surface

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