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Spatiotemporal Changes in Ghana's Mangrove Ecosystems and Pathways for Restoration Action

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Received: 20 February 2025 | **Revised:** 13 May 2025 | **Accepted:** 7 July 2025

Funding: The authors received no specific funding for this work.

Keywords: coastal regions | ecosystem restoration | global mangrove watch | mangrove ecosystems | random forest

ABSTRACT

The protection and restoration of mangrove ecosystems are recognized as one of the nature-based solutions to a changing climate. They are, however, threatened by anthropogenic and natural stresses. Efforts undertaken in the past years to develop global-scale mangrove extent maps either do not provide up-to-date maps or end up missing mangrove extents at local scales. This study aims to assess the spatiotemporal changes of Ghana's mangrove extent and evaluate the key factors causing these potential changes at the country's regional level. The random forest (RF) classifier was used to develop 2015, 2021 and 2024 mangrove extent maps for Ghana and compared them with each other at the country and regional levels to assess the changes over time. With Kappa coefficients higher than 0.8, the results indicate that Ghana's mangrove extent had declined by 15.4% from 2015 (68.41 km^2) to 2024 (57.87 km^2), with the country's Western, Central and Greater Accra regions experiencing a decline in their mangrove extents. Only the Volta region experienced an increase in its mangrove extent. These significant mangrove extent changes in Ghana at the three regions, as derived from a comprehensive literature review on Ghana's mangroves, are mainly attributable to urban expansion, indiscriminate waste disposal, wildfires, uncontrolled sand and salt mining, among others. This study highlights the need for countries to have national mangrove extent maps. This will help countries to effectively achieve the Global Mangrove Alliance's goals of halting loss, doubling protection and restoring half of the world's mangroves by 2030.

1 | Introduction

Mangroves are forest ecosystems found in bays, estuaries, lagoons and along the intertidal zones of coastal areas across the world (Mukherjee et al. 2014; Thomas et al. 2017; Bunting et al. 2018). Present in the earth's tropical, subtropical and warm temperate climate zones, and mostly consisting of woody vegetation, mangroves grow in over 120 countries and territories (Spalding 2010; Dahdouh-Guebas et al. 2021). More than 75 species belonging to 17 families of mangrove trees have been identified, and they are estimated to cover about 152,604 km^2 of the earth as of 2020 (Kathiresan 2010; Richards et al. 2020; Bunting, Rosenqvist, Hilarides, Lucas, Thomas, et al. 2022).

A study conducted by Worthington et al. (2020) on the biophysical typology of the world's mangroves revealed that as of 2016, 40.5% of the world's mangroves were deltaic, 27.5% were estuarine, 21.0% were open coast and 11.0% were lagoonal. Globally, the largest (i.e., 33%) extent of mangroves is found in South-East Asia, with Indonesia home to almost 20% of the world's mangroves (Spalding and Leal 2021; Bunting, Rosenqvist, Hilarides, Lucas, and Thomas 2022). North-Central America and West-Central Africa have the second and third largest global mangrove extents with 20,962 and 19,767 km^2, respectively. Regions with the lowest proportions of mangroves are East Asia and the Middle East, with 171 and 315 km^2, respectively (Spalding and Leal 2021; Bunting et al. 2018, 2022).

Mangrove ecosystems present several socioecological benefits in the form of provisioning services, regulatory and maintenance services, and cultural services to the coastal communities living in the intertidal zones. Some of these provisioning services include non-timber vegetation products such as food, chemical substances for medicines and wood products useful for construction, fuelwood and charcoal production, increasing the economic or food security of local communities (Nfotabong-Atheull et al. 2011; Friess 2016, Ofori, Asante, et al. 2023). As part of their regulatory and maintenance services, mangroves serve as green barriers protecting coastal cities and communities against environmental hazards like hurricanes through wave attenuation (Mazda et al. 2006; Horstman et al. 2014; Friess 2016). Mangroves are known to effectively store three to four times more carbon per equivalent area than terrestrial ecosystems (Donato et al. 2011; Murdiyarso et al. 2015; Alongi 2022). They are also known to serve as a source of revenue to communities and countries through ecotourism due to their scenic beauty (Dahdouh-Guebas et al. 2020).

Amidst the several socioecological benefits mangrove ecosystems provide, the IUCN Red List for Mangrove Ecosystems report revealed that more than half of the world's mangrove ecosystems currently face the risk of collapse by 2050 whereas 16% of the world's mangrove ecosystems are also projected to be submerged by sea-level rise by 2050 (IUCN, 2024). According to the 2024 State of the World's Mangroves report (Leal and Spalding 2024), 43.3% of the global mangrove loss between 2000 and 2020 was caused by the conversion of mangroves for aquaculture, oil palm plantations and rice cultivation. To address these issues, the Global Mangrove Alliance (GMA) has introduced key goals to tackle the issue of mangrove loss. The GMA's goals are to halt loss, double protection and restore half of the world's mangroves by 2030 (Leal and Spalding 2024).

However, one challenge facing mangrove restoration is the lack of effective measures to combat the uneven regional loss rate, which exceeds 3% (Bunting, Rosenqvist, Hilarides, Lucas, and Thomas 2022), caused by a combination of anthropogenic drivers such as agriculture, aquaculture and urbanization (Goldberg et al. 2020). For instance, Southeast Asian countries such as Indonesia, Bangladesh, India, Malaysia and Vietnam record the most extensive mangrove losses due to the conversion of mangrove forest into aquaculture and agricultural lands (Daru et al. 2013; Goldberg et al. 2020). In Africa, the highest losses in mangroves are the result of land reclamation, urban expansion and the exploration of other natural capital in the West-Central region in countries such as Nigeria, Ghana and Guinea-Bissau (Spalding and Leal 2021; Goldberg et al. 2020; Ofori, Asante, et al. 2023).

Such losses in mangroves have driven the need for assessing the spatial–temporal changes in mangrove forests present at the site or subnational scales in various African countries (Mensah et al. 2015; Yevugah et al. 2017). There are a few other studies that have mapped the mangrove extent at the country level in Africa. For example, a study conducted by Liu et al. (2021) mapped the mangrove forests across West Africa using a machine learning ensemble and satellite big data. Although both site and subnational scales are relevant to evaluate the mangrove extent and/or its changes with time, it becomes difficult to compile a holistic view of mangrove ecosystem functions and services, as well as the management implications at a country-wide level. To support tropical countries possessing mangroves in effectively developing their national ecosystem accounts, which is necessary in evaluating their progress in achieving their Nationally Determined Contributions (NDCs) under the Paris Agreement, there is a need for baseline maps on national ecosystems such as mangroves (Bunting, Rosenqvist, Hilarides, Lucas, and Thomas 2022). Countries with baseline maps of their mangrove ecosystems will be able to effectively leverage these ecosystems in their NDCs towards climate change mitigation and adaptation (Ofori, Hugé, et al. 2025).

Such mangrove ecosystem baseline maps reveal environmental descriptors that characterize mangrove ecosystems, including the biomass, drivers of land change and primary areas that require restoration and conservation at the national scale (Goldberg et al. 2020; Worthington et al. 2020; Bunting, Rosenqvist, Hilarides, Lucas, and Thomas 2022). In Africa, Ghana is one of the countries in which mangrove ecosystem conservation and restoration have gained greater attention in the last decade through support from reforestation programmes funded by TerraFund for AFR100, Terraformation and the USAID (Ofori, Asante, et al. 2023). These are projects being implemented by local organizations, with support from the local communities and government institutions.

It is important to note that although efforts have been undertaken to develop historical maps of global mangrove extents to support countries' decision-making processes, many of these maps are out of date and are constrained by spatial and bioclimatic discrepancies (Ximenes et al. 2023). Moreover, these maps, such as the Global Mangrove Watch (GMW) mangrove extent maps (Bunting, Rosenqvist, Hilarides, Lucas, and Thomas 2022; Bunting, Rosenqvist, Hilarides, Lucas, Thomas, et al. 2022), are not able to effectively capture the actual extent of mangroves at a national or subnational scale. This is due to their inability to capture fine fringes and highly fragmented mangrove stands, which are often present in many coastal landscapes (Bunting, Rosenqvist, Hilarides, Lucas, and Thomas 2022). This situation limits countries possessing mangroves from being able to understand the local dynamics of their mangrove ecosystems and to further develop effective strategies to address certain challenges that may arise from mangrove ecosystem conservation and management. Hence, the need to conduct mangrove ecosystem change assessments at the national or subnational level, providing countries the opportunity to better appreciate the changes in extent taking place in their mangrove ecosystems in previous years and presenting definite contexts on relevant actions needed to be taken in response to these changes.

In the past few years, the progress in machine learning classifiers and the widespread availability of high-performance cloud computing platforms, like GEE, have opened the opportunity to conduct mangrove ecosystem mapping by using optical and radar imagery for more efficient land use/land cover mapping (Aja et al. 2022). Different studies have explored the accuracy of the different machine learning classifiers in mapping mangrove ecosystems in different regions of the world to ascertain, which is most suitable (Liu et al. 2021). Some of these machine learning classifiers include Naïve bayes (NB), support vector machine (SVM), classification and regression trees (CART), random forest (RF), gradient boosting machine (GBM) and neural network (NN) (Liu et al. 2021). In Ghana, the few studies mapping mangrove ecosystems using machine learning classifiers have often used RF and SVM (Aja et al. 2022; Ashiagbor et al. 2021).

This study seeks to develop mangrove extent maps of Ghana for the years 2015, 2021 and 2024, assessing the spatiotemporal changes of the country's mangroves, and through a literature review, identifying the factors leading to these changes at the country and its regional level. Each of the years 2015, 2021 and 2024 reflects key milestones in Ghana's environmental governance and restoration efforts. The year 2015 serves as a baseline, capturing mangrove conditions prior to the implementation of major restoration interventions in 2015. It also aligns with the adoption of the Paris Agreement and the Sustainable Development Goals (SDGs), which globally elevated the importance of ecosystem-based climate action. In 2021, which serves as the midpoint year, several large-scale restoration programmes such as TerraFund for AFR100 were actively supporting mangrove restoration across West Africa, including Ghana. The inclusion of 2024 serves as the most recent year, which helps to appreciate whether these restoration efforts have led to the increase of Ghana's mangrove extent.

As the first study to develop a retrospective mangrove extent maps for the entire country, this research will provide critical insights to key stakeholders in Ghana, including policymakers, NGOs, academic institutions and local communities, on how the country's mangrove cover has changed since the introduction of restoration initiatives.

2 | Materials and Methods

2.1 | Study Area

Ghana is a West African country lying between 07°56′47.5″ N and 001°1.392′ W and occupies a surface area of 238,533 km^2 (Ampim et al. 2021), bordered by Burkina Faso to the north, Togo to the east, Côte d'Ivoire to the west and the Gulf of Guinea to the south. Based on the climate, natural vegetation and soils of Ghana, there are seven agroecological zones, which include Coastal Savannah, Wet Evergreen, Moist Evergreen, Deciduous Forest, Transition Zone Forest, Guinea Savannah and Sudan Savannah zones. The average minimum and maximum temperatures of Ghana are 21°C and 34.3°C, respectively (Bessah et al. 2021).

The study was conducted in the coastal regions of Ghana within the Wet-Evergreen and Coastal Savannah zones, extending over a coastline of 636.24 km long. The coastal regions include the Volta, Greater Accra, Central and Western Regions. These coastal regions experience bimodal rainy seasons, with major rains occurring between March and July and a minor rainfall season occurring between September and November. Over the last three decades, the mean annual total rainfall recorded for the Wet-Evergreen and Coastal Savannah zones is 1850 and 700 mm, respectively (Bessah et al. 2021).

From the 10-m 2020 WorldCover map developed by the European Space Agency (ESA) based on Sentinel-1 and Sentinel-2 data, a land-cover map of Ghana was developed to visualize the different land cover types present in Ghana (Figure 1).

2.2 | Mapping Ghana's Mangrove Extent

To understand the past changes in Ghana's mangroves from 2015 to 2024, we used the Google Earth Engine (GEE) platform as our mapping workflow, adapting the methodology developed by Barenblitt and Fatoyinbo (2020) in mapping Guyana's mangroves. More details of this methodology are provided in the following sections.

2.2.1 | Satellite Data Acquisition and Preprocessing

Before downloading the required satellite data for processing, eight grids of the same extent (12,445 km^2) overlayed across the coastal regions of Ghana were created in QGIS 3.16.14 and exported into the GEE platform. Because the study was conducted on a wide coastline of 636.24 km long, there was a need to create multiple grids over the entire coastline. This will help increase the accuracy of the image analysis as opposed to analysing a large area with a potential risk of recording higher classification errors. Based on the extent of each grid, a composite of Landsat 8 images was extracted with Landsat 8 Surface Reflectance Tier 1 (LANDSAT/LC08/C01/T1_SR) image collection used for the year 2021, whereas Landsat 8 Level 2, Collection 2, Tier 1 (LANDSAT/LC08/C02/T1_L2) image collection was used for the years 2015 and 2024. During the mapping of the years 2015 and 2024, Landsat 8 Surface Reflectance was no longer available; thus, we used the new collection (LANDSAT/LC08/C02/T1_L2) to map the mangroves of 2015 and 2024. The 'pixel_qa' or 'QA_PIXEL' band was used in performing cloud-masking of the acquired Landsat images.

The start and end dates used to filter the Landsat images to the extent of the grids were the first and last days of the year of interest (e.g., 1 January 2021 to 31 December 2021). Spectral indices such as the Normalized Difference Mangrove Index (NDVI) using Bands 4 and 5 and the Modified Normalized Difference Water Index (MNDWI) using Bands 3 and 6 were created from

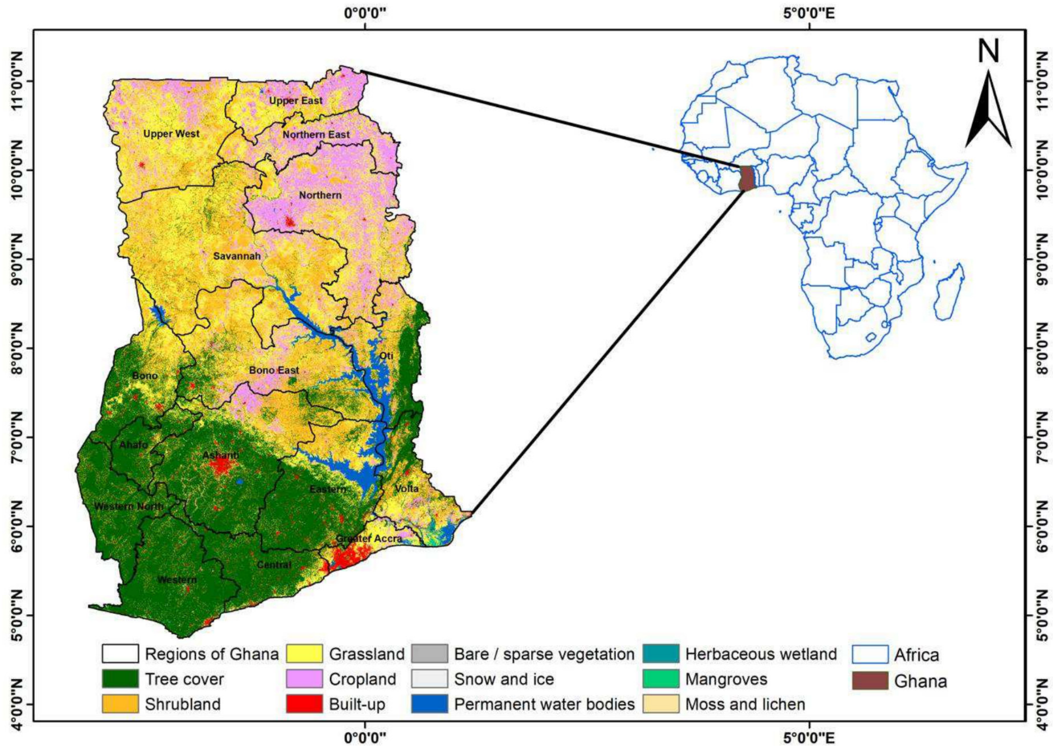

FIGURE 1 | A 2021 landcover map of Ghana. Map data were extracted from the 2021 WorldCover map developed and validated based on Sentinel-1 and Sentinel-2 data (European Space Agency [https://esa-worldcover.org/en]; Zanaga et al. 2022).

the Landsat images. Because mangroves in Ghana do not occur at higher elevations (> 60 m), the Shuttle Radar Topography Mission (SRTM) data were used to mask out areas of the Landsat images with much higher elevations. Pixels with an NDVI below 0.25 and an MNDWI below −0.50 were also masked out to exclude them from the analysis (Barenblitt and Fatoyinbo 2020). Excluding low-NDVI pixels (< 0.25) helps eliminate nonvegetated or sparsely vegetated areas that are unlikely to contain mangroves, whereas excluding pixels with low MNDWI (≤ 0.50) helps remove inland areas or uplands where mangroves are ecologically unlikely. A final composite image (Figure 2) for each grid was generated after applying all the masks to the Landsat images.

2.2.2 | Model Creation and Testing

A RF classifier was used in image classification due to its ability to use multiple decision trees to improve the accuracy and robustness of the classification model (Liu et al. 2021). Spectral indices such as Simple Ratio (Band 5 [near infrared]/Band 4 [visible red]), the ratio between Band 5 (visible red) and Band 6 (short wavelength infrared) and the ratio between Band 4 (near-infrared) and Band 6 (short wavelength infrared) were included in building the model for each grid to be classified. Training data (points and polygons) ranging from 100 to 250 each for mangrove and nonmangrove classes were created and merged. The training data were split into two, where 80% was used for training the model and 20% was used for testing the model. The spectral indices (and bands) included in the model were 'Band 5', 'Band 6', 'Band 4', 'NDVI', 'Modified Normalized Difference Water Index (MNDWI)', 'Simple Ratio (SR)' and 'Green Chlorophyll Vegetation Index (GCVI)' (Barenblitt and Fatoyinbo 2020). Before classification, the model's accuracy was tested against itself, and if it was 80% or more, it was found satisfactory for classification. In each assessment year, models were created for five of the grids (Grids 4, 9, 14, 18 and 23), which were used to classify the other three neighbouring grids (Grids 10, 19 and 24). The model accuracies for the five models ranged from 81% to 99%.

2.2.3 | Classification

The classification was done for each grid's processed satellite image per assessment year using a model with an acceptable accuracy measure (81%–99%). Classification was done using two classes, mangrove and nonmangrove. To reduce noise in the classified images, a mask function was used to exclude unconnected pixels in the classified images, considering the connected nature of mangrove tree communities.

2.2.4 | Postprocessing

All eight classified images for each grid per assessment year were merged and clipped to the extent of Ghana's coastal regions using QGIS 3.34 (QGIS Development Team 2023). Because mangroves are found in four coastal regions of Ghana (Western, Central, Greater Accra and Volta regions), a mangrove extent map was created for each coastal region for comparative analysis. The mangrove areal extent of the entire country and the coastal regions for each year (2015, 2021 and 2024) was also calculated for comparative analysis.

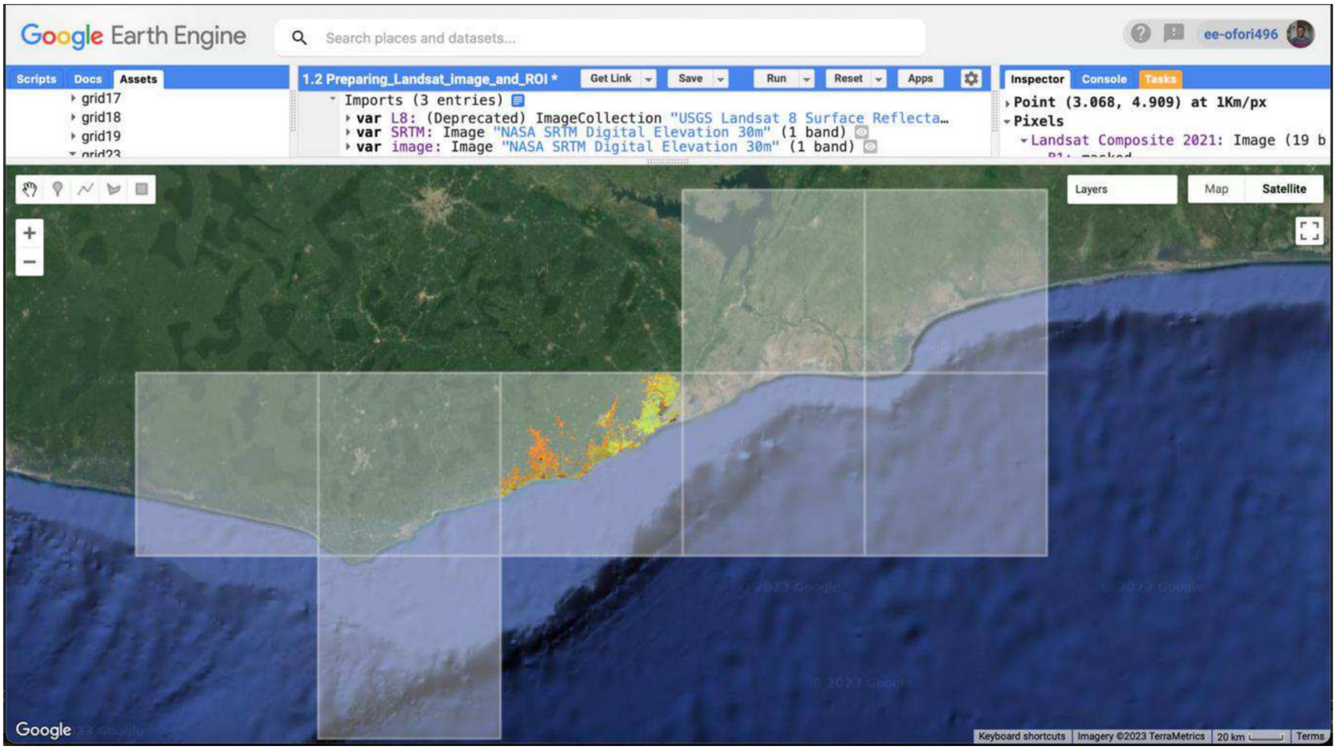

FIGURE 2 | An image showing the coastal extent of Ghana, with overlaying grids used for data acquisition and preprocessing of Landsat data for classification in Google Earth Engine. The grid with orange-coloured patches inside it represents a preprocessed Landsat 8 image. Image credits: Map data 2022 Google Imagery 2022 TerraMetrics.

2.2.5 | Classification Accuracy Assessment

To assess the accuracy of the classified images for each assessment year, a total of 450 random points (300 for mangrove and 150 for nonmangrove classes) were created across the entire coastal extent layer of Ghana. These random points for each assessment year were imported into Google Earth Pro 7.3.6.10201 (Google 2023), where the true feature class (mangrove or nonmangrove) on the ground was collected using the available historic mosaic imageries (Landsat/Copernicus/Airbus/Maxar technologies). In some sites of the Volta and Western regions of Ghana, where we were unsure of the presence of mangroves, field visits were conducted during and after the image classification period to verify the presence of mangroves. A confusion matrix was developed and used to calculate the Kappa indices of agreement: producer accuracy, user accuracy and overall accuracy of classification for each classified image. An accuracy value above 0.8 represents almost perfect agreement, values between 0.6 and 0.8 as strong agreement, values between 0.4 and 0.6 as moderate agreement, values between 0.2 and 0.4 as fair agreement and values between 0 and 0.2 as slight association (Landis and Koch 1977).

The quantity and exchange components of the differences' method developed by Pontius and Millones (2011) was also used to assess classification accuracy because the popular Kappa indices of agreement have been considered less efficient. Quantity and exchange errors were calculated and represented in bar charts using the PontiusMatrix42. Quantity and exchange disagreement describes the amount of difference between the reference map and a classified comparison map that is due to the less-than-perfect match in the proportions of the landuse/landcover categories. For quantity and exchange errors, a miss of Category X is a place that is Category X on the ground and not Category X on the map, whereas a false alarm of Category X is a place that is Category X on the map and not Category X on the ground. A hit of Category X occurs when Category X on the ground is also Category X on the map (Ofori, Arachchilage, et al. 2022).

2.3 | Literature Review

To identify the activities driving mangrove cover changes in the four coastal regions (Western, Central, Greater Accra and Volta) of Ghana from 2015 to 2024, we used the Systematic Evidence Syntheses method to conduct a systematic review on studies that focused on activities contributing to Ghana's mangrove changes at various mangrove ecosystems in the country. Using the search key, 'Ghana AND Mangrove', we accessed 18 studies from Google Scholar, of which five were identified to be relevant after reviewing their titles and abstracts.

3 | Results

3.1 | Ghana's Mangrove Extent Changes

The application of the RF classifier for land use/land cover classification on the preprocessed high-resolution Landsat 8 satellite images yielded Ghana's mangrove extent maps for the years 2015, 2021 and 2024. Out of these maps, we produced maps for

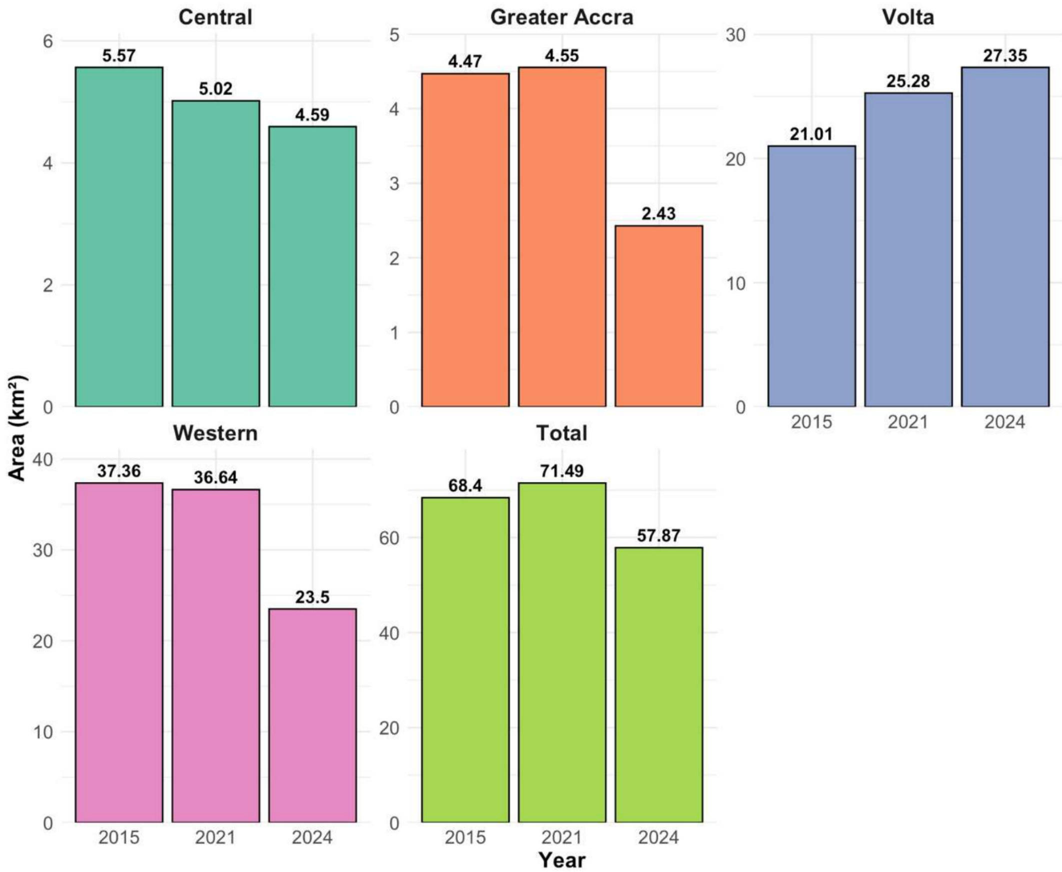

FIGURE 3 | Faceted bar charts showing the changes in Ghana's mangrove extent from 2015 to 2024 at the national (total) and regional levels (Central, Greater Accra, Volta and Western regions).

the country's four coastal regions (Figure 4). Ghana's mangrove extent increased from 68.41 km^2 in 2015 to 71.49 km^2 in 2021, indicating a 4.5% increase, and declined to 57.87 km^2 in 2024, indicating a 19.1% decrease. From 2015 to 2024, Ghana's mangroves experienced an overall decrease in extent by 15% (Figure 3).

For Ghana's coastal regions, the Western region recorded the highest mangrove extent for the years 2015 (37.36 km^2) and 2021 (36.64 km^2), whereas the Volta region recorded the highest mangrove extent for the year 2024 (27.35 km^2). The Greater Accra region recorded the least mangrove extent across all the assessment years, recording a 45.6% decline from 4.47 km^2 in 2015 to 2.43 km^2 in 2024. The Western region experienced a decline in mangrove extent by 37.1% from 37.36 km^2 in 2015 to 23.50 km^2 in 2024 (Figures 3 and 4). The Central region also recorded a decline in its mangrove extent by 17.4% from 5.57 km^2 in 2015 to 4.60 km^2 in 2024. Volta was the only region that experienced an increase in its mangrove extent, recording a 30.2% increase from 21.01 km^2 in 2015 to 27.35 km^2 in 2024.

3.2 | Accuracy Assessment

A classification accuracy assessment conducted using Google Earth Pro's 2015, 2021 and 2024 aerial images resulted in a confusion matrix with overall accuracies of 83.77% for 2015, 89.78% for 2021 and 82.22% for 2024, with the year 2021 recording the highest overall accuracy. For user accuracies of mangroves, 75.67%, 85.33% and 73.33% were recorded for the years 2015, 2021 and 2024. The user accuracies recorded for nonmangroves in the years 2015, 2021 and 2024 were 100%, 98.67% and 100%, respectively. For producer accuracies of mangroves, 100%, 99.22% and 100% were recorded for the years 2015, 2021 and 2024. The producer accuracies recorded for nonmangroves in the years 2015, 2021 and 2024 were 67.27%, 77.08% and 65.22%, respectively.

Assessment of quantity and exchange allocation disagreement was also done for mangroves and nonmangroves for the years 2015, 2021 and 2024. For the year 2015, nonmangroves recorded a hit of 150 out of 150 and a miss quantity error of 73, whereas mangroves recorded a hit of 227 out of 300, with a false alarm quantity error of 73. For the year 2021, nonmangroves recorded a hit of 150 out of 150 and a miss quantity error of 44, whereas mangroves recorded a hit of 256 out of 300, with a false alarm quantity error of 44. For the year 2024, nonmangroves recorded a hit of 150 out of 150 and a miss quantity error of 80, whereas mangroves recorded a hit of 220 out of 300, with a false alarm quantity error of 80 (Figure 5).

3.3 | Drivers of Ghana's Mangrove Cover Changes

A literature review of selected mangrove studies examined changes in Ghana's mangrove cover across different coastal sites. The review revealed that urbanization, salt production, agricultural activities, sea erosion and tidal inundation were the major contributors to mangrove loss in Ghana (Table 1).

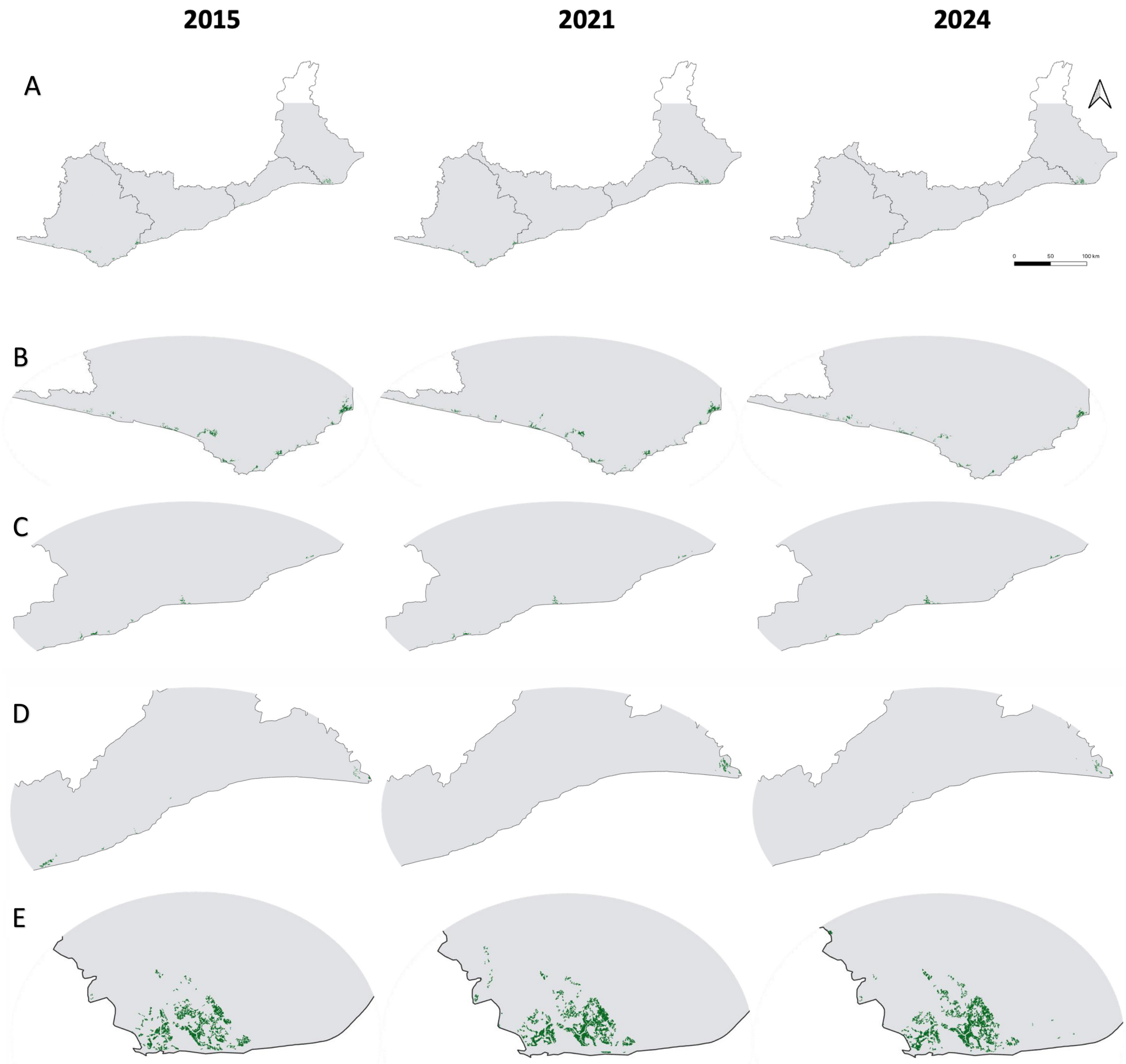

FIGURE 4 | The 2015, 2021 and 2024 mangrove extent maps of the entire coast of Ghana (A) and its Western (B), Central (C), Greater Accra (D) and Volta (E) regional mangrove extents. Green represents mangroves, and grey represents nonmangroves.

Out of the six studies that were relevant for this review, two focused on mangrove sites in the Western region, one focused on mangrove sites in the Greater Accra region and the remaining two focused on the mangrove sites in the Volta region. None of the studies focused on the mangrove sites in the Central region of Ghana.

4 | Discussion

4.1 | Performance of Random Forest Classifier in Mangrove Mapping

Using the Kappa Indices of Agreement, it was identified that all the classified maps for the years 2015, 2021 and 2024 scored a Kappa coefficient higher than 0.8. This indicates a higher agreement between the classified image and the reference data, and the higher efficiency of our RF models used to classify Ghana's mangrove extents in the different years. The use of the quantity and exchange components of differences methods provided further details on the classification accuracy by providing the number of mangroves that were wrongly classified as non-mangroves and vice versa for each assessment year. It was identified that the RF models rightly classified all nonmangroves across the assessment years, resulting in zero false alarm quantity errors for nonmangroves, meaning what was classified as nonmangroves on the map were truly nonmangroves on the ground. However, this was not the case for mangroves, which recorded false alarm quantity errors across the years, that is, some pixels classified as mangroves on the map were rather nonmangroves on the ground. The major causes of these quantity errors include

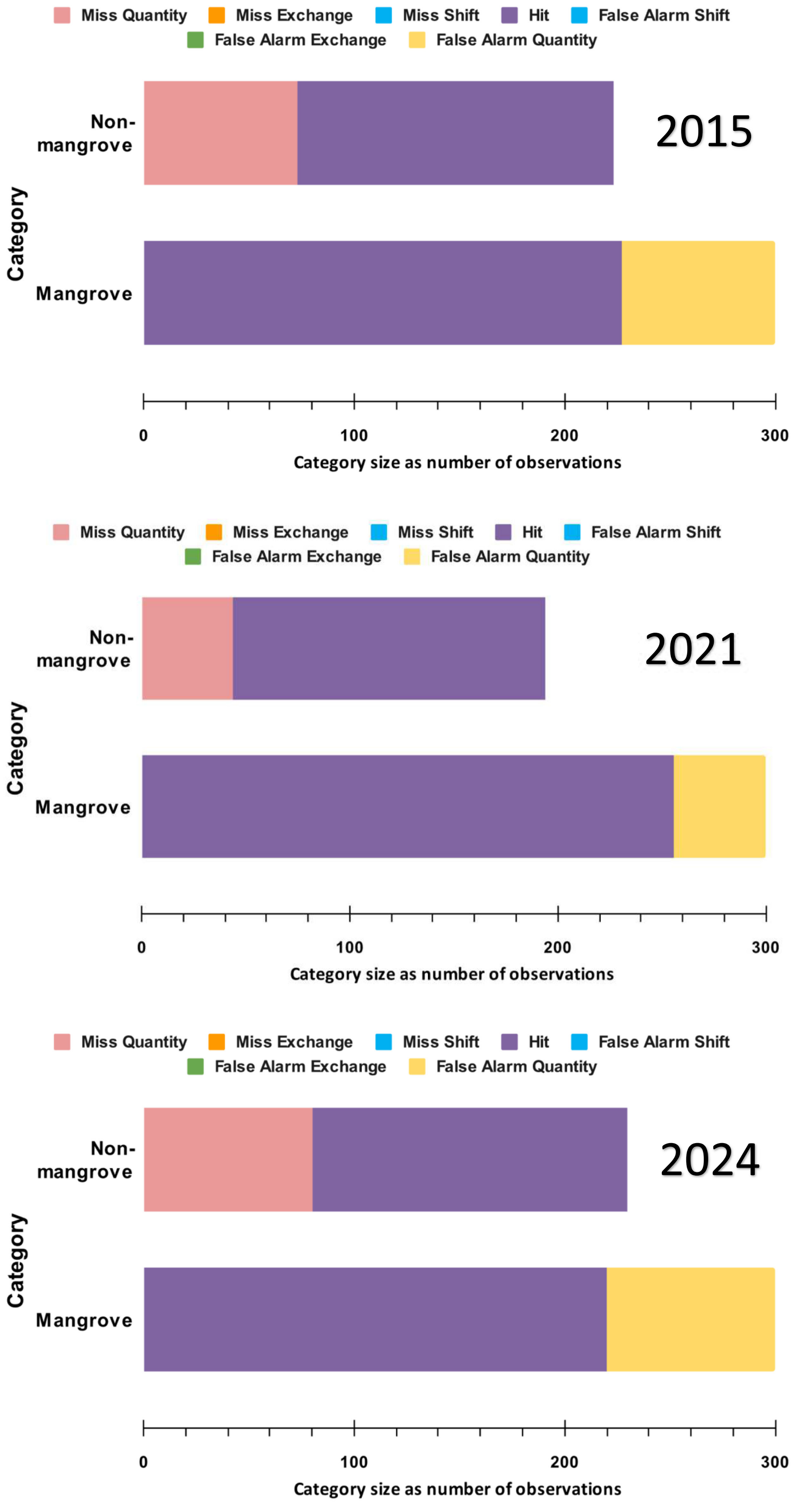

FIGURE 5 | Legend on next page.

FIGURE 5 | Quantity and exchange classification errors recorded for nonmangroves and mangroves classification for the years 2015, 2021 and 2024. The magnitude of each quantity and exchange error recorded during the classification of nonmangroves and mangroves is indicated on the *x* axis as 'category size as number of observations'. A miss of Category X is a place that is Category X on the ground and not Category X on the map, whereas a false alarm of Category X is a place that is Category X on the map and not Category X on the ground. A hit of Category X occurs when Category X on the ground is correctly classified as Category X on the map.

TABLE 1 | Drivers of mangrove cover changes in Ghana's four coastal regions.

Drivers of Ghana's mangrove cover change			
Western region	**Central region**	**Greater Accra region**	**Volta region**
Kankam et al. (2022) Site/location: Essiama, Sanzule, and Atuabo Drivers: Urbanization Timeline: 2008–2018	NA	Adade et al. (n.d.) Site/location: Songhor Ramsar site Drivers: Salt production Timeline: 1990–2015	Peters and Kusimi (2023) Site/location: Keta Ramsar site Drivers: Urbanization, farming, sea erosion and tidal inundation Timeline: 1991–2018
Aja et al. (2022) Site/location: Anlo Beach Wetland complex Drivers: Urbanization, agricultural activities Timeline: 2009–2019	NA	NA	Duku et al. (2021) Site/location: Keta Ramsar site Drivers: Conversion to marsh/grassland and agricultural land Timeline: 1991–2020

coconut plantations located in the Western region that present similar traits to mangrove ecosystems by possessing a closed canopy-like structure and being inundated with lagoon/estuary water during high tides. In some areas, these coconut plantations and mangroves were mixed within the same area, forcing the models to classify some of these coconut plantations as mangroves.

4.2 | Spatiotemporal Changes in Ghana's Mangrove Extent (2015–2024)

Using the RF classifier with different classification models, this study has assessed the extent of mangroves on the entire coast of Ghana and in its four coastal regions for the years 2015, 2021 and 2024. The 15.4% decrease in Ghana's mangrove extent and its respective regional (Central, Greater Accra and Western) extent declines recorded in this study from 2015 to 2024 can be attributed to a number of factors. First, there has been relatively higher coastal development occurring in the Central and Greater Accra regions of Ghana since the 19th century. For example, infrastructural development has already taken place in coastal areas of the Central region, which once hosted the capital city of Ghana (Cape Coast) until 1877, and the Greater Accra region, which now hosts the capital city of Ghana (Accra) since the colonial era. The Greater Accra region, located on Ghana's east coast, hosts the biggest port in the country, that is, Tema Port. The reported increased coastal development or urbanization in the Greater Accra and Central regions is confirmed by the 2021 population census of Ghana, which recorded that the percentages of the urban population in the Greater Accra, Central and Western regions were 91.7%, 57.9% and 51.6%, respectively, revealing a major population of these regions inhabiting the coastal capital cities of Accra, Cape Coast and Takoradi, respectively (Ghana Statistical Service 2021). Between the years 2010 to 2021, the Greater Accra and Central regions of Ghana recorded the highest population densities, recording 445.5 and 67 persons/km^2 in 2021, respectively.

In the Greater Accra region, lagoons have been filled with solid and liquid waste (Ofori, Asante, et al. 2023), and mushy coastal areas have been reclaimed for human settlement, causing a 17.4% decline in the region's mangrove extent. For example, the Sakumo Ramsar site, which used to possess the largest mangrove extent in the region, has experienced a major increase in real estate development at the expense of the entire ecosystem possessing mangroves (Danso et al. 2021). The Densu Delta and the Songhor Ramsar sites are equally facing pressure from infrastructural development, particularly driven by the region's rapid population growth (Frank et al. 2019). The effects of population growth in the coastal regions of Ghana on mangroves have also been emphasized by Aheto et al. (2016) and Nortey et al. (2016). Moreover, the Songhor Ramsar Site is known to face mangrove destruction through factors such as indiscriminate waste disposal, wildfires and shoreline recession through sand winning, agricultural activities, overgrazing, overexploitation of mangroves, uncontrolled sand and salt mining (Adade et al. n.d.; Fianko and Dodd 2019; Ofori, Asante, et al. 2023).

The Western region has experienced several mangrove restoration efforts in the last decade. Major of these mangrove restoration and protection activities have taken place in the Shama, Ahanta-West, Ellembelle and Jomoro districts of the Western region (USFS-IP 2018). Amidst these efforts, the region has experienced a decline in its mangrove extent by 37.1% from 2015 to 2024, with a major portion of this decline taking place after 2021. Such restoration activities usually should lead to an increase in mangrove extent in the Western region and not as we see in this study. This implies that mangrove restoration activities in these areas may not be effective enough with high survival rates (Zimmer et al. 2022). Moreover, because no study has been conducted to assess the success rate of any of these mangrove restoration projects, it is a challenge to assess the contribution of mangrove restoration projects to Ghana's mangrove extent. The decline in the region's mangrove extent is also attributed to urbanization, oil mining and agricultural activities such as coconut plantations, resulting in dieback and clearing of mangroves, respectively (Aja et al. 2022; Kankam et al. 2022; Asante et al. 2023; Ofori, Asante, et al. 2023).

The Volta region has experienced an increase in its mangrove extent in the last decade due to mangrove restoration and conservation efforts. The region is known for its large-scale reforestation projects implemented for various reasons. For example, there are records of large-scale carbon projects currently being implemented, with potential ones in the pipeline. There are also reforestation projects implemented by organizations like Friends of the Earth-Ghana, A Rocha Ghana, Seawater Solutions and Regenerative Development of Anlo Wetlands (ReDAW), towards biodiversity conservation, ecological restoration and socioeconomic development. The Wildlife Division of the Forestry Commission of Ghana is also known for its mandate to manage the Keta-Lagoon Complex Ramsar site through its monitoring, protection, restoration and research activities. Although studies have reported the loss of mangroves in the Keta-Lagoon Complex Ramsar site (Appeaning Addo et al. 2018; Duku et al. 2021; Peters and Kusimi 2023) due to overharvesting of mangroves, urbanization, agricultural activities, sea erosion and tidal inundation, the economic benefits from the harvesting of mangroves for firewood production have promoted increased planting of mangroves (mainly *Rhizophora racemosa* G. Mey [Red mangrove], *Avicennia germinans* [L.] Stearn) by individuals in some major firewood-producing communities such as Salo, Agbortoe and Anyanui located within the Keta-Lagoon Complex Ramsar site (Ofori, Asante, et al. 2023; Sekey et al. 2023). The development of these mangrove plantations has, however, increased monospecific (*Rhizophora racemosa*) mangrove stands with limited ecological functions and benefits (Mukherjee et al. 2014; Ofori, Asante, et al. 2023).

The loss of Ghana's mangroves in the Western, Central and Greater Accra regions, primarily driven by human activities such as overexploitation of mangroves, urbanization, salt production, indiscriminate waste disposal, agricultural activities and sand mining, presents a significant ecological challenge. These coastal forests serve as critical habitats for biodiversity, support local livelihoods and provide essential ecosystem services, including coastal protection and carbon sequestration (Ofori, Hugé, et al. 2025). However, due to increasing pressure from anthropogenic activities, mangrove degradation continues at an alarming rate. Despite their ecological and economic importance, Ghana has yet to implement comprehensive management policies dedicated to the protection and sustainable use of its mangrove ecosystems (Ofori, Asante, et al. 2023). The absence of a national framework for mangrove conservation leaves these vital ecosystems vulnerable to unchecked exploitation and degradation. Establishing clear policies, such as the designation of protected areas, community-based conservation initiatives and sustainable harvesting regulations, would be crucial in mitigating further loss and ensuring the long-term viability of Ghana's mangrove ecosystems. Without immediate policy interventions, the continued decline of mangroves could lead to severe environmental consequences, including increased coastal erosion, loss of biodiversity and reduced resilience to climate change impacts.

4.3 | Policy Gaps and the Need for a National Mangrove Restoration Strategy

The government of Ghana should prioritize the development of a comprehensive mangrove restoration action plan aimed at implementing and scaling up community-led mangrove restoration initiatives in the Western, Central and Greater Accra regions. This plan should be informed by lessons learned from existing restoration efforts in the Volta region, where community participation has played a crucial role in the success of conservation projects. A study by Ofori, Hugé, et al. (2025), which reviewed the NDCs of African countries, found that Ghana's 2021 NDCs did not include any specific commitments or actions related to the protection and restoration of its mangrove ecosystems. This omission highlights a critical gap in the country's climate adaptation and mitigation strategies, given the vital role that mangroves play in carbon sequestration, coastal protection and biodiversity conservation.

Furthermore, it has been observed that most ongoing mangrove restoration initiatives in Ghana are not government-led but rather driven by nongovernmental organizations (NGOs) with local community groups. These efforts have been largely concentrated in the Volta region, followed by the Western region, despite evidence from this study indicating that the Western region has experienced a significant decline in its mangrove cover over the past decade. The lack of government leadership and coordinated policy support has resulted in fragmented and regionally imbalanced restoration efforts. To address this, the government must integrate mangrove conservation into national climate and biodiversity strategies, ensuring that restoration activities are evenly distributed across all affected regions. A well-structured national action plan should include clear objectives, funding mechanisms, stakeholder engagement strategies and a long-term monitoring framework to track progress and measure the effectiveness of restoration interventions. It should also promote sustainable mangrove use, ensuring that restoration efforts align with local economic activities such as ecotourism, sustainable fishing and responsible harvesting of mangrove resources. By taking a proactive approach, the government can enhance ecosystem resilience, strengthen climate adaptation efforts and secure the long-term sustainability of Ghana's coastal communities.

4.4 | Limitations of Global Mangrove Datasets and Implications for Local Mapping

Although we find the GMW maps to be relevant in understanding the changes in Ghana's mangrove extent from 1996 to 2020, it is important to mention that, like all global maps, it bears the limitation of having classification errors. Although these maps

FIGURE 6 | A visual comparison between the mangrove extent of an area in the Volta region of Ghana (A) as captured in the 2020 GMW map (B) and that of the present study's 2021 mangrove extent map (C). The black areas in (B) and (C) are areas classified as mangroves, whereas the white areas in (C) are areas classified as nonmangroves. From the 2021 satellite image of the area of interest (A), it can be deduced that some nonmangrove areas (having the same colour as mangroves) are falsely classified as mangroves in the 2020 GMW map (B). Image source: Map data 2022 Google Imagery 2022 TerraMetrics.

have undergone validation using published records of mangrove presence, conducting comprehensive global accuracy assessments poses challenges that hinder the quantitative comparison of performance across maps. Additionally, the accuracy of each map is impacted by spatial heterogeneity, where the quality of regional mapping varies, and this variation is not adequately captured by a global statistic of accuracy alone (Ximenes et al. 2023). Conducting an assessment on the 2020 GMW mangrove extent layer of Ghana produced by Bunting, Rosenqvist, Hilarides, Lucas, Thomas, et al. (2022) revealed that some areas that were grasses on the ground (as identified from ground-truthing) were wrongly classified as mangroves (Figure 6). From the Landsat satellite imagery, one would easily identify coastal grassland as mangroves if ground-truthing is not further undertaken to control classification. It is therefore possible that such classification errors were recorded in the mangrove maps of previous years and in other coastal regions of Ghana and beyond.

Although global mangrove extent datasets serve as valuable resources for informing national policies and decision-making processes (Bunting et al. 2018), they come with several limitations that can impact their accuracy and applicability. One major limitation is their inability to capture fine fringes and highly fragmented mangrove stands, which are often present in many coastal landscapes (Bunting, Rosenqvist, Hilarides, Lucas, and Thomas 2022). This issue arises due to the spatial resolution of global datasets, which may not be sufficiently detailed to detect small or sparsely distributed mangrove patches. As a result, critical mangrove habitats may be underrepresented or omitted entirely, affecting conservation planning and management efforts.

Additionally, global datasets are more prone to classification errors compared to regional or site-specific datasets. In many cases, they tend to misclassify nonmangrove areas as mangroves, leading to an overestimation of mangrove coverage. This higher classification error can cause discrepancies in national and local mangrove extent estimates, influencing restoration priorities and policy decisions. Such inaccuracies can result in either a false gain or a false loss in reported mangrove extent, which can mislead stakeholders relying on these datasets for environmental assessments and climate adaptation planning.

Another challenge is the inconsistency between different studies, as various global, regional and national datasets often produce conflicting estimates of mangrove extent (Otero et al. 2016; Ximenes et al. 2023). This variability makes it difficult for researchers, policymakers and conservationists to determine which dataset is the most reliable for a given context. For example, Ghana's mangrove extent estimates differ significantly depending on the dataset used. The 2015 global mangrove extent map estimated Ghana's mangrove cover at 182.55 km^2 (Bunting, Rosenqvist, Hilarides, Lucas, Thomas, et al. 2022), whereas the 2017 West African mangrove extent dataset estimated it at 120.34 km^2 (Liu et al. 2021).

Furthermore, the results of this study found Ghana's 2015 mangrove extent to be 68.41 km^2, which is significantly lower than both previous estimates. Compared to Bunting, Rosenqvist, Hilarides, Lucas, Thomas, et al. (2022), this study's estimate represents nearly half the recorded extent, and when compared to Liu et al. (2021), it is almost a third of the reported extent for 2017. These discrepancies highlight the importance of using high-resolution, locally validated datasets that are tailored to specific regions to ensure accurate and reliable mangrove extent measurements. To improve the precision of mangrove mapping, there is a need to integrate remote sensing approaches with ground-truthing efforts and to develop standardized methodologies that align global, regional and site-specific assessments.

4.5 | Limitations of the Study

The study primarily used Landsat 8 imagery (30-m spatial resolution), which may not be able to detect small or narrow mangrove patches, leading to an underestimation of mangrove extent. Higher resolution datasets (e.g., Sentinel-2 or UAV-based data) could have provided more detailed mapping of narrow mangrove patches. Moreover, we did not conduct extensive ground-truthing across all assessment years. Instead, we relied on experience from previous field verification in specific sites of the Volta, Greater Accra and Western regions. This introduced classification errors, particularly in areas where mangrove cover is fragmented or where spectral signatures are similar to other vegetation types. Lastly, this study identified only five relevant studies on Ghana's mangrove cover changes from Google Scholar. The limited number of reviewed sources may have excluded key local or grey literature that could provide additional insights into the drivers of mangrove cover change.

5 | Conclusions

Our study presents a country-wide mangrove extent map for Ghana, with its spatiotemporal changes, and makes comparisons between its mangrove extents located in the four coastal regions of Ghana. The study revealed a 15.4% decrease in Ghana's mangrove extent from 2015 to 2024. Such a decrease in the country's mangrove extent informs of the need to effectively tackle the root causes of mangrove ecosystem loss in Ghana. Global mangrove ecosystem maps may be relevant for understanding the status of mangrove ecosystems at the global scale, but when it comes to country-level analysis of mangrove ecosystem dynamics, countries are encouraged to develop their maps for effective decision-making.

To support countries in mapping their full mangrove extent and analysing spatiotemporal changes, this study proposes a scalable methodology that can be adapted to country-specific contexts. The gridding approach employed facilitates the development of more accurate and consistent maps using the RF classifier. Furthermore, we recommend the use of the quantity and exchange components of differences method introduced by Pontius and Millones (2011) for classification accuracy assessment, as it provides a more diagnostic and interpretable measure of classification performance than traditional metrics.

Different dynamics of mangrove extent changes are also seen in the coastal regions, where the Volta region records an increase in its mangrove extent from 2015 to 2024, whereas the Western, Central and Greater Accra regions record a decrease in their mangrove extent. Factors such as urbanization, indiscriminate waste disposal and agricultural activities accompanied by an increase in population density, have resulted in the decline of mangrove ecosystems in the Western, Central and Greater Accra regions from 2015 to 2024. The increase in mangrove extent in the Volta region is best explained by restoration projects undertaken by NGOs with local communities. We expect that the findings in this study will serve as a key source of data for the scientific community, NGOs, governmental organizations and local communities, driving the need for a comprehensive mangrove ecosystem action plan, which will promote effective decision-making and actions towards mangrove ecosystem conservation and restoration across the four coastal regions of Ghana.

Author Contributions

Samuel A. Ofori: conceptualization, investigation, formal analysis, methodology, software, validation, visualization, writing – original draft preparation. **Frederick Asante:** investigation, methodology, validation, writing – review and editing. **Tessia A. B. Boateng:** writing – review and editing. **Alvin Adu-Asare:** methodology, software, visualization. **Farid Dahdouh-Guebas:** supervision, validation, writing – reviewing and editing.

Acknowledgements

The authors thank Abigail Barenblitt and NASA–Applied Remote Sensing Training Program for their publicly available tutorial and GEE script on mapping mangrove extent, which was adapted for this study.

Ethics Statement

The authors have nothing to report.

Conflicts of Interest

The authors declare no conflicts of interest.

Data Availability Statement

The data that support the findings of this study are openly available in Zenodo (at 10.5281/zenodo.15394114).

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