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Mapping spatio-temporal changes in mangroves cover and projection in 2050 of their future state in Benin

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Photo 1.
Picture of mangroves in Benin, village of Togbin-Daho, Municipality of Abomey-Calavi.
Photo K. V. Salako, 2018.

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RÉSUMÉ

Cartographie de l'évolution spatio-temporelle des mangroves au Bénin et projection de leur état futur à l'horizon 2050

Les mangroves sont des écosystèmes précieux qui apportent à l'humanité des bénéfices socio-économiques, environnementaux et culturels essentiels. Cependant, elles connaissent un déclin alarmant en raison des activités humaines et des risques naturels. L'évaluation de leur dynamique spatio-temporelle est indispensable pour leur suivi et pour guider leur gestion afin d'en assurer la pérennité. Nous avons évalué la dynamique spatio-temporelle des mangroves et établi leurs tendances prévisionnelles en utilisant des techniques de télédétection et l'analyse en chaîne markovienne. Des images Landsat TM/ETM+/OLI (pour 1988, 2001 et 2019) ont été obtenues, traitées, classées et analysées à l'aide de techniques de télédétection et de SIG. Les changements observés au cours de ces périodes (1988-2001, 2001-2019 et 1988-2019) ont été utilisés pour prédire les tendances à l'horizon 2050, à l'aide de l'analyse en chaîne markovienne. Les résultats montrent que la zone de mangrove étudiée, qui occupait 5205,24 ha en 1988, a diminué de 62,07 % entre 1988 et 2001 mais a augmenté de 18,84 % de 2001 à 2019. Cette augmentation est attribuée au renforcement des efforts de restauration de la mangrove. Les mangroves ont été principalement converties en prairies (52,35 % en 1988-2001 et 7,31 % en 2001-2019) et en d'autres types de végétation (17,57 % en 1988-2001 et 27,05 % en 2001-2019). Leur déclin a été plus important dans les communes d'Abomey-Calavi et de Ouidah, lesquelles nécessitent donc des efforts de conservation plus importants. Notre projection basée sur l'analyse en chaîne markovienne suggère que ces mangroves continueront à décliner, mais lentement. Cette étude fournit des informations essentielles pour guider les actions de conservation des mangroves à prévoir dans la zone d'étude.

Mots-clés : écosystèmes côtiers, dynamique, télédétection, chaîne de Markov, Bénin.

ABSTRACT

Mapping spatio-temporal changes in mangroves cover and projection in 2050 of their future state in Benin

Mangroves are precious ecosystems that provide vital socio-economic, environmental and cultural benefits to humanity. However, they are declining alarmingly due to human activities and natural hazards. Assessment of their spatio-temporal dynamics is essential to monitor these ecosystems and guide their management to ensure their sustainability. We assessed the spatio-temporal dynamics of mangroves and predicted their future trends using remote sensing techniques and Markovian chain analysis. Landsat images TM/ETM+/OLI (for 1988, 2001 and 2019) were obtained, processed, classified and analyzed using remote sensing techniques and GIS. The changes observed during these periods (1988-2001, 2001-2019 and 1988-2019) were used to predict future trends up to 2050, using Markovian chain analysis. The results showed that the mangrove area studied, which occupied 5205.24 ha in 1988, declined by 62.07% between 1988 and 2001 but increased by 18.84% from 2001 to 2019. This increase is attributed to strengthened mangrove restoration efforts. The mangroves had mainly been converted into grassland (52.35% in 1988-2001 and 7.31% in 2001-2019) and other vegetation types (17.57% in 1988-2001 and 27.05% in 2001-2019). Their decline was most severe in the municipalities of Abomey-Calavi and Ouidah, which therefore require greater conservation efforts. Our projection based on Markovian chain analysis suggests that these mangroves will continue to decline, but slowly. This study provides essential information to guide future mangrove conservation action in the study area.

Keywords: coastal ecosystems, dynamics, remote sensing, Markov chain, Benin.

RESUMEN

Cartografía de los cambios espacio-temporales de la cobertura de los manglares y proyección de su estado futuro al año 2050 en Benín

Los manglares son ecosistemas preciosos que proporcionan beneficios socioeconómicos, medioambientales y culturales vitales para la humanidad. Sin embargo, están disminuyendo de forma alarmante debido a las actividades humanas y a los peligros naturales. La evaluación de la dinámica espacio-temporal es esencial para su seguimiento y para orientar su gestión sostenible. Evaluamos la dinámica espacio-temporal de los manglares y predecimos sus tendencias futuras utilizando técnicas de teledetección y análisis de cadenas de Markov. Se obtuvieron, procesaron, clasificaron y analizaron imágenes Landsat TM/ETM+/OLI (de 1988, 2001 y 2019) mediante técnicas de teledetección y SIG. Los cambios observados durante estos periodos (1988-2001, 2001-2019 y 1988-2019) se utilizaron para predecir las tendencias futuras en el horizonte 2050 mediante un análisis de cadenas de Markov. Los resultados mostraron que los manglares, que ocupaban 5 205,24 ha en 1988 en la zona de estudio, experimentaron un descenso del 62,07 % entre 1988 y 2001, pero un aumento del 18,84 % entre 2001 y 2019. Esto último se atribuye al incremento de los esfuerzos de restauración de los manglares. Los manglares se convirtieron principalmente en praderas (52,35 % en 1988-2001 y 7,31 % en 2001-2019) y otros tipos de vegetación (17,57 % en 1988-2001 y 27,05 % en 2001-2019). Los municipios de Abomey-Calavi y Ouidah fueron los lugares donde el declive de los manglares fue mayor, por lo que requieren mayores esfuerzos de conservación. La proyección futura basada en el análisis de la cadena de Markov sugiere que los manglares seguirán disminuyendo, pero lentamente. Este estudio proporciona información esencial para orientar las futuras acciones de conservación de los manglares en la zona de estudio.

Palabras clave: ecosistemas costeros, dinámica, teledetección, cadena de Markov, Benín.

Introduction

Mangroves (photo 1) are forest ecosystems encountered in intertidal areas of estuarine systems formed mainly by halophytic woody plants that are adapted to saline and anaerobic conditions in coastal regions (Hogarth, 1999). These ecosystems are found in tropical and subtropical regions between 30°N and 30°S and represent 0.7% of all tropical forests (Giri *et al.*, 2011). They provide vital socio-economic, environmental and cultural benefits to humanity. For example, mangrove forests offer significant protection to coastal communities against natural hazards such as coastal erosion, tsunamis, and storms (Chang *et al.*, 2006; Danielsen *et al.*, 2005). They also provide a diverse range of goods (e.g., food, medicine, construction materials, fuel), and services (e.g., water filtration, faunal breeding, nesting, nursing, feeding grounds). They support biodiversity and sequester significant amounts of CO_2 (Gilman *et al.*, 2008). Despite their significance in providing socio-economic and ecological services, mangroves worldwide are declining (Salazar-Ortiz, 2017). Estimations suggest that mangroves have globally declined at a rate of about 1% annually (Wilkie and Fortuna, 2003), though Goldberg *et al.* (2020) reported a relatively slower annual rate of 0.13% between 2000 and 2016. About 20-35% of global mangrove extent was lost over the last 50 years (Polidoro *et al.*, 2010). In Africa, 30% of mangrove forests were lost during last decades. Future predictions suggest 30-40% of coastal wetlands (IPCC, 2007) and 100% of mangrove forests (Gilman *et al.*, 2008) could be lost in the next 100 years if the present rate of loss continues. This would cause a reduction in the supply of important ecosystem goods and services provided by mangrove forests (Gilman *et al.*, 2008) and the likely extinction of several fauna species that they host. Like other forests, mangrove degradation impacts fauna species (Buelow *et al.,* 2017) through fragmentation that reduces connectivity among habitats, vital space, distribution, and productivity (Carr *et al.,* 2017). It is now clear that without carefully planned conservation, much of the remaining mangrove forest areas are likely to continue to decline (Beger *et al.,* 2010).

The main causes of this decline are both natural and human-induced (Salazar-Ortiz, 2017), but anthropogenic factors are recognized as the main drivers of mangrove forests decline, accounting for 62% of global losses between 2000 and 2016 (Goldberg *et al.*, 2020). Studies have consistently found that anthropogenic factors such as aquaculture development, shifting cultivation, grazing, fuelwood gathering, logging, economic development, cattle ranching, and mining are primarily responsible for the deforestation of mangroves (Giri *et al.*, 2008; Goldberg *et al.*, 2020). Other studies have shown that rainfall deficits during 1960 and 1970 in Africa were important factors of mangroves decline (Faye *et al.*, 2018).

In West Africa, although some authors have showed a regenerative trend for about 25 years (Andrieu *et al.*, 2020; Lombard *et al.*, 2020; Andrieu, 2018; Balla Dièye *et al.*, 2013), in some countries however, mangroves are still declining (Orekan *et al.*, 2019; Folega *et al.* 2017). In Benin, previous studies suggest that mangroves are still declining, although the magnitude of this decline and its future trajectory are not well understood. Mangroves provide crucial ecosystem goods and services to local communities in coastal area of Benin (Teka *et al.,* 2018). The growing pressures on mangroves prompt the need to better understand their spatio-temporal dynamics. Spatio-temporal dynamics generate useful information for decision-makers including national and local authorities but also non-governmental organizations (NGOs) for better planning their conservation and management actions (Massó *et al.,* 2010). Although there have been some recent attempts to assess mangrove forests spatial-temporal dynamics in Benin (Orekan *et al.,* 2019; Orekan *et al.,* 2018), we still lack detailed information on these spatial-temporal changes for their sustainable management. In particular, what are the places (e.g., municipalities) where mangroves declined the most and what was the annual rate of loss? Does mangroves loss pattern vary across periods, and if so, what are the underlying factors? And based on their past dynamics, what could be the future trajectory of mangroves? Such information is essential to plan better management of mangroves.

Remote sensing techniques and GIS are widely used approaches for mapping, monitoring and detecting changes in forest cover (Mayaux *et al.*, 2003), including in mangroves (e.g., Roy *et al.,* 2019; Islam *et al.*, 2020). Furthermore, knowledge on land use/land cover transition has been used as inputs in Markovian chain model to predict the future expansion and land-use/land-cover change in many instances (e.g., Padonou *et al.,* 2017).

The aim of this study was to (i) assess the spatio-temporal dynamics of mangrove forests in the coastal area of Benin, and (ii) predict their future trend. We addressed these objectives using remote sensing techniques, GIS, and Markovian chain model on data from three Landsat TM scenes (1988, 2001, and 2019).

Material and methods

Study area

This study was conducted in Benin (figure 1), a West African country located between 6°10'-12°25'N and 0°45'-3°55'E. The study particularly focused on the coastal area in the south, where mangrove forests are found on the Ramsar sites 1017 and 1018. The mangrove forests grow within a wetland complex area that includes Porto-Novo Lagoon, the Lake Ahémé, and the Chenal Aho. The coastal area covers approximately 12,000 km² representing about 10.5% of the total land surface of Benin (Teka *et al.*, 2018). Mangrove forests are concentrated between 6°10'-6°40' N and 1°40'-

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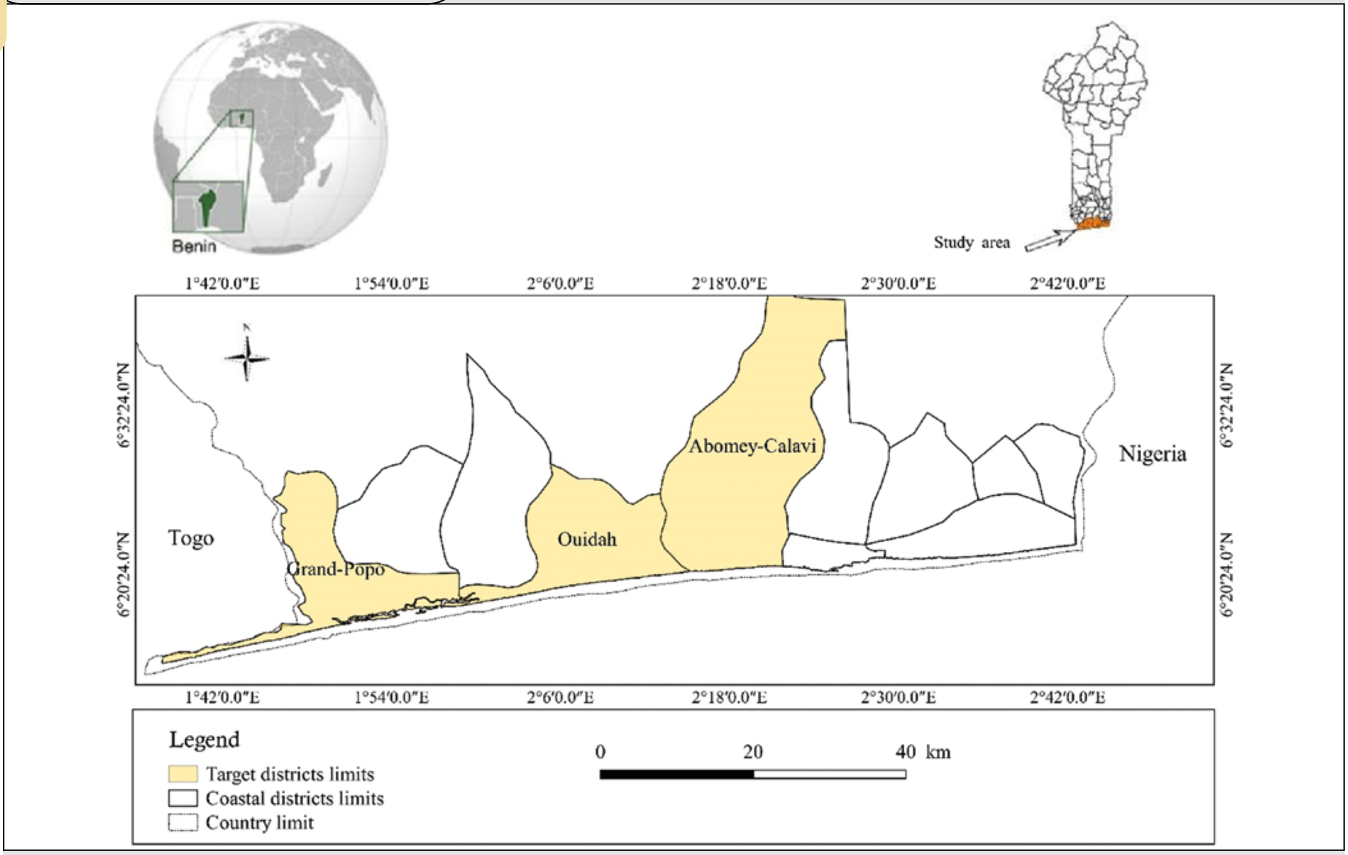

Figure 1.
Map of the study area.

2°45'E (Sinzogan *et al.*, 2019). The climate is equatorial with a mean total rainfall of 1,200 mm/year. There are two rainy seasons (March-late July and September-November) and two dry seasons (late July-early September and late November-early March) (Adam and Boko, 1993). Mean daily temperature is around 27 °C, and relative humidity varies from 78% in January–February to a maximum of 95% in September. The soils are sandy, hydromorphic, and ferralitic, hosting two main true mangrove species namely *Rhizophora racemosa* and *Avicennia germinans*. Other associate mangrove species frequently encountered are *Dalbergia ecastaphyllum* and *Drepanocarpus lunatus*. Herbaceous species include *Paspalum vaginatum*, *Sesuvium portulacastrum*, *Philoxerus vermicularis, Acrostichum aureum* (mangrove fern) and to some extent *Fimbristylis ferruginea*, *Crotalaria retusa*, *Hibiscus tiliaceus*, *Annona senegalensis*, *Chrysobalanus orbicularis*, *Elaeis guineensis*, and *Cocos nucifera* (Sinsin *et al.*, 2018). The most important fauna species include *Jacana actophilornis, Hippopotamus amphibious, Trichechus senegalensis, Lepidochelys olivacea, Dermochelys coriacea, Cercopithecus erythrogaster,* and *Tragelaphus spekei*. Benin's coastal area is characterized by a high population density estimated as 800 inhabitants/km^2 (INSAE, 2015). A previous study by Teka *et al.* (2018) suggests that high human density in Benin coastal area mediates increasing human economic activities such as fishery, salt production, and wood collection for domestic uses and services which in turns accelerate the decline of mangroves.

Remote sensed data and source

Classic remote sensing technics applied by Roy *et al.* (2019) was considered. This technic consisted into five main steps: (i) acquisition of freely available satellite images, (ii) images classification, (iii) field data verification, (iv) images validation, and (v) images interpretation.

Three Landsat TM/ETM+/OLI images (resolution of 30 m × 30 m pixels), respectively for 1988, 2001, and 2019 (table I) were downloaded from the United States Geological Survey (USGS) website[1]. These three years were chosen because they are characterized by different events and different mangrove forest stages. First, population density varied considerably between the periods (INSAE, 2015). Second, the importance of mangrove restoration activities differed markedly between the periods. In 1988, the population density in the Benin coastal area was 1,347,618 inhabitants which rose to 1,826,820 inhabitants in 2001 (i.e., +35.6%). During this period, there were insufficient governmental actions to preserve mangrove forests. From year 2001 to 2019, the human population rose to 3,211,228 inhabitants (i.e., a 138% and 75.8% increase compared to 1988 and 2001, respectively). This period is however characterized by vital governmental and NGOs actions to preserve pristine mangroves and restore degraded mangrove forests including (i) restauration of degraded mangrove sites through

[1] http://earthexplorer.usgs.gov/

plantations, (ii) raising of local communities' awareness, and (iii) several governmental decrees banning exploitation of mangroves and repressions (Teka *et al.*, 2018). The dry season images were considered in order to avoid cloud cover and perform a more precise image classification (Solly *et al.*, 2018). In addition to focusing on the region as a whole, the analyses further considered the three coastal municipalities that host the major part of mangrove forests namely Grand Popo, Ouidah and Abomey-Calavi (figure 1).

Pre-processing of data and classification

The images were geometrically and radiometrically corrected (chander and Markam, 2003). The obtained images were subset by the boundaries of the study area using Envi 4.7 software. These images were used as inputs to perform classification by supervised classification methods. The Maximun Likelihood Classification (MLC) technique was used for this purpose. The MLC is a reliable and probability-based classication technique that has been widely applied to multi-temporal classification (Das and Angadi, 2020). The three reflectance bands most useful in distinguishing vegetation ecosystems (band 3: red, 0.63-0.69 µm; band 4: near infrared, 0.76-0.90 µm and band 5: mid infrared, 1.55-1.75 µm) were used to process the images.

For LANDSAT 7 TM and LANDSAT 4-5 TM images classifications, spectral bands 4-5-3 (near infrared, medium infrared and red) were used to perform the colored composition. These spectral bands were used because: (i) the near infrared is particularly sensitive to plant biomass, (ii) the medium infrared is sensitive to water stocked in plants and (iii) the red is the spectral band that allows correct identification of vegetation. Concerning Landsat 8 OLI image classification, spectral bands 5-6-3 (near infrared, medium infrared, and red) were used to perform the colored composition consistently with Bonn and Rochon (1992) and Oszwald (2005) who pointed out that spectral characteristics of these bands allow a reliable discrimination of vegetation types. The signature of each class was tabulated to perform the classification. For each soil occupation class and each year (1988, 2001 and 2019), regions of interest (training ROIs and control ROIs) were selected for images classification. ROIs used for the classification are the homogeneous zones with area superior to 20 pixels (Barima *et al.*, 2009); they are distributed in all the study area according the distribution of soil occupation classes. Images of 2019 were first classified and their ROIs were chosen using field information. Field data, namely direct observations coupled with GPS coordinates of 50 points for each soil occupation class were collected in 2019 (from October to November 2019) in order to ensure a correct image classification (Manandhar *et al.*, 2009). For the classification of images of 1988 and 2001, their ROIs were selected considering spectral signature of each soil occupation identified for year 2019 after Landsat 8 OLI 2019 classification following Barima *et al.* (2016), Barima *et al.* (2009) and Munyemba and Bogaert (2014). This method suggests that soil occupation classes identified in the study area in 2019 are the same for years 1988 and 2001 and that only the areas of the soil occupation classes change across dates (N'Da *et al.*, 2008).

Indexes such as soil brightness (SB), soil wetness (SW) and soil greenness were taken into account for ROI selection. Five soil occupation classes were finally defined: (i) mangrove forests (include all mangrove forests present in the coastal area and mainly composed of *R. racemosa* and *A. germinans*), (ii) meadows and swamps (include areas composed by tanne – mangrove areas degraded dried up and covered by grasses – and swamp grasses), (iii) other forests and plantations (include other vegetation areas composed of natural forests, tree plantations and fallows but excluding mangrove forests), (iv) human habitations (include agglomerations, infrastructures, and uncovered soils), and (v) water bodies (include areas composed of continental water areas like lagoons and lakes). The statistics of each soil occupation class were then quantified for each year for the whole study area and per municipality using Envi software (version 4.7).

A confusion matrix was tabulated for each period and based on reference points. A confusion matrix is the most commonly used method in remote sensing application to assess the accuracy of classification (Foody, 2002). Error of commission and error of omission were calculated for each class. The overall accuracy and kappa coefficient were also calculated in order to assess the accuracy of image classification (Skupinski *et al.*, 2009).

Land use/land cover transition probability matrices

Transition probability matrices were elaborated for three periods 1988-2001, 2001-2019 and 1988-2019 to describe the changes in each soil occupation class. Each matrix represents the probability of the persistence of each soil occupation class, or the probability of a transition to another soil occupation class from the first to the last year in the period (Godard, 2005). For a given period, these values were obtained by superimposing the two maps (at t_0 and t_1) using Envi software and this allows to detect changes in land use between these dates. Values in the matrix were standardized to obtain annualized changes and to make comparisons.

Table I.
Characteristics of different scenes downloaded and used for the analysis.

Sensor type	Image ID	Acquisition date
Landsat 4-5 TM	LT04_L1TP_192056_20170209_01_T1.tar	12-02-1988
Landsat 7 ETM+	LE07_L1TP_192056_20170206_01_T1.tar	04-04-2001
Landsat 8 OLI	LC08_L1TP_192056_20190130_01_T1.tar	08-01-2019

The projection system was WGS 1984 UTM Zone 31N for all images.

Future scenario for mangrove forests

The annualized transition matrices were used to predict the proportion of each land cover class, particularly mangrove at any time based on a Markovian chain model. The projections were based on assumptions that dynamics observed in 1988-2001 (scenario 1), 2001-2019 (scenario 2), or 1988-2019 (scenario 3) will prevail. The model was validated using a χ^2 test. For this test, the area expected from the 2019 scenarios based on the 1988-2001 period was compared with the area for 2019, and the area expected from the 2001 scenarios based on the whole period 1988-2019 was compared with the area for 2001 as in Padonou *et al.* (2017).

Mangrove deforestation rate

For the mangrove forest class, the annual deforestation rate (*r*) was calculated using the formula by Puyravaud (2003):

$$r = \frac{1}{t_2 - t_1} \times \ln(A_2/A_1)$$

In this formula, *r* represents the deforestation rate (calculated in % of mangrove loss per year); A_1 and A_2 represent initial and final mangrove forest areas, respectively (i.e., at date t_1 and t_2); t_1 and t_2 represent the start date and the end date of the period in years considered for the calculation (I = 1988, 2001, and 2019); $r < 0$ indicates deforestation, whereas $r > 0$ rather indicates expansion (i.e., no deforestation), $r = 0$ indicate forest stability i.e., stagnation.

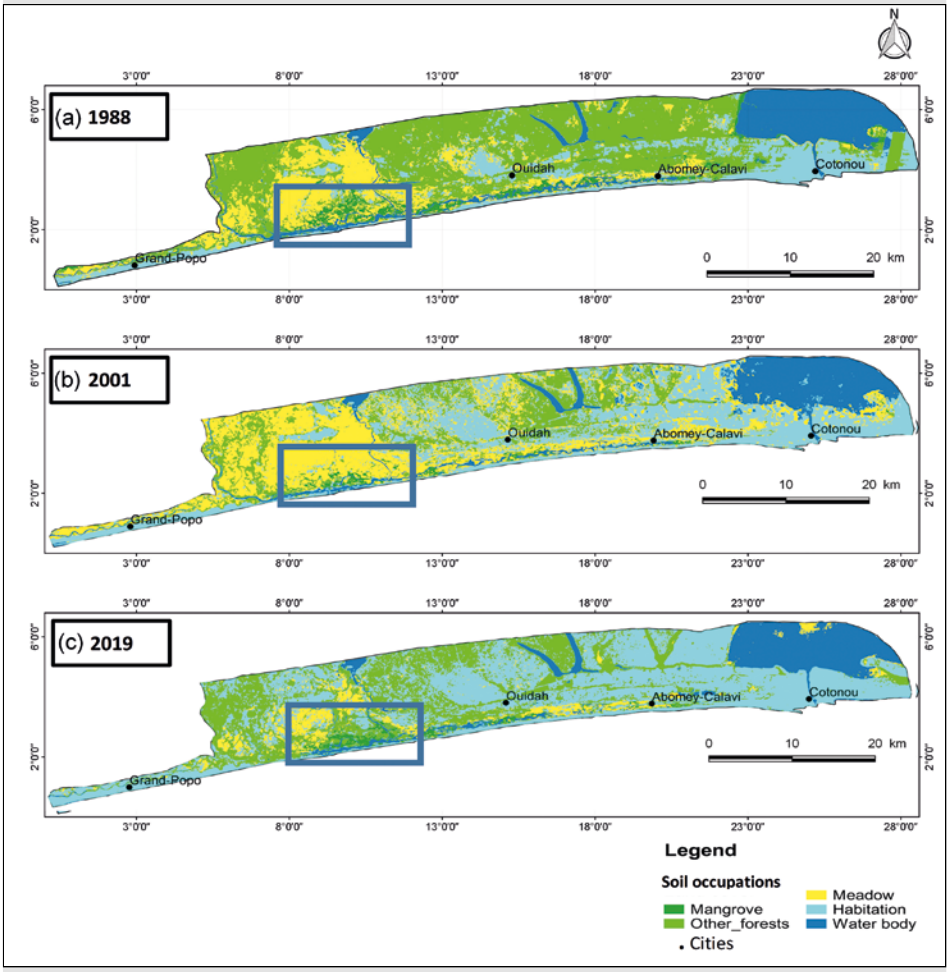

Figure 2.
Maps of soil occupations of the coastal region of Benin in 1988, 2001 and 2019.

Results

Accuracy assessment of the classification

Table II shows the confusion matrix together with the overall accuracy and kappa coefficient. Values in the diagonals of this matrix contain the proportions of well-classified pixels (presented in bold) and the off-diagonals contain the proportions of misclassified pixels. Overall, the classifications were correct for the 1988 image (kappa = 0.95; overall accuracy = 96.05%) with a negligible, 0.38% confusion between mangrove forests and water bodies classes. A similar classification was achieved for the 2001 image (kappa coefficient = 0.99, Overall accuracy = 99.11%), with a 2.38% confusion with other forests and 1.59% with meadows. Considering the 2019 image, similar accuracy values (kappa = 0.93; overall accuracy = 95.77%) were obtained with a marginal confusion between mangrove forests and meadows (1.13%) and other forests (1.13%).

Soil occupations and mangrove deforestation

Figures 2, 3 and 4 show the land cover maps in 1988, 2001, and 2019, and changes across the periods, respectively. The mangrove forests' area decreased during period 1 (1988-2001) and increased during period 2 (2001-2019). Mangrove forests covered 5,205.24 ha in 1988 (5.4%), decreased to 1,974.24 ha (2.0%) in 2001, and increased to 2,346.21 ha (2.4%) in 2019. Thus, about 62.2 % of mangrove areas were lost from 1988 to 2001 (–3231 ha) whereas 18.84% (371.97 ha) were restored from 2001 to 2019 (figures 2 and 4). At the scale of the three main municipalities harboring mangroves, results showed quite different trends. From 1988 to 2001, all the three sites lost important areas of mangrove forests: 71.71% (309.33 ha), 50.69% (897.66 ha) and 28.20% (452.43 ha) in Abomey-Calavi, Ouidah and Grand-Popo municipalities, respectively (figure 5). This indicates that Ouidah and Grand Popo were the muni-

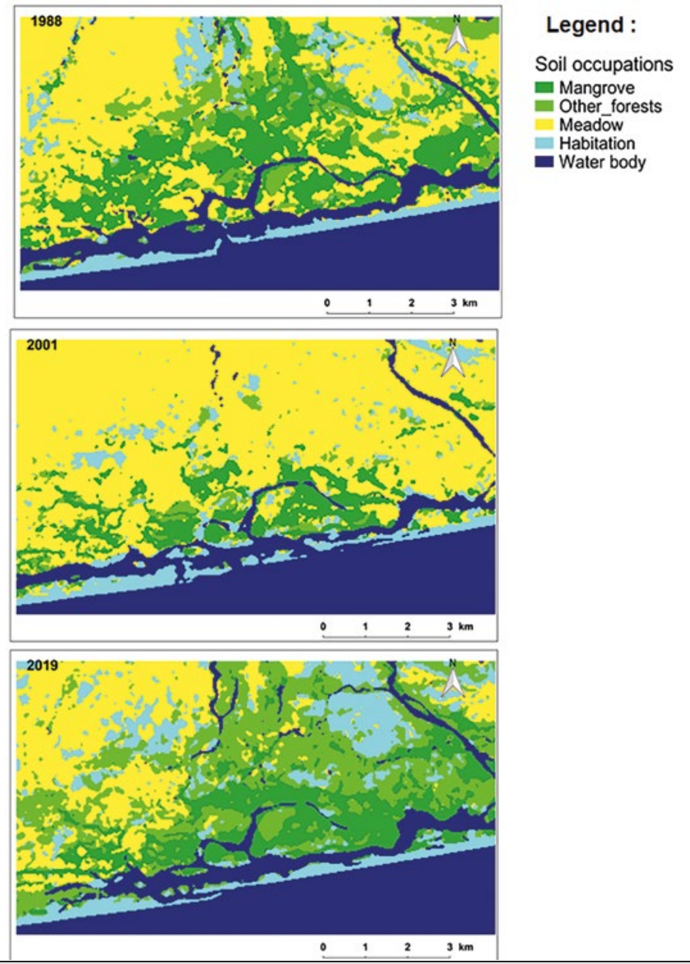

Figure 3.
A zoom of area delimitated on figure 2 showing more details on soil occupation changes between 1988, 2001 and 2019.

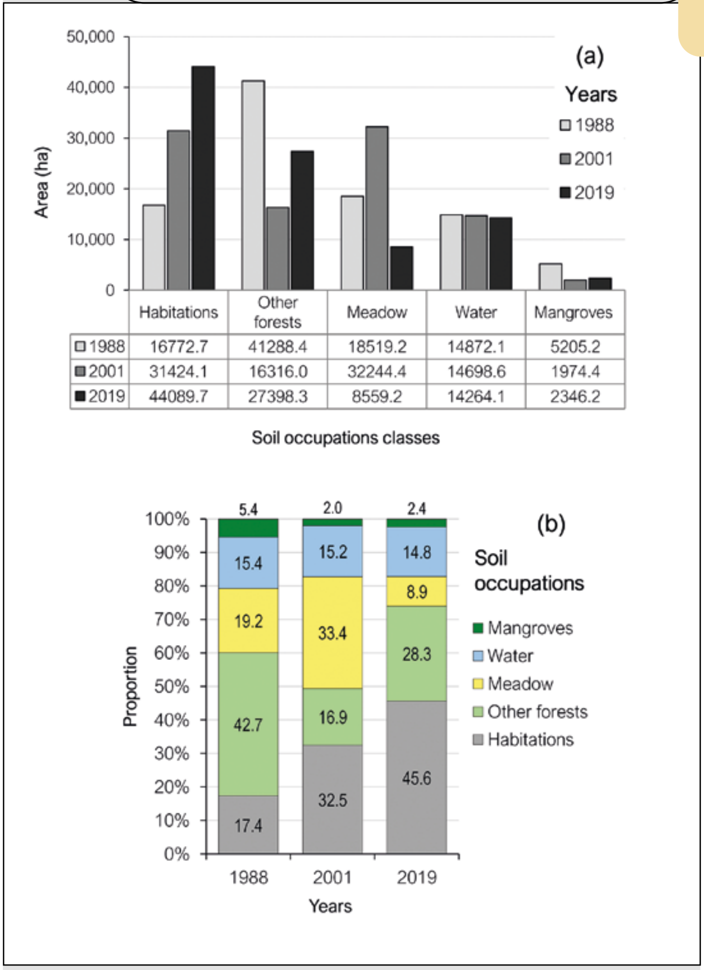

Figure 4.
Soil occupation classes (area in ha and in %) of the coastal region of Benin for 1988, 2001 and 2019.

cipalities with the largest losses of mangroves. However, during the period 2001-2019, the mangrove area increased by 8.76% (100.89 ha) and 70.32% (613.98 ha) in Grand-Popo and Ouidah, respectively but in contrast decreased in Abomey-Calavi by 20.7 ha, (16.96 %), although with a lesser intensity compared to the first period.

The average annual deforestation rate of mangrove forests was r = –0.074 between 1988 and 2001 and +0.009 between 2001 and 2019, indicating deforestation in the first period but expansion in the second period.

Transition matrices of soil occupation classes

Table III shows the transition matrices between pairs of soil occupations from 1988 to 2019, 2001 to 2019, and 1988 to 2019. From 1988 to 2001, 80% of mangrove forests were degraded and converted principally into meadow (52.35%), other forests (17.57%), water bodies (5.18%) and human habitations (4.97%). Between 2001 and 2019, 46% of initial mangrove forests area in 2001 have been disturbed. During this period, 7.31% of mangroves were converted mainly into meadow, 4.72% into human habitations, and 27.05% into other forests. Considering the whole period (i.e., between 1988 and 2019), 52.35% of mangrove forests were converted into meadow, 4.97% into human habitations, 17.57% into other forests, and 5.18% into water bodies.

Future scenarios for mangroves based on Markov chain analysis

Figure 6 shows the future trends of soil occupation, particularly mangroves at horizon 2050, predicted based on the dynamics of 1988 to 2001 (figure 6a), 2001 to 2019 (figure 6b), and 1988 to 2019 (figure 6c). The difference between the observed and simulated probabilities using the 2019 soil occupation map was not significant (χ^2 = 0.264, p › 0.05). Thus, the model could be applied for simulating future trends in soil occupations. The future projection that took into account the landscape occupation dynamic observed during the first period (1988 to 2001) predicted that mangroves, other forests, and water bodies will decrease by 3.9%, 36.2%, and 1.3% by horizon 2050, respectively, compared to their 1988 occupations. In contrast, meadow and human habitations will increase by 12.7% and 28.6%, respectively, by 2050. Assuming that trend observed in the second period (2001-2019) will continue, mangroves will remain relatively constant. However,

Table II.
Confusion matrix for the three years.

Year 1988	Class	Mangrove	Other forests	Meadow	Habitation	Water
	Mangrove	99.62	0.00	4.19	0.00	0.00
	Other forests	0.00	100.00	0.40	0.12	0.00
	Meadow	0.00	0.00	90.42	7.31	0.00
	Habitation	0.00	0.00	0.80	92.57	0.00
	Water	0.38	0.00	4.19	0.00	100.00
	Overall Accuracy = 96.05%; Kappa Coefficient = 0.95					
Year 2001	**Class**	**Mangrove**	**Other forests**	**Meadow**	**Habitation**	**Water**
	Mangrove	96.03	0.00	0.00	0.00	0.00
	Other forests	2.38	98.14	0.00	0.00	0.00
	Meadow	1.59	1.03	99.03	0.15	0.00
	Habitation	0.00	0.83	0.97	99.85	0.00
	Water	0.00	0.00	0.00	0.00	100.00
	Overall Accuracy = 99.11%; Kappa Coefficient = 0.99					
Year 2019	**Class**	**Mangrove**	**Other forests**	**Meadow**	**Habitation**	**Water**
	Mangrove	97.74	0.00	0.00	0.00	0.00
	Other forests	1.13	99.18	2.31	4.03	14.27
	Meadow	1.13	0.00	92.57	0.64	6.21
	Habitation	0.00	0.82	5.11	95.33	2.78
	Water	0.00	0.00	0.00	0.00	76.74
	Overall Accuracy = 94.77%; Kappa Coefficient = 0.93					

meadow and water body areas will experience a 26.9% and 1.6% decrease from their initial areas in 2001 by horizon 2050. Other soil occupations such as other forests and human habitations will increase by 2050 by 11.6% and 17%, respectively. If the dynamics observed during the last 31 years (1988-2019) continue, then mangrove forests and classes such as other forests, meadow, and water bodies will decrease by 3.4%, 0.1%, 7.1%, and 11.4%, respectively by horizon 2050 in favor of human habitations, which will increase by 35.3%.

Discussion

This study used remote sensing techniques, and GIS in combination with Markovian chain model on satellite images to map spatio-temporal dynamics of mangrove forests and predict their future trends in Benin. Several other studies have used these modelling techniques to assess land use and land cover changes and predict their future courses (e.g., Padonou *et al.*, 2017) including in mangrove ecosystems (Roy *et al.*, 2019; Islam *et al.*, 2020).

Classification accuracy assessment

There were very low confusions between the main soil occupations. The values of the overall accuracy and kappa coefficient showed a great reliability of the classification. These values are consistent with other studies on mangrove forest dynamics. For example, the overall accuracy ranged between 90 and 97 in Orekan *et al.* (2018) and the Kappa coefficient was greater than 0.86 in Leempoel *et al.* (2013). These similar statistics indicate that image classifications were accurate enough for assessing the spatio-temporal dynamics of mangroves.

Spatio-temporal dynamics of mangroves and future scenario

Two trends were observed for mangroves in Benin during the study period. Mangroves declined between 1988 and 2001 but increased from 2001 to 2019. Between 1988 and 2001, significant proportions of mangroves were converted into meadow and human habitations. Orekan *et al.* (2018) reported a 39.42% loss of mangroves between

1986 and 2000 in the Avlo locality, which hosts large mangrove areas in Benin. Previous studies in Benin and in West Africa have also reported a decline of natural forests due to the human perturbations (Sambieni *et al.*, 2015; Dimobe *et al.*, 2012). These findings are also consistent with other studies in West African countries. For e.g., in Togo, Folega *et al.* (2017) reported a significant loss of mangrove forests between 1986 and 2014. Similarly, in Cameroon, mangroves have experienced a 52% decline in their area during the last three decades (Kana *et al.*, 2019). Many other countries outside Africa have also reported a major decline in mangroves cover (e.g., 36% between 1967 and 2009 in China and 35% between 1975 and 2005 in Myanmar (Leempoel *et al.*, 2013). Our results showed mangroves are principally converted into meadow. However, a small part of mangroves was also converted into other forests. Conversion of mangroves into other forests is due to the restauration of some degraded mangroves areas dominated by *A. germinans* (second mangrove forest species in Benin) with plantations of *Acacia auriculiformis*. *Acacia auriculiformis* is a fast-growing tree species used as the principal substitute species to mangrove wood in Benin's coastal area and successfully grows in

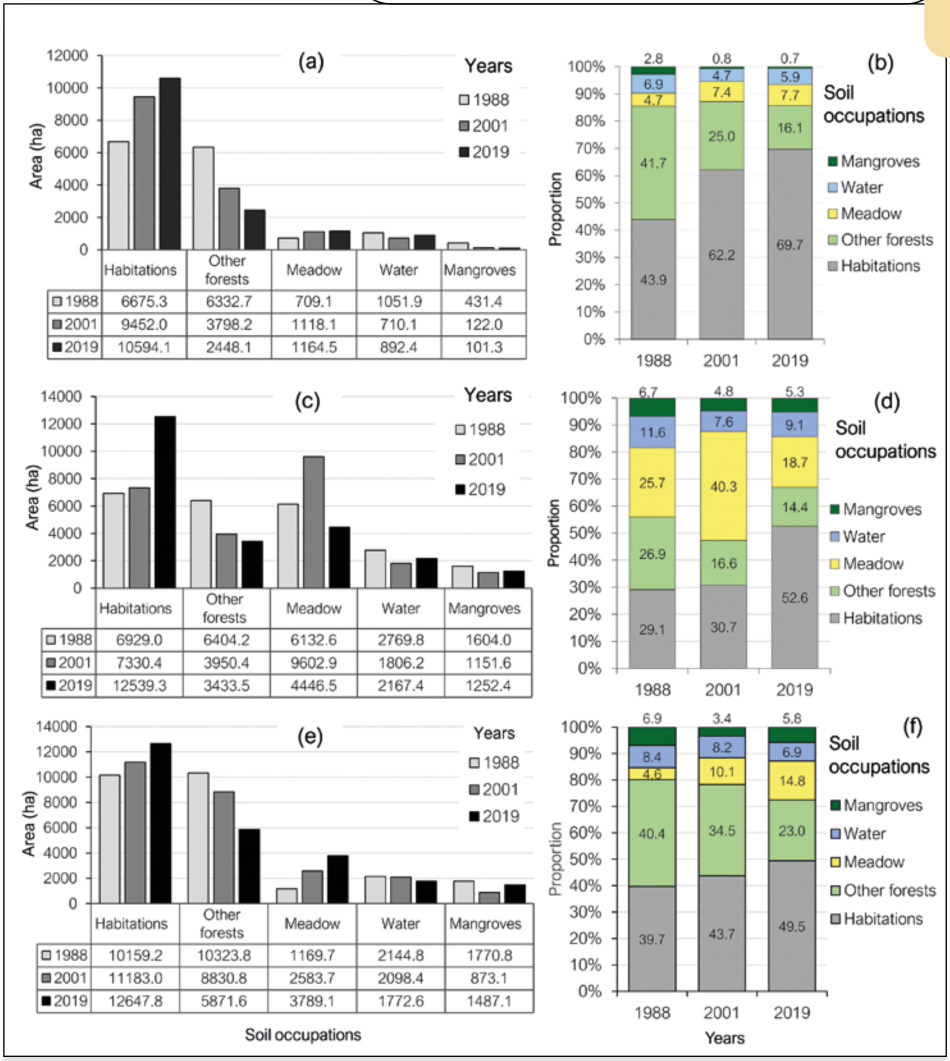

Figure 5.
Soil occupation classes (area in ha and in %) of three municipalities of the coastal area of Benin for 1988, 2001 and 2019: a-b) Abomey-Calavi, c-d) Grand-Popo, e-f) Ouidah.

Photo 2.
Woods of *Rhizophora racemosa* collected for domestic uses, village of Azizakouè, Municipality of Ouidah.
Photo K. V. Salako, September 2020.

Table III.
Transition matrices (area in ha) between 1988-2001-2019 soil occupations in the coastal area of Benin.

	Class	Year 1988 Mangrove	Habitation	Meadow	Other forests	Water body	Total
Year 2001	Mangroves	1037.1	15.9	473.5	240.4	207.4	1974.2
	Meadow swamps	2725.0	2067.5	12850.2	13907.6	694.8	32245.1
	Habitation	258.8	13960.3	3912.5	12663.7	625.2	31420.4
	Other forests	914.7	448.7	1081.4	13784.5	90.5	16319.6
	Water body	269.7	280.4	201.7	692.2	13254.2	14698.2
	Total	**5205.2**	**16772.7**	**18519.2**	**41288.4**	**14872.1**	**96657.6**
	Class	**Year 2001 Mangrove**	**Habitation**	**Meadow**	**Other forests**	**Water body**	**Total**
Year 2019	Mangroves	1069.6	38.2	962.6	194.2	81.7	2346.2
	Meadow swamps	144.4	600.8	6567.5	470.4	776.2	8559.2
	Habitation	93.2	25742.7	12806.3	4565.5	882.0	44089.7
	Other forests	534.1	4411.7	10961.6	10968.9	522.0	27398.3
	Water body	133.2	630.8	946.4	116.9	12436.7	14264.1
	Total	**1974.4**	**31424.1**	**32244.4**	**16316.0**	**14698.6**	**96657.6**
	Class	**Year 2019 Mangrove**	**Habitation**	**Meadow**	**Other forests**	**Water body**	**Total**
Year 2019	Mangroves	1272.2	27.7	656.8	111.2	278.4	2346.2
	Meadow swamps	907.4	359.2	5153.2	1212.1	920.7	8552.6
	Habitation	535.6	15025.7	8006.0	20157.0	361.4	44085.7
	Other forests	1939.5	1194.7	4262.3	19400.4	599.9	27396.8
	Water body	550.6	161.3	434.2	406.4	12711.7	14264.1
	Total	**5205.2**	**16768.5**	**18512.6**	**41287.1**	**14872.1**	**96657.6**

these areas. The success of this restauration is due to the fact that *A. germinans* stands do not grow in lagoons as opposed to *R. racemosa*, which offers proper habitat to *A. auriculiformis*.

Rising human population densities in coastal areas and anthropogenic activities are recognized as the principal driver of mangrove forests degradation, and hence their decline. Indeed, coastal populations use mangrove forests as a source of timber and wood for fuel, fencing, and habitat constructions. In the coastal region of Benin, fishery and salt production activities are well developed and depend highly on wood from mangroves (Teka *et al.*, 2018). Salt production covers approximately 100% of local, and approximately 60% of the national consumption (INSAE, 2009) and constitutes the second most important activity in mangroves areas after fishery. As such, apart from the use of wood for daily domestic utilizations (photo 2), salt production and fishery represent important sources of pressure on mangrove forests. Fishermen cut and use mangrove trees to make local fish traps known as *Acadja*, and this local fishing technique is a major cause of the destruction of mangrove ecosystems in Benin. Extraction of fuelwood from mangroves in Benin is severe because there are few alternative sources of energy available for domestic use in the study area (Teka *et al.*, 2018). This is consistent with the observation that mangrove deforestation and degradation for fuelwood is the major driver of mangrove ecosystem perturbation (Giri *et al.*, 2015). This high pressure on mangrove forests is further mediated by the rising population density in the region which likely increases mangrove deforestation. For example, compared to 1988, the population increased by about +35.6% in 2001 and 138% in 2019 (INSAE, 2015). Increase in human population size means increase of pressures on mangroves through various activities they practice. This trend has been particularly observed in the municipalities of Abomey-Calavi and Ouidah where population density (inhabitants per km^2) in 2019 reached about five and three times higher than in 1988 (Abomey-Calavi: 235, 571, 1217; Ouidah: 192, 228, 481; respectively, in 1988, 2001, and 2019) with important loss of mangrove forests. This is higher compared to Grand Popo (114, 140, 199; respectively in 1988, 2001, and 2019) (INSAE, 2015).

These anthropogenic pressures are generally due to widespread poverty (Armah *et al.*, 2010), which is true for Benin Republic. In this study, human pressures are pointed out as more important parameters causing mangroves loss. However, it's important to note that others natural factors (e.g., high salinity, low availability of nutrients and poor microbial activities in the soil substrates) could also have contributed to mangrove degradation, although the impacts of these factors may not be as significant as the anthropogenic ones (Kathiresan, 2002).

After the first period characterized by mangroves decline (i.e., 1988-2001), we found an 18.84 % increase of mangrove area between 2001 and 2019. A similar trend was recorded for mangroves by Gevana *et al.* (2015) in Philippines, Roy *et al.* (2019) in India and Islam *et al.* (2020) in Bangladesh. According to these authors, such an increase is attributable to continuous restoration activities of degraded mangroves. Expansion of mangroves has also been reported in Senegal in the last decades (see Andrieu *et al.*, 2020; Andrieu, 2018; Balla Dièye *et al.*, 2013) although the weighting of factors between natural regeneration and human made plantations is controversial. In Benin, the increase in mangroves cover has certainly resulted from increased efforts of mangroves restoration in the coastal region. This was achieved through intensive production and plantation of seedlings of mangrove species *R. racemosa* and *A. germinans* on degraded sites in collaboration with local communities but also the increased sensitization to raise local communities' awareness for the conservation of mangroves. These actions were concomitantly led by the national forest department but also several NGOs working in the field of nature conservation. The restoration activities were more important in Grand Popo, likely because this municipality is hotspot of mangroves in Benin. The restoration efforts observed in this period should continue in order to bring adequate solutions to reverse the future predictions that mangroves' area will either decline or remain relatively constant. Traditional conservation of forests through sacred groves, which has been effective for mangroves (Teka *et al.*, 2018), should be encouraged to limit the illegal haversting of mangrove forest for fuelwood and other uses.

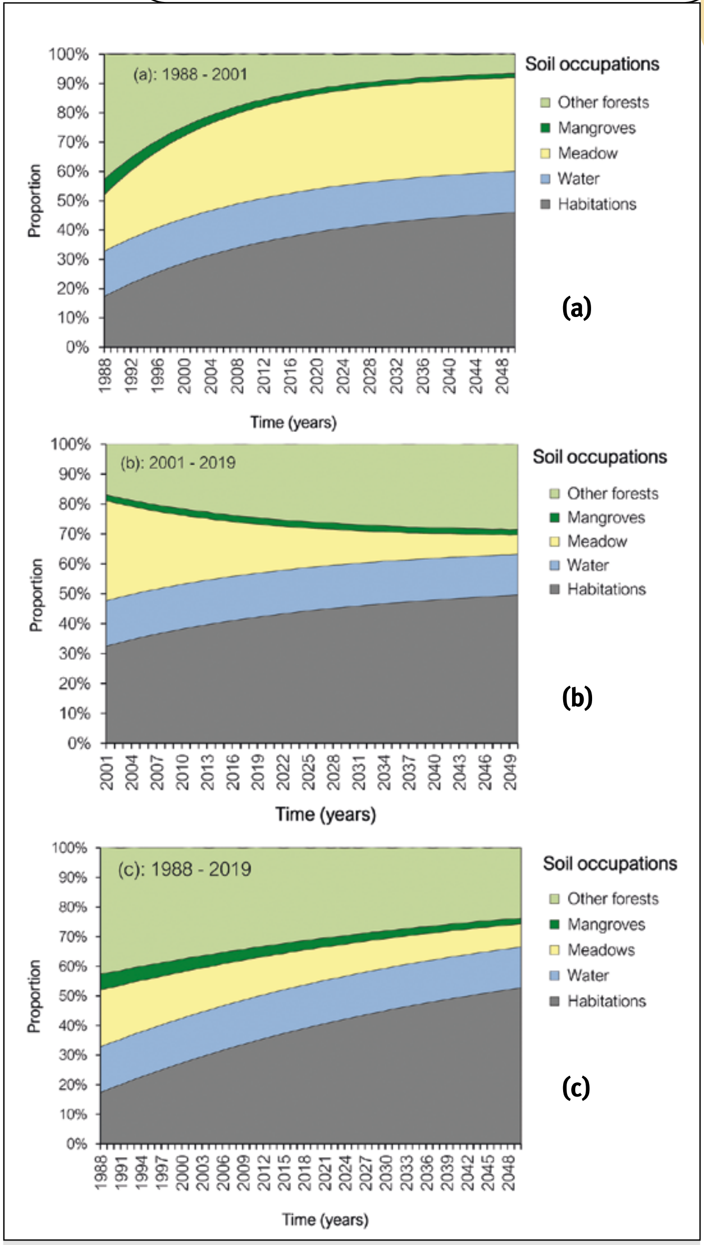

Figure 6.
Simulated evolution of the five soil occupation classes under three future scenarios. Dynamics observed during the periods (a) 1988-2001; (b) 2001-2019; and (c) the total study period (1988-2019). Future evolution of soil occupations at horizon 2050 according to three dynamic scenarios.

Implications for conservation of mangroves

The long-term dynamic of mangroves in the study area predicted a regression in the next three decades. Adequate actions must be taken in areas where mangroves are still conserved, and restoration efforts should be increased to ensure that degraded areas are restored. New mangrove restoration projects should be initiated either by the national forest department or by NGOs. This can be achieved for instance through national government-supported competitive grants for NGOs. Support can also be obtained through advocacy towards technical partners. These restoration projects should be participative and involve local communities to ensure that they participate in the conservation initiatives.

Another major issue that needs to be addressed is related to alternative sources of wood harvested from mangroves due to the challenges of reconciling conservation and human daily needs in wood in the region. As long as sustainable alternatives are not offered to local communities, it would be difficult to eradicate the illegal harvesting of mangroves, which is a major factor of their decline in Benin (Zanvo *et al.*, 2021). Plantations of fast-growing species as a source of firewood such as *Acacia auriculiformis*, which is wide spread in other regions of the country, might offer interesting alternatives. However, studies are needed to understand the socio-economic and institutional motivations for local people to adhere to these conservation efforts. Our study revealed that mangroves decline was most severe in the municipalities of Abomey-Calavi and Ouidah.

These municipalities, therefore require greater conservation efforts to ensure that existing mangroves are preserved but also that degraded sites are restored. Additional detailed investigations are needed on fauna species identified as locally extinct or very rare to inform further conservation actions on these species.

Conclusion

Using remote sensing techniques and GIS, this study showed that mangroves dynamics experienced two contrasting trends: a sharp decline in the first period (1988-2001) and an expansion in the second period (2001-2019). However, over the entire period, mangroves have globally declined. Projections using markovian chain analysis suggest that mangroves will continue to decline in the next three decades if the past trends continue. This study provides useful information and demonstrated the usefulness of the used modelling techniques to understand the past dynamics of mangrove forests and their future trend, which are essential to guide future conservation actions. In the municipalities where mangroves are mainly found in the study area, Abomey-Calavi and Ouidah experienced the largest decline of mangroves. These municipalities should be given greater priorities in future conservation and sustainable management initiatives.

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