Landscape historic through spatial changes of mangroves in Benin Coastal area (West-Africa) using random forest algorithm applied to Landsat imagery

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Résumé :
Les mangroves sont reconnues comme l'écosystème majeur des zones côtières et pourvoyeuses de divers biens et services. Cependant, elles sont confrontées à des pressions anthropiques croissantes et nécessitent un suivi continu. Assurer la gestion durable de ces écosystèmes implique une surveillance permanente de leur dynamique. Dans cette optique, la présente étude, menée sur les mangroves du Bénin (Afrique de l'Ouest), vise à évaluer l'impact des perturbations anthropiques sur la dynamique de leur couverture au cours des quatre dernières décennies (incluant les sites Ramsar 1017 et 1018). La méthodologie adoptée est basée sur des techniques de télédétection utilisant des images Landsat acquises entre 1986 et 2023. L'algorithme Random Forest a été utilisé pour le traitement des images. Les résultats ont révélé que, quelle que soit la période, les taux de précision globale obtenus après l'analyse post-classification varient de 84,56 % à 96,52 %, témoignant d'une classification satisfaisante des images. Ces résultats ont mis en évidence un recul de la couverture de mangrove entre 1986 et 2013, suivi d'une augmentation entre 2013 et 2023. Sur le site Ramsar 1017, les mangroves ont perdu environ 61,90 % (3 261,06 ha) de leur superficie initiale entre 1986 et 2000. Entre 2000 et 2014, la perte de couverture a été négligeable, estimée à 2,29 % (59,04 ha). En revanche, de 2014 à 2023, les mangroves ont connu une progression estimée à environ 16,66 % (324,63 ha). La même tendance a été observée sur le site Ramsar 1018, avec une perte de 31,12 % (459,63 ha) puis de 27,44 % (279,18 ha) respectivement entre 1986 et 2001 et entre 2001 et 2013, suivie d'un gain estimé à 39,89 % (279,18 ha) entre 2013 et 2023. L'analyse des changements d'occupation du sol a révélé que, quel que soit le site ou la période, les mangroves ont été principalement converties en prairies, en zones de végétation diversifiée et en plans d'eau (par exemple, sur le site Ramsar 1017, entre 1986 et 2001, environ 568,26 ha de mangroves ont été transformés en prairies, 33,66 ha en zones de végétation diversifiée et 35,46 ha en plans d'eau). Les principaux changements observés dans cette étude, portant sur les zones côtières du Bénin, confirment la vulnérabilité des mangroves face à la pression anthropique.
Mots-clés : Mangrove, Dynamique, Télédétection, Bénin.

Abstract :
Mangrove forests, recognized as the main ecosystem of coastal zones and providing various goods and services, are facing are facing increasing anthropogenic pressures and require continuous investigation. Ensuring the sustainable management of these ecosystems implies permanent monitoring of their dynamics. In line with this, the present study carried out on the mangrove forests of Benin (West-Africa) aimed to evaluate the effect of anthropic perturbation on their cover dynamics over the past four decades (including both Ramsar sites 1017 and 1018). The adopted method focused on remote sensing techniques using Landsat images acquired between 1986 and 2023. The Random Forest algorithm was used for image processing. Results revealed that whatever the period, the overall accuracy values obtained after post-classification analysis ranged from 84.56% to 96.52% indicating a correct image classification. From these results, a decline in mangrove cover was observed between 1986 and 2013 followed by an increase from 2013 to 2023. In Ramsar site 1017, mangroves lost about 61.90% (3261.06 ha) of their initial area from 1986 to 2000. Between 2000 and 2014, mangrove cover loss was negligible and estimated at 2.29% (59.04 ha). In contrast, from 2014 to 2023, mangroves experienced an increase estimated at about 16.66% (324.63 ha). The same trend was observed in Ramsar site 1018, with a loss of 31.12% (459.63 ha) and 27.44% (279.18 ha) respectively from 1986 to 2001 and from 2001 to 2013 followed by a gain estimated at 39.89% (279.18 ha) between 2013 and 2023. Landscape changes analysis revealed that regardless of the site or period, mangroves were mainly converted into meadow, other plant and water body (e.g. in Ramsar site 1017, from 1986 to 2001, about 568.26 ha of mangroves were converted into meadows, 33.66 ha into other plant, and 35.46 ha into water body). The principal changes observed in this study focused on Benin coastal zones confirm the vulnerability of mangrove forests facing anthropogenic pressure.
Keywords: Mangrove, Dynamics, Remote sensing, Benin.

1. Introduction

Mangrove ecosystems are typical forests growing on muddy soils, principally in subtropical and tropical areas (Maia et al., 2005). They represent a complex biome distributed in intertidal zones under the influence of oceans and freshwater (Giri et al., 2011; Hogarth, 2015). According to existing statistics, these forests cover about 152,361,000 ha of tropical and subtropical shorelines (Li et al., 2019; Van et al., 2015), representing only 0.7% of the tropical forest area (Giri et al., 2011). Despite their low cover rate, mangroves are recognized as one of the most productive ecosystems in the tropics (Nguyen et al., 2020; Kasawani, 2021). They provide essential goods and services to people living in coastal regions (Giri et al., 2015; Giri et al., 2011b). These ecosystems deliver a wide range of ecological and socio-economic benefits to local communities (Alongi, 2002; Barbier, 2007). Mangroves also provide suitable habitats for many species of flora and fauna, including mammals, reptiles, birds, monkeys, etc. (Liu et al., 2008). In addition, they represent important breeding grounds for aquatic species and enhance the resilience of ecosystem-dependent coastal communities (Nguyen et al., 2020). These forests are recognized for their crucial role in coastal stabilization and protection (Lee et al., 2014), as well as for their contribution to the reduction of greenhouse gas emissions and the mitigation of the negative effects of global warming (Howard et al., 2017; Pham et al., 2019). As is the case with other natural resources, people in developing countries depend on mangroves for their daily needs. In Benin, previous studies have confirmed that the local population engages many activities depending on mangroves and uses their resources for various purposes. Timber collection for firewood and house construction, followed by fishing, are the main uses of mangrove resources (Tèka et al., 2019; Gnansousou et al., 2022; Kochoni et al., 2025). However, like many coastal and marine ecosystems, mangroves are being lost at an extremely rapid rate (Spalding, 2010; Romañach et al., 2018). They have been severely degraded due to population growth, industrialization, urban expansion, and agricultural activities (Pham et al., 2019; FAO, 2008; Satyanarayana et al., 2011). In coastal areas, the rate of urbanization has been identified as the principal driver causing the direct conversion of mangrove areas (FAO, 2013; Veettil and Quang, 2019). The existing literature reveals that at least one-third of all mangrove forests have been lost during the last few decades (Thomas et al., 2017; Romañach et al., 2018). During the 1990s, the annual rate of mangrove loss was estimated at 1%, representing twice the rate of terrestrial rainforest loss (Mayaux et al., 2005; Alongi, 2002). Similarly, between 1980 and 2005, about 35% of mangrove forests were lost (Millennium Ecosystem Assessment, 2005). Thus, mangroves are among the most vulnerable ecosystems, with a dramatic decline due to anthropogenic disturbances (Kuenzer et al., 2011; Godoy and Lacerda, 2015). As in other countries, mangroves in Benin are facing many challenges, primarily caused by wood harvesting and, secondly, by the high rate of urbanization from the implementation of numerous projects related to roads, hotels, tourist parks, and other infrastructure. Recently, with the implementation of a special government program called the “Programme d’Action du Gouvernement (PAG),” coastal areas of Benin hosting mangroves have experienced significant changes affecting land use and land cover. Considering that urbanization is increasing in these areas, mapping and monitoring mangrove forest patterns have become high priorities. Without an active policy to stop the degradation and preserve mangrove forests, the range of ecosystem services provided by these ecosystems will be significantly reduced or lost in many sites. To address this problem and ensure the effective conservation of coastal wetland ecosystems such as mangroves, effective change-detection monitoring using remote sensing tools appears to be an appropriate solution (Chang et al., 2021; Sun et al., 2021). Land cover change assessment provides relevant information to support ecosystem monitoring and management as well as to implement appropriate measures for conservation (Pontius et al., 2004; Aldwaik and Pontius, 2012). This is particularly important for mangrove ecosystems due to their high vulnerability (Lewis, 2005; Loon et al., 2016). In light of these findings, this study aims to assess the spatio-temporal dynamics of mangrove cover in Benin, where coastal areas are experiencing rapid urbanization. Specifically, both Ramsar Sites (1017 and 1018) hosting mangrove forests were considered for an overall analysis of mangrove cover changes from 1986 to 2023. Remote sensing techniques using the Random Forest algorithm were applied to Landsat images for this purpose, supported by extensive field observations.

2. Presentation of the study area

The present research was carried out on the mangrove forests of Benin (West Africa), located between 6°10′–12°25′N and 0°45′–3°55′E. It focused specifically on the southern region of Benin, mainly in the coastal area hosting mangrove forests. The study area is characterized by an equatorial climate, with a mean annual rainfall of 1,200 mm and a mean daily temperature of around 27°C. In Benin, mangroves are found at two principal sites, namely Ramsar Site 1017 and Ramsar Site 1018. From a biophysical perspective, Ramsar Site 1017 hosts the largest proportion of mangrove ecosystems and is

characterized by a high level of urbanization (roads, hotels, markets, etc.) and high population density. This site includes six main municipalities: Abomey-Calavi, Ouidah, Grand-Popo, Comè, Kpomassè, and Bopa. In contrast, Ramsar Site 1018, characterized by a low population density and a low rate of urbanization, hosts a smaller area of mangrove forest. This site includes only three municipalities: Sèmè-Podji, Porto-Novo, and Aguégués. Salt production represents one of the most important threats affecting mangrove forests in Benin due to firewood collection (Zanvo et al., 2021). While salt production is the principal economic activity developed in Ramsar Site 1017 and affects mangrove stands through fuelwood harvesting, Ramsar Site 1018 is characterized by fishing as the main economic activity (Gnansounou et al., 2021; Tèka et al., 2019).

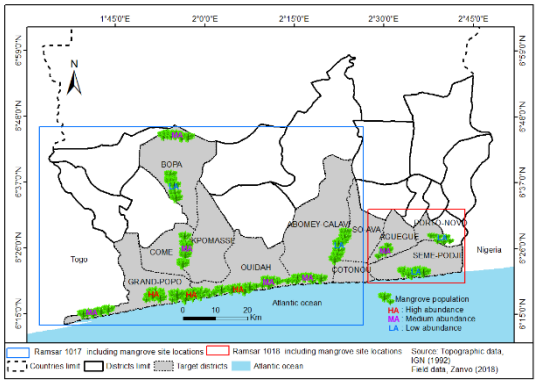


Fig. 1: Map of the study area

3. Method

3.1. Image selection and sources

The methodology adopted in this study was based on remote sensing techniques to classify satellite images and assess changes in land use and land cover within mangrove forests in the coastal region of Benin, West Africa. To ensure consistent and accurate image interpretation, only Landsat satellite imagery was used. Specifically, Level-2 Landsat ETM+/OLI products with a spatial resolution of 30 × 30 m were obtained from the United States Geological Survey (USGS) database. Landsat imagery was selected primarily because it provides a consistent archive covering the study period from 1986 to 2023. Furthermore, the data are freely accessible and provide an adequate spatial resolution for detecting changes in mangrove forests and other land-cover types within the coastal environment. Following the approach proposed by Solly et al. (2018), high-quality images acquired during the dry season were preferentially selected to minimize the influence of seasonal variations and atmospheric conditions. The study area comprises two geographically distinct Ramsar sites, namely Ramsar Sites 1017 and 1018. For each site, four observation dates were selected to analyze land-cover dynamics over approximately four decades. Thus, changes were assessed using three time intervals of approximately 10 years. These relatively long intervals were considered appropriate for detecting gradual changes in mangrove extent, particularly given the limited spatial representation of mangrove areas and the progressive effects of anthropogenic pressure. The selection of the four dates for each Ramsar site was primarily based on the availability of cloud-free, high-quality Landsat imagery. Accordingly, the selected years for Ramsar Site 1017 were 1986, 2000, 2014, and 2023, whereas the selected years for Ramsar Site 1018 were 1986, 2001, 2013, and 2023.

Table 1: Characteristics of Landsat images considered

Sensor type	Image ID	Acquisition date
	Ramsar site 1017	
Landast 4-5 TM	LT05_L2SP_191056_20201014_02_T1	26-02-1986
Landast 7ETM+	LE07_L1TP_192056_20200917_02_T1	04-04-2000
Landsat 8 OLI	LC08_L1TP_192056_20200910_02_T1	28-02-2014
Landsat 8 OLI	LC08_L2SP_192056_20240103_02_T1	21-12-2023
	Ramsar site 1018	
Landast 4-5 TM	LT05_L2SP_191056_20201014_02_T1	26-02-1986
Landast 7 ETM+	LE07_L2SP_191056_20200917_02_T1	09-12-2001
Landsat 8 OLI	LC08_L2SP_191056_20200912_02_T1	18-12-2013
Landsat 8 OLI	LC08_L2SP_191056_20240109_02_T1	14-12-2023

The period from 1986 to 2023 was selected to assess the gradual effects of increasing urbanization on coastal ecosystems, particularly mangrove forests. Over recent decades, coastal areas have experienced increasing urbanization driven by population growth and the development of various infrastructures, including accommodation facilities and tourist parks. These developments have contributed to changes in major land-cover types, particularly mangroves, other plant, meadows water body. In response to the degradation of mangrove ecosystems and to mitigate the effects of anthropogenic pressure, several conservation and management measures have been implemented. These include (i) raising awareness among local communities about mangrove conservation, (ii) restoring degraded mangrove forests, and (iii) enforcing restrictions on mangrove tree harvesting. Therefore, the 1986–2023 period was considered in this study to examine long-term changes in mangrove ecosystems and assess the relationship between increasing urbanization and conservation as

well as restoration efforts across Ramsar Sites 1017 and 1018.

3.2. Field observations and Image Classification

Image classification was performed in two main steps: (i) preparation of the study area and (ii) image processing and classification. Six spectral bands (B1, B2, B3, B4, B5, and B7) were selected for image processing. Following band selection, the study areas were extracted using the corresponding shapefiles for each Ramsar site. RGB color composites were generated to facilitate the visual discrimination of the different land-cover types. A supervised classification approach was adopted using five major land-cover classes, based on the main land uses observed in the study area and the classification scheme proposed by Zanvo et al. (2021) for the coastal region of Benin. The five classes were: (i) meadow, (ii) other plant, (iii) mangrove, (iv) built and soil, and (v) water bodies. The other plant class included natural forests and plantations. These two vegetation types were grouped into a single class because natural forests are relatively sparse in the study area and the remaining forested areas are frequently intermixed with plantations. Training samples were generated for each land-cover class by combining field observations obtained from GPS coordinates with high-resolution imagery from Google Earth. A total of 370 GPS points were collected in 2023 across the study area, covering all five land-cover classes, to support accurate image classification. The GPS locations were overlaid on the most recent satellite imagery (2023) to identify representative training areas. The number of training samples varied among land-cover classes according to their abundance and spatial distribution within each Ramsar site. For each land-cover class and observation date, between 105 and 216 Regions of Interest (ROIs), including training and validation ROIs, were randomly selected for each Ramsar site. Overall, 2804 ROIs were obtained across the two Ramsar sites and all observation dates. The ROIs were randomly divided into training and validation datasets using a 70:30 ratio, with 70% of the samples used for classification and 30% reserved for validation, following Chen et al. (2024). According to Barima et al. (2009), ROIs used for classification correspond to homogeneous areas covering more than 20 pixels. The 2023 images were classified first using the available field information from the GPS survey combined with Google Earth imagery, following the approach of Manandhar et al. (2009). For the earlier observation dates (1986, 1986, 2000, 2001, 2013, and 2014), ROIs were subsequently identified based on the spectral signatures of the land-cover classes established from the 2023 classification, following the approaches proposed by Barima et al. (2016) and Munyemba and Bogaert (2014). This approach ensured consistency in the identification of land-cover classes across the different observation dates. The classified polygons and processed images for each year and Ramsar site were exported to the R statistical environment for land-cover classification using the Random Forest algorithm. Post-classification analysis included the generation of confusion matrices and transition matrices. Transition matrices were used to quantify and characterize land-cover changes between consecutive observation periods for each Ramsar site, following Godard (2005). Classification accuracy was assessed using confusion matrices and the Kappa coefficient. Confusion matrices are widely used in remote sensing to evaluate the accuracy of image classification (Foody, 2002), while the Kappa coefficient provides an additional measure of agreement between the classified map and the reference data (Skupinski et al., 2009).

Finally, descriptive statistical analyses were performed to calculate the proportion (%) of each land-cover class for each observation date and Ramsar site. The results were subsequently visualized using graphs generated in R.

4. Results

4.1. Confusion matrices and overall accuracy of classified images

Confusion matrices (Table 2) were generated for each observation year to assess the classification accuracy e and the proportion of correctly classified pixels for each land-cover class. The diagonal elements of the confusion matrices, (in bold), represent the proportions of correctly classified pixels, whereas the off-diagonal elements indicate the proportions of misclassified pixels. The results presented in Table 2 showed that the overall classification accuracy ranged from 84.56% to 96.50%, depending on the observation year and Ramsar site. These results indicate a high accuracy and confirm the reliability of the land-cover classification. Most classification errors were associated with limited confusion between the mangrove class and two other land-cover classes, namely other plant and water bodies. For Ramsar Site 1017, the proportion of correctly classified pixels for the mangrove class ranged from 87.20% to 93.40%, whereas for Ramsar Site 1018, it ranged from 84.56% to 96.50%. Overall, these results indicate that mangrove areas were satisfactorily discriminated from the other land-cover classes across the different observation dates.

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Table 2: Confusion matrix of classified images in Ramsar site 1017

Year 1986					
Class	Meadow	Other plant	Mangrove	Built and soil	Water body
Meadow	**82.22**	2.2	5.6	5.74	2.7
Other plant	10.38	**91.5**	0.2	0	0
Mangrove	3.2	6.3	**90.2**	0	0
Built and soil	0	0	0	**94.26**	0
Water body	4.2	0	4	0	**97.3**
Overall accuracy [%] = 91.8871					

Year 2000					
Class	Meadow	Other plant	Mangrove	Built and soil	Water body
Meadow	**94.5**	1.3	6.4	7.16	2.45
Other plant	1.14	**88.41**	4.01	0	0
Mangrove	0	9.55	**87.203**	0	2
Built and soil	0	0	0	**91.24**	0
Water body	4.36	0	2.3	1.55	**95.55**
Overall accuracy [%] = 96.5233					

Year 2014					
Class	Meadow	Other plant	Mangrove	Built and soil	Water body
Meadow	**91.77**	3	4.6	5.39	2.1
Other plant	0	**87.28**	0	0	0
Mangrove	5.23	8.72	**93.40**	0	0
Built and soil	0	0.52	0	**94.61**	0
Water body	2	0	2	0	**97.9**
Overall accuracy [%] = 88.8585					

Year 2023					
Class	Meadow	Other plant	Mangrove	Built and soil	Water body
Meadow	**95.25**	1.98	3	7.79	1.88
Other plant	0.75	**94.02**	3.67	0	0
Mangrove	4	4	**93.33**	0	1
Built and soil	0	0	0	**90.21**	0
Water body	0	0	0	2	**97.12**
Overall accuracy [%] 93.7555					

Table 3: Confusion matrix of classified images in Ramsar site 1018

Year **1986**					
Class	Meadow	Other plant	Mangrove	Built and soil	Water body
Meadow	**93.88**	2.2	3.37	4.36	3.01
Other plant	0	**94.33**	4.33	0	1.1
Mangrove	4.12	3.2	**91.27**	0	0
Built and soil	0	0.1	0	**95.63**	0.06
Water body	2	0	0	0	**95.51**
Overall accuracy [%] = 96.1968					

Year 2001					
Class	Meadow	Other plant	Mangrove	Built and soil	Water body
Meadow	**80.45**	3	9.83	6.4	3.7
Other plant	4.16	**91.34**	0	0	0
Mangrove	1.2	4.66	**89.1**	0	2
Built and soil	2	0	0	**91.22**	0
Water body	12.01	0	0	1.5	**94.3**
Overall accuracy [%] = 96.5010					

Year 2013					
Class	Meadow	Other plant	Mangrove	Built and soil	Water body
Meadow	**74.24**	28	6.7	8.1	4.5
Other plant	0.9	**61.29**	0	0.2	0
Mangrove	12.76	10.41	**88.3**	0	1.05
Built and soil	5.1	0	0	**91.7**	0
Water body	6	0	5	0	**93.45**
Overall accuracy [%] = 84.5616					

Year 2023					
Class	Meadow	Other plant	Mangrove	Built and soil	Water body
Meadow	**93.11**	2	8.36	5.74	1.29
Other plant	1.56	**90.23**	0	0	0
Mangrove	0.3	6.77	**89.34**	0	2
Built and soil	1	0	0	**93.21**	0
Water body	4	0	2.3	1	**96.71**
Overall accuracy [%] = 95.3541					

4.2. Trends of land cover changes evolution

The results of this study revealed distinct trends in land-cover dynamics across the coastal region of Benin, depending on the Ramsar site considered (1017 and 1018). While some land-cover classes decreased between consecutive observation periods, others increased. In Ramsar Site 1017, mangrove forests experienced a continuous decline during the periods: 1986–2000 and 2000–2014. Between 1986 and 2000, mangrove forests lost approximately 3,261.06 ha of their initial area. Similarly, a loss of approximately 59.04 ha was recorded between 2000 and 2014. In contrast, during the 2014–2023 period, mangrove forests experienced an increase, with a gain of approximately 324.63 ha. A similar pattern was observed in Ramsar Site 1018. Mangrove forests lost approximately 459.63 ha between 1986 and 2001, followed by a further loss of approximately 279.18 ha between 2001 and 2013. However, between 2013 and 2023, mangrove forests experienced an increase of approximately 405.81 ha. The class other plant

Table 3: Confusion matrix of classified images in Ramsar site 1018 also exhibited contrasting trends across the different periods. In Ramsar Site 1017, this class increased by approximately 2,343.30 ha between 1986 and 2000, followed by a relatively small decrease of 137.16 ha between 2000 and 2014. From 2014 to 2023, the class experienced a substantial increase of approximately 6,274.08 ha. A similar pattern was observed in Ramsar Site 1018, where the other plant class increased by approximately 586.44 ha between 1986 and 2001, followed by a decrease of approximately 303.75 ha between 2001 and 2013. From 2013 to 2023, the class increased substantially, with a gain of approximately 3,238.56 ha. The expansion of the other plant class is likely associated with the implementation of several reforestation and planting projects, as this class includes both plantations and natural forests. The built and bare-soil class also showed contrasting trends. In Ramsar Site 1017, this class increased substantially by approximately 6,248.70 ha between 1986 and 2000. This increase was followed by a decline of approximately 3,673.35 ha between 2000 and 2014 and a further decrease of 1,140.57 ha from 2014 to 2023. In Ramsar Site 1018, the built and bare-soil class decreased by approximately 1,047.96 ha between 1986 and 2001.

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It subsequently increased by approximately 521.82 ha from 2001 to 2013 and by 228.96 ha between 2013 and 2023. In Ramsar Site 1017, the meadow class decreased by approximately 402.21 ha from 1986 to 2000, followed by an increase of approximately 443.79 ha between 2000 and 2014. However, from 2014 to 2023, this class experienced a substantial decrease of approximately 6,043.05 ha. In Ramsar Site 1018, meadow areas increased by approximately 873.54 ha between 1986 and 2001 and by 158.49 ha from 2001 to 2013. Conversely, between 2013 and 2023, this class decreased by approximately 3,956.04 ha. Overall, water bodies showed relatively limited changes throughout the study period in both Ramsar sites. No substantial variations in the extent of this land-cover class were observed between the different observation periods.

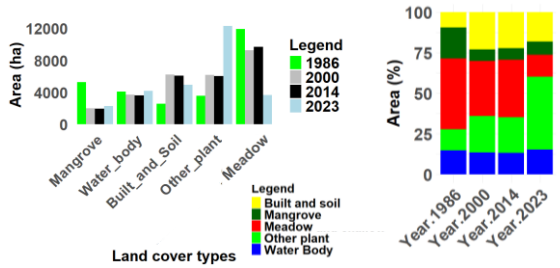


Fig. 2: Statistic of land cover in Ramsar site 1017 from 1986 to 2023

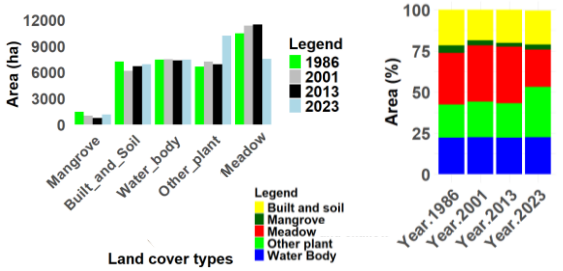


Fig. 3: Statistic of land cover in Ramsar site 1018 from 1986 to 2023

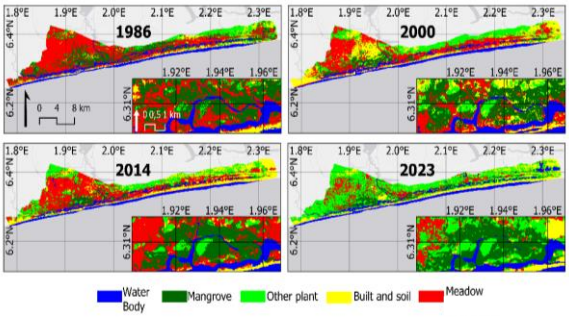


Fig. 4: Map of land cover dynamics in Ramsar site 1017 from 1986 to 2024

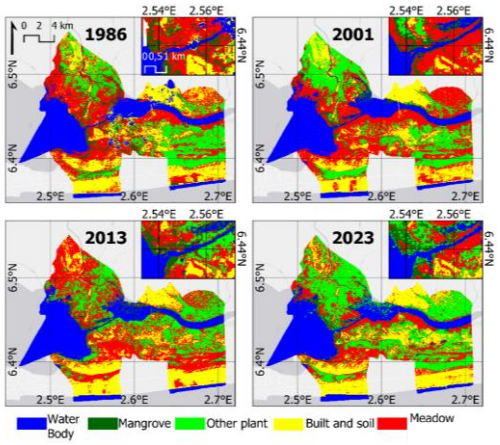


Fig. 5: Map of land cover dynamics in Ramsar site 1018 from 1986 to 2024

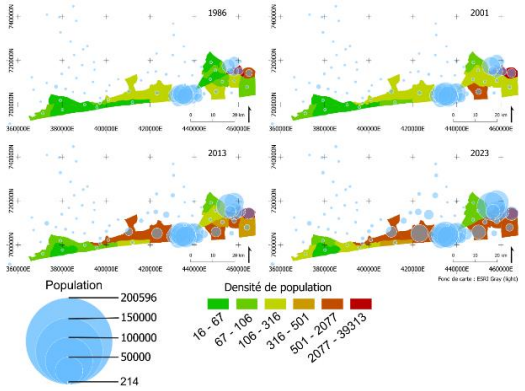


Fig. 6: Dynamic of population density in Benin's coastal area hosting mangroves (1986 to 2023)

4.3. Transition matrices of soil occupations

The following tables present the spatial transitions observed across the different Ramsar sites and observation periods. A general analysis of Tables 3 and 4 indicates that mangrove forests were primarily converted into meadow and other plant. In Ramsar Site 1017, approximately 568.26 ha of mangrove forests were converted into meadow areas between 1986 and 2000. A similar transition was observed between 2000 and 2014, during which approximately 545.85 ha of mangrove forests were converted into meadow. Between 2014 and 2023, approximately 830.88 ha of mangrove forests underwent the same transition. In Ramsar Site 1018, approximately 513.18 ha and 175.50 ha of mangrove forests were converted into meadow during the periods 1986–2001 and 2001–2013, respectively. Between 2013 and 2023, approximately 357.84 ha of mangrove forests were converted into meadow. Regarding the other land-cover classes, the transition matrices showed that, regardless of the Ramsar site and observation period, other plant class was mainly converted into mangroves, meadow, and built and bare-soil areas. Similarly, meadow was primarily converted into mangroves, water bodies, and built-up and bare-soil areas.

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Table. 4: Transition matrix of Ramsar site 1017

		Year 2000					
	Classes	Meadow	Other plant	Mangrove	Built and soil	Water body	Total (ha)
Year 1986	Meadow	**6860.97**	1774.26	568.26	2694.69	13.05	11911.23
	Other plant	277.56	**2252.97**	33.66	991.62	0.09	3555.9
	Mangrove	1288.8	1780.38	**1354.41**	820.53	23.76	5267.88
	Built and soil	289.08	380.61	15.03	**1654.56**	236.07	2575.35
	Water body	553.77	1.89	35.46	84.06	**3415.77**	4090.95
	Total (ha)	9270.18	6190.11	2006.82	6245.46	3688.74	27401.31

		Year 2014					
	Classes	Meadow	Other plant	Mangrove	Built and soil	Water body	Total (ha)
Year 2000	Meadow	**6197.94**	1324.8	545.85	940.5	261.09	9270.18
	Other plant	977.85	**3491.73**	167.94	1551.87	0.72	6190.11
	Mangrove	677.88	222.12	**1084.86**	17.19	4.77	2006.82
	Built and soil	1649.52	1010.16	118.89	**3416.4**	50.49	6245.46
	Water body	210.78	4.23	30.24	149.13	**3294.36**	3688.74
	Total (ha)	9713.97	6053.04	1947.78	6075.09	3611.43	27401.31

		Year 2023					
	Classes	Meadow	Other plant	Mangrove	Built and soil	Water body	Total (ha)
Year 2014	Meadow	**3191.13**	4722.84	830.88	486.72	482.4	9713.97
	Other plant	195.3	**5243.04**	81	414.63	119.07	6053.04
	Mangrove	57.87	634.68	**1203.21**	44.64	7.38	1947.78
	Built and soil	185.31	1700.91	31.14	**3901.41**	256.32	6075.09
	Water body	41.31	25.65	126.18	87.12	**3331.17**	3611.43
	Total (ha)	3670.92	12327.12	2272.41	4934.52	4196.34	27401.31

		Year 2023					
	Classes	Meadow	Other plant	Mangrove	Built and soil	Water body	Total (ha)
Year 1986	Meadow	**2920.59**	6463.35	918.72	1384.02	224.55	11911.23
	Other plant	107.37	**2088.9**	37.44	1256.22	65.97	3555.9
	Mangrove	513.99	3226.41	**988.92**	411.48	127.08	5267.88
	Built and soil	77.76	459.18	14.94	**1746.09**	277.38	2575.35
	Water body	51.21	89.28	312.39	136.71	**3501.36**	4090.95
	Total (ha)	3670.92	12327.12	2272.41	4934.52	4196.34	27401.31

Table. 5: Transition matrix of Ramsar site 1018

		Year 2001					
	Classes	Meadow	Other plant	Mangrove	Built and soil	Water body	Total (ha)
Year 1986	Meadow	**6527.7**	1898.91	513.18	972.27	529.2	10441.26
	Other plant	1694.52	**4482.36**	69.93	386.46	4.23	6637.5
	Mangrove	712.98	302.31	**241.92**	62.19	157.41	1476.81
	Built and soil	2109.87	471.87	36	**4432.05**	144.27	7194.06
	Water body	269.73	68.49	156.15	293.13	**6623.01**	7410.51
	Total (ha)	11314.8	7223.94	1017.18	6146.1	7458.12	33160.14

		Year 2013					
	Classes	Meadow	Other plant	Mangrove	Built and soil	Water body	Total (ha)
Year 2001	Meadow	**5921.37**	3600.27	175.59	1491.84	125.73	11314.8
	Other plant	3910.05	**2964.87**	31.86	313.83	3.33	7223.94
	Mangrove	398.79	211.95	**243.63**	3.42	159.39	1017.18
	Built and soil	1160.91	95.4	1.89	**4852.44**	35.46	6146.1
	Water body	82.17	47.7	285.03	6.39	**7036.83**	7458.12
	Total (a)	11473.29	6920.19	738	6667.92	7360.74	33160.14

		Year 2023					
	Classes	Meadow	Other plant	Mangrove	Built and soil	Water body	Total (ha)
Year 2013	Meadow	**4444.47**	5265.27	357.84	1308.96	96.75	11473.29
	Other plant	2009.79	**4349.79**	295.11	207.99	57.51	6920.19
	Mangrove	71.82	202.5	**224.55**	0.18	238.95	738
	Built and soil	1080.18	166.86	7.38	**5338.8**	74.7	6667.92
	Water body	36.45	211.77	136.17	21.69	**6954.66**	7360.74
	Total (ha)	7642.71	10196.19	1021.05	6877.62	7422.57	33160.14

		Year 2023					
	Classes	Meadow	Other plant	Mangrove	Built and soil	Water body	Total (ha)
Year 1986	Meadow	**4284.27**	3569.22	590.04	1417.95	579.78	10441.26
	Other plant	1279.71	**4644**	77.58	602.46	33.75	6637.5
	Mangrove	518.13	529.02	**193.14**	56.43	180.09	1476.81
	Built and soil	1344.87	1086.21	41.04	**4526.55**	195.39	7194.06
	Water body	215.73	367.74	119.25	274.23	**6433.56**	7410.51
	Total (ha)	7642.71	10196.19	1021.05	6877.62	7422.57	33160.14

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The following pictures present principal anthropogenic drivers affecting mangrove dynamics in coastal areas of Benin.



Fig. 7: a; Partial views of mangrove forests in Benin coastal zones b; Mangrove stand logged for touristic park implementation at Azizakouè (Ouidah, Benin) c; Pile of Mangrove timbers for firewood Codjo-Codji (Grande-Popo, Bénin) d; Partial view of «Route des pêches» in Abomey-Calavi (Benin) e; Bridge implemented cross mangrove forest at Adounko (Abomey-Calavi, Benin).

Photographies taken by S. Zanvo in 2023.

5. Discussion

Mangrove forests are recognized as fragile ecosystems that provide important social, economic, and environmental benefits and therefore contribute significantly to sustainable coastal management. Consequently, scientific research on their spatial dynamics and ecological condition has become a priority for researchers and other stakeholders involved in forest and coastal resource management. In this context, the present study assessed the long-term dynamics of mangrove forests in the coastal region of Benin between 1986 and 2023 using remote sensing techniques. Landsat imagery was used to assess changes in mangrove cover across the two Ramsar sites considered in this study (1017 and 1018). The use of Landsat data offers several advantages, including a spatial resolution of 30 m, multiple spectral bands, and the availability of a long-term historical archive of satellite imagery (Nguyen et al., 2016). Image processing followed conventional remote-sensing approaches previously applied by Munyemba and Bogaert (2014) and Barima et al. (2016). The overall classification accuracy obtained in this study ranged from 84.56% to 96.50%, indicating a satisfactory level of reliability for the land-cover classification. The analysis revealed contrasting trends in mangrove dynamics between the Ramsar sites and observation periods. Overall, the results showed that mangrove forests lost more than half of their initial area between 1986 and 2014 in both Ramsar sites. The substantial decline observed during this period is consistent with previous studies reporting significant mangrove degradation in Benin. As illustration, Zanvo et al. (2021) estimated a 60% loss of mangrove ecosystems in Ramsar Site 1017 from 1988 to 2001. Similarly, Orékan et al. (2019) reported a 4% decline of the mangrove cover across the coastal region of Benin between 2005 and 2015. The same author (Orékan et al.,2018) estimated a 17% decline between 1986 and 2016 for the Avlo district, one of the most important mangrove hotspots in Benin. The decline of the mangrove cover observed in Benin is part of a broader pattern degradation reported across Africa and other tropical regions. Considering the case of Togo, which shares similar coastal ecosystems with Benin, Folega et al. (2017) reported a 47% loss of mangrove cover between 1986 and 2014. Regarding the Cameroon, previous assessments estimated mangrove losses of approximately 250,000 ha in 2005 (FAO, 2005), while Zogning Lontsi et al. (2021) reported considerable degradation of the remaining mangrove forests as a result of habitation and coastal infrastructure development. Similar trends have also been documented outside Africa. In China, Jia et al. (2018) reported a decrease in mangrove area from 48,801 ha to 18,702 ha between 1973 and 2000.

Tin et al. (2019) estimated at approximately 84% of mangrove areas had been converted to other land uses over a 44-year period in Vietnam. For the Quang Ninh region of Vietnam, Nguyen et al. (2022) reported a decline of 2,168.3 ha between 1986 and 2020, mainly associated with unplanned aquaculture, urban development, and other land uses. Similarly, Tuholske et al. (2017) estimated that 19.1% of a mangrove forest of Honduras was converted to urban areas between 1985 and 2015, while Mondal and Saha (2018) reported that approximately 4% of mangrove areas in India were converted to other land uses between 1975 and 2015. Several factors can contribute to mangrove degradation, including both natural hazards and anthropogenic pressures. Natural disturbances, such as tropical cyclones, can cause substantial losses of mangrove vegetation. In the Philippines, for example, Buitre et al. (2019) reported significant mangrove losses associated with tropical cyclones. However, anthropogenic pressures are increasingly recognized as major drivers of mangrove degradation. These pressures include

population growth, poverty, inadequate environmental governance, and insufficient enforcement of regulations governing mangrove use (Zogning Lontsi et al., 2021). Previous studies have highlighted the effects of aquaculture (Hu et al., 2018), industrial activities (Godoy et al., 2018), upstream dam construction (Lu and Siew, 2006), and agricultural expansion (Jia et al., 2018) on mangrove ecosystems. Land development for housing, urban expansion, and infrastructure construction can also directly affect mangrove habitats (NAREI, 2015). In Benin, one of the major anthropogenic pressures affecting mangrove ecosystems is salt production. Local populations harvest mangrove wood for use as firewood for salt production and fish smoking, as well as for domestic energy needs (Zanvo et al., 2021; Gnansounou et al., 2022; Tèka et al., 2018). Padonou et al. (2022) also highlighted the substantial contribution of mangrove wood to the energy requirements of local salt-production facilities. In addition to direct wood harvesting, increasing urbanization may represent an important pressure on mangrove ecosystems on the coastal region of Benin. Since approximately 2014, the coastal area has experienced substantial infrastructure development, including roads, bridges, and accommodation facilities. These developments form part of the broader implementation of the Programme d'Action du Gouvernement (PAG), initiated in 2016, and have contributed to changes in land-cover patterns along the coast. The development of the "Route des Pêches", a major road connecting Abomey-Calavi and Ouidah, provides an example of these changes. Infrastructure development along this corridor has modified the spatial configuration of coastal land-cover types and have contributed to the loss of the ecotonal zone between mangrove ecosystems and the sea (including areas dominated by grasses and other coastal vegetation). Although the present study demonstrates changes in land cover, the observed spatial patterns should not be interpreted as direct evidence that urbanization alone caused mangrove loss. Rather, urban expansion, infrastructure development, wood harvesting, and other anthropogenic pressures may act simultaneously and interactively to influence mangrove dynamics. Given the degradation observed across the study period, mangrove monitoring and conservation measures should be strengthened to prevent further declines. Zanvo et al. (2022) recommended specific conservation strategies according to the conservation status of mangrove sites, including preserved, poorly preserved, and non-preserved areas. In particular, the municipalities of Ouidah and Abomey-Calavi should receive particular attention because of their high population density, extensive habitation, and significant mangrove resources. Mangrove sites with important remaining stands, including Avlo, Aguégué, Houankpè Daho, Ahouandji, and Adounko, should also be incorporated into sustainable management strategies involving local communities and community leaders. Mangrove conservation is particularly important because healthy mangrove ecosystems support local livelihoods and economic activities, including fisheries and ecotourism. Conversely, mangrove degradation may increase the vulnerability of coastal communities by reducing the availability of natural resources. For example, the decline of mangrove-associated habitats may negatively affect fishing activities and consequently reduce the income of local fishers (Johnson-Bhola, 2020). Despite the substantial mangrove decline observed between 1986 and 2014, the results also revealed an increase in mangrove cover during the most recent observation period. Mangrove cover increased by approximately 2.57% in Ramsar Site 1018 between 2013 and 2023 and by approximately 0.54% in Ramsar Site 1017 between 2014 and 2023. This recent increase may be associated with mangrove restoration activities and the strengthening of forest-conservation measures. However, because the present study is based primarily on remotely sensed land-cover changes, these potential drivers should be considered as plausible explanations rather than direct causal relationships. The observed increase in mangrove cover coincides with several restoration and conservation initiatives implemented in Benin over recent decades. Both public institutions and non-governmental organizations have implemented projects focusing on local community awareness, mangrove conservation, and the restoration of degraded areas. In addition to conventional seedling planting (restoration), hydrological restoration has been explored as an alternative approach for restoring mangrove ecosystems in Benin. This approach has been implemented experimentally at sites within Ramsar Sites 1017 and 1018. According to the information reported in previous studies, hydrological restoration in the Djègbamey area (municipality of Ouidah) contributed to the recovery of approximately 100 ha of degraded mangrove habitat. Although this technique may involve substantial financial and logistical costs, its effectiveness warrants further evaluation to determine its suitability for application at a larger scale. Restoration initiatives involving NGOs and national forest-management institutions have also been implemented in several degraded areas of Ramsar Site 1017. These activities, together with other conservation measures, may have contributed to the recent expansion of mangrove cover observed in the present study. Forest legislation may represent another factor supporting mangrove conservation. Government restrictions on mangrove destruction and the implementation of

restoration policies have potentially contributed to reducing direct pressure on mangrove forests and promoting their recovery. Traditional conservation practices may also contribute to mangrove protection in Benin. As reported by Gnansounou et al. (2025), traditional forms of conservation, including the sacralization of certain forest areas, continue to play a role in the protection of mangrove ecosystems. Zanvo et al. (2021a), as well as Tèka et al. (2019) and Vogt (2010), highlighted the role of the "Zangbeto traditional institution", which relies on customary rules, taboos, and totems to regulate access to and use of natural resources. According to Zanvo et al. (2021a), mangrove sites protected under these traditional systems may prohibit tree cutting, with sanctions applied to individuals who violate established rules. Such community-based and culturally embedded conservation mechanisms may complement formal forest-management policies. Nevertheless, the recent increase in mangrove cover should not necessarily be interpreted as definitive evidence of successful restoration. Zanvo et al. (2021b), for example, reported an approximately 18% increase in mangrove cover between 2001 and 2019. Comparison with the present results suggests that mangrove dynamics may have varied considerably depending on the period and spatial extent considered. Differences between estimates may also result from differences in satellite data, classification methods, spatial resolution, observation dates, and land-cover definitions. These methodological differences should therefore be considered when comparing estimates across studies. The continuing development of the coastal region also suggests that mangrove ecosystems remain exposed to significant anthropogenic pressure. Consequently, further research is needed to identify the environmental and management conditions that optimize mangrove restoration. In this regard, Sinsin et al. (2021) investigated mangrove seedling emergence and early growth along a salinity gradient. Their findings highlight the importance of considering salinity conditions during nursery production and transplantation. To reduce the risk of osmotic stress following transplantation, the authors recommended using low or moderate salinity water in nurseries according to the salinity conditions of the receiving environment. The use of alternative fuelwood species may also help reduce pressure on mangrove forests. Rather than relying exclusively on mangrove wood, local communities could be encouraged to use suitable alternative species for domestic and economic purposes. Acacia auriculiformis has been identified as one of the main substitute species accepted by local populations (Zanvo et al., 2021a). However, the ecological implications of large-scale use of alternative species should also be carefully considered to avoid creating new environmental pressures. Overall, sustainable mangrove management in Benin requires the integration of ecological restoration, effective legislation, scientific monitoring, and community participation. The involvement of local populations, community leaders, governmental institutions, and NGOs in conservation initiatives is particularly important. Based on the case of the Vietnam, Nguyen et al. (2022) reported that inappropriate regulations, institutional weaknesses, and insufficient participation of local communities contributed to mangrove deforestation. Community-based mangrove management can therefore represent an important component of long-term conservation strategies by supporting local livelihoods while reducing pressure on mangrove resources. Such an approach can contribute to the sustainable development of coastal economic activities, including fisheries and ecotourism, while maintaining the ecological functions of mangrove ecosystems (Buncag, 2021).



Fig. 8: Mangrove sites preserved by the Divinity the Divinity « Zangbeto » in Benin.

Conclusion

This study assessed the vulnerability of natural resources in the coastal region of Benin, with particular emphasis on mangrove dynamics within Ramsar Sites 1017 and 1018. The results revealed two contrasting trends in mangrove cover. Mangrove areas generally decreased from the beginning of the study period until approximately 2013–2014, whereas an increase was observed during the most recent period, from 2013/2014 to 2023. Despite this recent recovery, the overall results indicate substantial long-term disturbance and degradation of mangrove ecosystems in both Ramsar sites. The observed changes in mangrove cover may be associated with several anthropogenic pressures, particularly the expansion of human settlements and infrastructure linked to ongoing urbanization in the coastal region, combined with mangrove wood harvesting. These pressures can contribute to the degradation and fragmentation of mangrove habitats. Mangrove loss may consequently affect biodiversity, aquatic organisms, and the livelihoods of local communities that depend on mangrove-associated resources, particularly fisheries and other natural-resource-based economic activities. Considering the observed degradation and the continuing pressures on mangrove ecosystems, appropriate conservation

and management measures should be strengthened to ensure the long-term preservation of coastal biodiversity. Three main actions are recommended:

(i). Promotion of alternative species and restoration of degraded areas: The use of suitable substitute species should be promoted to reduce pressure on mangrove wood resources, while restoration activities should be strengthened in degraded mangrove areas. Restoration approaches should be adapted to local environmental conditions and supported by appropriate scientific monitoring.

(ii). Strengthening community awareness and environmental education: Awareness campaigns should be reinforced among local populations to improve understanding of the ecological and socioeconomic importance of mangrove ecosystems and to reduce unsustainable harvesting and other destructive practices.

(iii). Development of targeted socioeconomic programs: Specific programs should be developed to improve the professional integration and income-generating opportunities of young people and women in coastal communities. Providing alternative livelihood opportunities could contribute to reducing unemployment and poverty and, consequently, decrease dependence on mangrove resources and other natural ecosystems. Ultimately, the sustainable management of mangrove forests in Benin requires an integrated approach combining ecological restoration, environmental education, effective enforcement of conservation regulations, and socioeconomic development. Strengthening the participation of local communities, government institutions, NGOs, and other stakeholders will be essential to reconcile mangrove conservation with the socioeconomic needs of coastal populations.

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