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Monitoring mangrove restoration projects in Senegal, Benin, Costa-Rica, and Philippines using remote sensing

Suivi des projets de restauration de la mangrove au Sénégal, au Bénin, au Costa Rica et aux Philippines par télédétection

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Introduction

- 1 Mangroves are coastal forests found in the intertidal zone of tropical and subtropical regions. They are also an important social-ecological system (Berkes *et al.*, 2008), where many human communities are dependent on mangroves for their livelihood and well-being. They are, however, sensitive to human activities and from 1980 to 2000 the earth's mangrove cover diminished by 180,000 ha per year, i.e., a worldwide cumulative loss of 35% which corresponds to a 1.5% annual decrease in overall cover (FAO, 2007). As soon as the early 2000's this rate of decline reduced (Feller *et al.*, 2017). From 2010 to 2020, the rate of decreasing cover dropped to 0.07% with "only" 10,200 ha per year of net loss (FAO, 2023). Because the trend is still negative and mostly because Blue Carbon is becoming a major objective of global environment governance, many ecological restoration projects of mangroves were set up around the world to comply with regulatory requirements driven by environmental impact assessments and as voluntary programs (Bosire *et al.*, 2008; Curnick *et al.*, 2019). Unfortunately, a lot of restoration projects failed to achieve their objectives (Elster, 2000) and for others the results are

missing or incomplete. Regarding project failures, several hypotheses have been put forward to try to explain this: limited understanding of the ecological processes that enable the establishment and survival of mangroves; inappropriate choice of replanted species; and lack of consideration of hydrological processes and physico-chemical properties of soil and/or interstitial water (Kentula, 2000; Lewis & Streever, 2000). Moreover, monitoring is often inadequate, unpublished, or not carried out at all, preventing effective scientific feedback and lessons learned from failed or successful restoration projects. The recent guides to mangrove restoration all agree that project monitoring phases are just as important as the implementation phase (UNEP-Nairobi Convention, 2020). Yet, these recommendations are rarely adopted given that mangrove habitats are temporarily flooded and often located in inaccessible areas, and so traditional observation methods are extremely time-consuming and costly (Kuenzer *et al.*, 2011).

- 2 To judge the efficiency of a mangrove restoration project and compare them, monitoring restoration projects is unquestionably critical. Here, we assess changes of mangrove cover at six restoration sites located in Senegal, Benin, Costa Rica, and Philippines using high resolution remote sensing specifically dedicated to mangrove monitoring. Remote sensing is widely used for monitoring mangrove cover (Kuenzer *et al.*, 2011), to follow anthropogenic degradation (Yagoub & Kolan, 2006), to assess productivity and biomass (Hu *et al.*, 2020) or water quality (Lotfinasabasl *et al.*, 2018) but surprisingly, remote sensing is seldom used to monitor mangrove restoration projects. However, consultants, experts, and scientists can use remote sensing with a low “knowledge barrier” which facilitates the dissemination of results and discussions. The main questions addressed here is: **How effective are the various methods in increasing the mangrove area among those proposed in 6 ecological mangrove restoration sites in Senegal, Benin, Costa Rica, and Philippines?**
- 3 For this study, Landsat 5, Landsat 8, and Sentinel-2 images were analyzed, all of which are free and open-access, to ensure the replicability of the method by all users. Two cross-temporal analyses were conducted: a pre-restoration analysis (covering the past 29 years) and a post-restoration analysis. Other studies typically do not perform this type of cross-temporal analysis and focus solely on post-restoration monitoring (Alexandris *et al.*, 2013), which is to be considered the main result. It is important to note that the primary goal of the pre-restoration analysis in this study is not to serve as a direct comparison with post-restoration outcomes, but rather to contribute to the historical reconstruction of mangrove dynamics prior to restoration initiatives, supplemented by an analysis of available literature. This historical approach enriches our understanding of the trajectories on the last decades of mangrove ecosystems, thus anchoring the observed restoration effects within an extended temporal perspective.

Material and Method

Study sites

- 4 We analysed satellite images taken of six mangrove restoration sites. Three are in west Africa, respectively in Senegal (Saint-Louis River mouth and Saloum Delta) and Benin (Mono River mouth), two are in Costa Rica (Chomes and Cuajiniquil) and one in the Philippines (Tambaliza). All these sites are part of the Mangroves Initiative funded by

the FFEM (Fonds Français pour l'Environnement Mondial). General information of these projects is summarized in table 1. The restoration actions carried out at each of these sites are summarised in table 2. Moreover, of all the projects studied, only three have a clearly stated reason for the degradation of the site's mangroves in the report. Cuajiniquil and Tambaliza are former abandoned aquaculture ponds, while Chomes is a former abandoned salt works. The following sections present, for each site, all the contextual elements necessary for interpreting the restoration results.

Mono River mouth, Benin

- 5 The need for mangrove restoration in this area arose primarily from a significant alteration in the hydro- sedimentary regime after the construction of the Nangbeto dam in 1987 along the Mono River. The dam substantially mitigated the seasonal fluctuations of the river (Rossi, 1996), resulting in numerous floods and heightened coastal erosion. Preceding the restoration effort was a thorough physico-chemical assessment of the soil and pore water, focusing on parameters such as pH, salinity, and redox potential, conducted in both the affected area and a reference zone containing presumed-healthy mangroves. The restoration initiative commenced with the aim of reinstating soil and pore water physico-chemical conditions akin to those observed in the reference area. To achieve this, a network of channels was excavated to recreate natural hydrological conditions. Subsequently, 40,000 propagules of *Avicennia germinans* were strategically planted along the channel's edge to initiate a natural regeneration process for the area.

Saloum Delta, Senegal

- 6 The breach of the Sangomar spit in 1987 triggered a significant increase in coastal erosion, accompanied by notable sedimentation from 1988 to 2017 due to the progressive expansion of the Sangomar breach (Shahrokhi, 1990). Mangroves directly facing the breach were eroded, while in other areas, new sediment deposits emerged, which were rapidly covered by mangroves. Restoration efforts included the reforestation of 5 hectares of *Chrysobalanus icao* along the shoreline to rehabilitate the dune, along with the construction of a 500-meter breakwater.

Senegal River mouth, Senegal

- 7 Regarding the mouth of the Senegal River, the primary factor contributing to mangrove regression was a shift in the hydrological regime resulting from the construction of two upstream dams: the Diama dam in 1986 and the Manantali dam in 1988 (Taïbi *et al.*, 2009). Similar trends were observed in other Senegalese mangroves during this period due to a prolonged drought (1968-1998), leading to heightened salinity and acidity in the upper-tidal zone (Andrieu, 2018). To address erosion and facilitate mangrove recruitment, *Casuarina equisetifolia* (filao) and mangroves were strategically planted on the langue de Barbarie to repair dunes.

Cuajiniquil, Costa-Rica

- 8 The restoration zone encompasses 7 hectares of abandoned salt evaporation ponds that were discontinued approximately 10 years ago (FFEM). Although the area is no longer under significant anthropogenic pressure, the historical activity led to elevated salinity and hypoxia in the soil and pore water, conditions incompatible with mangrove forest development (FFEM). Prior to restoration, a comprehensive physico-chemical assessment, focusing on pH, salinity, and redox potential, was conducted in both the affected area and a reference zone housing presumed-healthy mangrove. Similar to the restoration approach at the Mono River mouth (Benin), efforts commenced with the excavation of channels across the site to facilitate water circulation, mitigate salinity, and enhance oxygen levels in the soil and pore water. Subsequently, 26,000 seeds of *Avicennia germinans* and *Rhizophora mangle* were strategically planted along channel edges to stimulate natural mangrove regeneration.

Chomes, Costa-Rica

- 9 The mangroves of Chomes underwent severe deforestation, primarily due to mariculture projects, particularly shrimp production (FFEM). A stretch of 350 hectares between the village of Chomes and the sea was transformed into illegal shrimp ponds, exploiting state land (FFEM). Presently, about a third of these ponds lie abandoned. Among them, three ponds situated to the northeast, covering approximately 24 hectares, were abandoned over a decade ago and were designated as a potential restoration site. However, the restoration efforts were limited to preliminary background research on the mangroves of the area and the documentation of anthropogenic stressors. Despite the absence of active restoration initiatives, this site was included in the analysis as a control site to observe natural changes within an abandoned shrimp pond.

Tambaliza, Philippines

- 10 The Tambaliza site represents a former abandoned aquaculture pond, once surrounded by remnants of mangrove (FFEM). The initial creation of the pond involved the removal of mangrove vegetation, resulting in disrupted hydraulic connections (FFEM). This alteration led to notably high maximum tidal heights and the absence of freshwater inflows. The pond was abandoned post-2013, and even before the commencement of restoration efforts, signs of natural regeneration were evident, with young mangrove stands already establishing themselves. The restoration interventions comprised the construction of infrastructures to facilitate the restoration of hydrological connections, coupled with the reforestation of 2 hectares. This reforestation effort involved planting 36,000 plants of *Avicennia sp.* and *Rhizophora sp.*

Table 1 - Restoration projects information (WACA: West Africa Coastal Areas Management Program)

Project	Costa Rica & Benin	WACA	Philippines
Total funding	6.6 M€	10 M€	4.5 M€

Organisations carrying out the restoration	NGO Corde + Institut Epomex	Centre de Suivi Écologique (CSE)	Conservation International (CI)
Project start	04/2017	11/2018	01/2015
Project end	04/2021	12/2022	01/2021
Sites	Cuajiniquil; Chomes; Mono River mouth	Saloum Delta ; Saint-Louis River mouth	Tambaliza

Table 2 - Restorations actions undertaken for each site.

Sites/Restoration actions	Mangrove's replantation	Breakwater	Plant replanting for sediment maintenance	Rehabilitation of hydrological connections
Benin: Mono River mouth	X			X
Senegal: Saloum delta		X	X	
Senegal: Saint Louis River mouth	X		X	
Costa Rica: Cuajiniquil	X			X
Costa Rica: Chomes	Site abandoned during the project, no restoration actions			
Philippines: Tambaliza	X			X

Satellites images

- 11 No free open-access satellite covers several decades with very high resolution. Here, we are constrained to a choice between Landsat, which has been available since the 1980s with a 30-meter pixel resolution, and Sentinel-2, available since 2015 with a better resolution (10 meters). We decided to avoid mixing both satellites for one site. The landscape structures of the case studies vary: the three African case studies involve large mangrove patches, whereas the dynamics in Costa Rica and the Philippines concern small aquaculture ponds (some of which are represented by only one Landsat pixel).
- 12 Therefore, we opted for Landsat for the African sites, which allowed us to include a longer timescale in the restoration study, aiding in better interpretation of dynamics. Sentinel-2 was chosen for the other sites, limiting the temporal perspective but enabling detection of changes not visible with Landsat. To contextualize pre-

restoration conditions for these sites, we relied on other information sources, such as existing scientific literature and FFEM documents, when available, to provide a historical overview before the restoration efforts. The technical characteristics of the satellite images are presented in Table 3.

- 13 Two types of images are commonly employed in the literature for mangrove monitoring via remote sensing: high-resolution images (such as Landsat, Sentinel, or SPOT) with an average resolution of 10 to 30 meters, and very high-resolution images (such as WorldView, Quickbird, or IKONOS) with much finer resolution capabilities, sometimes less than one meter. The very high-resolution images are favored for visual interpretation and on-screen digitization classification, while high-resolution images are typically processed using pixel-based classification techniques (Alexandris *et al.*, 2013). High-resolution images are frequently used to monitor ecosystems at a regional or global scale, but they are often deemed too coarse for detailed local observations (Cissell *et al.*, 2018).
- 14 Beyond the question of spatial scale, the suitability of one method over the other is mainly dependent on the mapping objectives. As noted by Kuenzer *et al.* (2011), high-resolution images are not appropriate for local observations intended to differentiate species or visualize individual mangroves. Similarly, Alexandris *et al.* (2013) pointed out the difficulty in visualizing young mangroves smaller than three meters using these images. However, high-resolution images offer several advantages:
 - The temporal resolution allows for frequent mapping.
 - Long-term monitoring is facilitated by the availability of data spanning more than three decades.
 - Sentinel and Landsat images are free of charge, while very high-resolution images from private operators are costly and do not adhere to FAIR principles.
- 15 High-resolution imagery is the most useful data type for assessing restoration success (Kuenzer *et al.*, 2011). Despite these advantages, it is crucial to consider the limitations of this data type, which include reduced image precision, the expertise required for data analysis and interpretation, dependency on weather conditions, and the need for specific software.
- 16 To mitigate the limitation of image precision, a simplified nomenclature was adopted in this study to reduce classification errors. Additionally, a nested classification approach was implemented to minimize classification errors, an approach often overlooked in this type of study.
- 17 In summary, the choice to use Landsat and Sentinel images in this study is justified by the straightforward mapping objectives, data accessibility, and cost-free nature (Andrieu *et al.*, 2020; Upadhyay *et al.*, 2015). Furthermore, this study aims to synthesize different sites that require different scales and benefit from varying data volumes. The scale of the project (and the size of the surrounding mangrove systems) is the first driver of the choice between Landsat (large sites requiring regional comparison) and Sentinel (small sites surrounded by small mangrove areas). Understanding long-term dynamics to interpret short-term restoration is the second driver of image choice. For example, Sentinel-2 was chosen for Costa Rica due to the well-known history of the salt basin, whereas Landsat was chosen for Senegal to capture the complex climate variability.

Table 3 - Technical characteristics of the satellite images taken of the restoration sites.

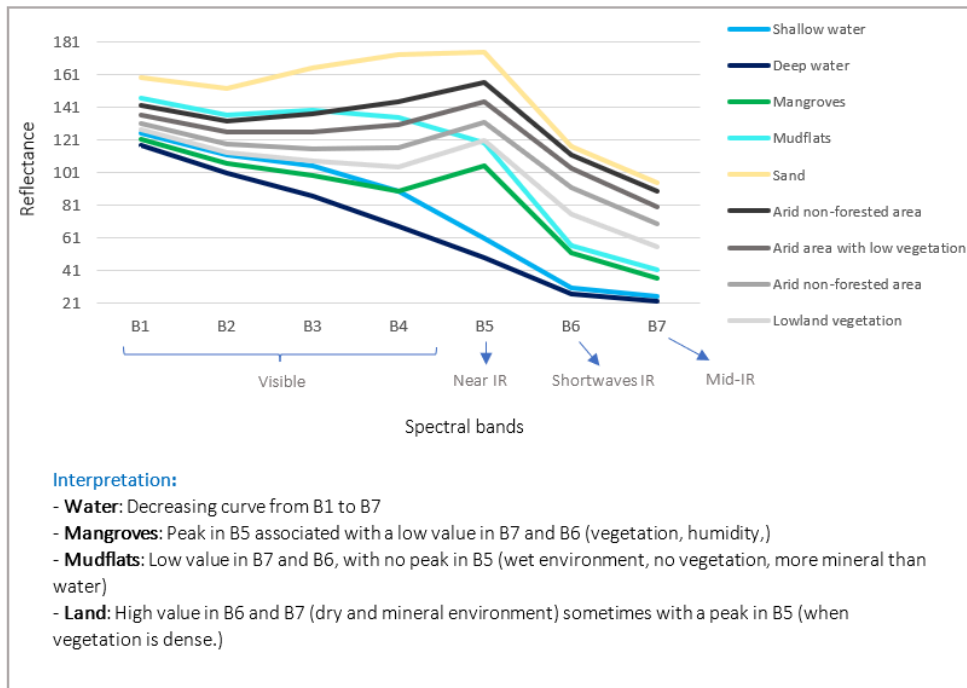
Sites	Location	Satellite	Resolution	Date
Costa Rica, Chomes	10°02'14.99" N 84°54'24.38" O	Sentinel 2	10m×10m	27/03/2016 04/03/2021
Costa Rica, Cuajiniquil	10°55'15.12" N 85°42'56.14" O	Sentinel 2	10m×10m	18/02/2016 23/03/2021
Tambaliza, Philippines	11°16'51.48" N 123°10'43.92" E	Sentinel 2	10m×10m	03/08/2016 30/03/2022
Senegal, Saint Louis River mouth	15°55'35.53" N 16°29'07.71" O	Landsat	30m×30m	10/03/1988 04/03/2017 20/03/2021
Senegal, Saloum Delta	13°54'11.05" N 16°43'45.76" O	Landsat	30m×30m	10/03/1988 19/03/2017 20/03/2021
Benin, Mono River mouth	6°17'46.16" N 1°55'45.13" E	Landsat	30m×30m	12/02/1988 04/03/2016 27/02/2021

Remote sensing processes

- 18 All image processing was done using the TerrSet® software.
- 19 We applied the simplest nomenclature: (1) water (coastal waters, rivers, and tidal channels); (2) mangroves (mangrove forests); (3) mudflats (salt flats in the upper-tidal zone or mud-banks in the lower tidal zone not covered by mangrove), this type does not occur in each site; (4) dry-land (all areas never flooded by tides).
- 20 As a first step, pan-sharpening or resampling was needed for Sentinel-2 images given that Sentinel-2 satellite sensors are equipped with 13 spectral bands of which 10 are used for our processing. Among these 10 bands, four have a spatial resolution of 10 m and the six others have a 20 m resolution. To process these images, we standardized the spatial resolution to 10 m by pan-sharpening.
- 21 We then mapped surface cover using a pixel-based unsupervised classification with nine classes by applying the K-means algorithm. We obtained images with nine classes and radiometric curves corresponding to their respective mean reflectance values. The analysis of each of these curves allowed us to match the cover type with the pre-established nomenclature to obtain a preliminary map of land cover (Figure 1).
- 22 The signature curves for one landcover category (eg. mangrove) may change slightly on one site at two dates (because of tides for example) and they differ between Landsat and Sentinel-2. However, the differences do not create a bias in the overall image processing because Clustering is not based on an automatic assignation of a class from a

spectral metric (eg. thresholding the NDVI). Clustering, instead, is based on the separability of classes on the global dataset. To be sure that the separability is high enough with both satellites, Accuracy assessment has been done on both.

Figure 1 - Radiometric curves defining nine classes of cover (Saint-Louis River mouth site, Senegal, 2017, Landsat 8 Operational Land Imager (OLI) sensor)



- 23 According to the method of the stacked Kmeans (Andrieu, 2018; Andrieu *et al.*, 2019) we proceeded to verify the mapping results with a series of stacked classifications within each of the four initial classes by applying the same K-Means algorithm. Four images each with five classes and associated mean reflectance curves were obtained for each of the water, mangroves, mudflats, and land classes. By analysing these curves, we can, if necessary, reassign classes during the first classification. More information on this process is presented in figure 2 and 3. In figure 2 and 3, the spectral diversity highlighted by the K-means algorithm reveals significant intra-mangrove heterogeneity, likely indicative of various ecological factors such as species composition, vegetative structure, and soil moisture. The first class of mangrove is the one showing the highest “peak” in the reflectance in Near Infrared. It corresponds to the green, dense, high canopies. The second class of mangrove is the one a much lower slope between red and Near Infrared (ie the NDVI). It corresponds to a less green, less dense, less high canopies but still a dense forest kind of spectral profile. The third class of mangrove is barely characterized by the peak in Near Infrared therefore a low and open vegetation, it corresponds to the transition between Mangrove and mudflat in the Senegalese zonation pattern. To apply a robust classification in space and time at a level of such a typology of plant formation a much higher volume of data is required (Rossi, 1996). However, to meet the requirements of our study on the effectiveness of restoration measures, we have adopted a simplified classification of mangroves. This approach ensures analytical clarity and facilitates the interpretation of results for environmental management and policy actions. This methodological simplification is

not intended to provide an exhaustive typology of mangroves but to verify the validity of the restoration at the landscape scale.

Figure 2 - Classification of cover within the mangroves class (Saint-Louis River mouth site, Senegal, in 2017, Landsat 8 OLI sensor)

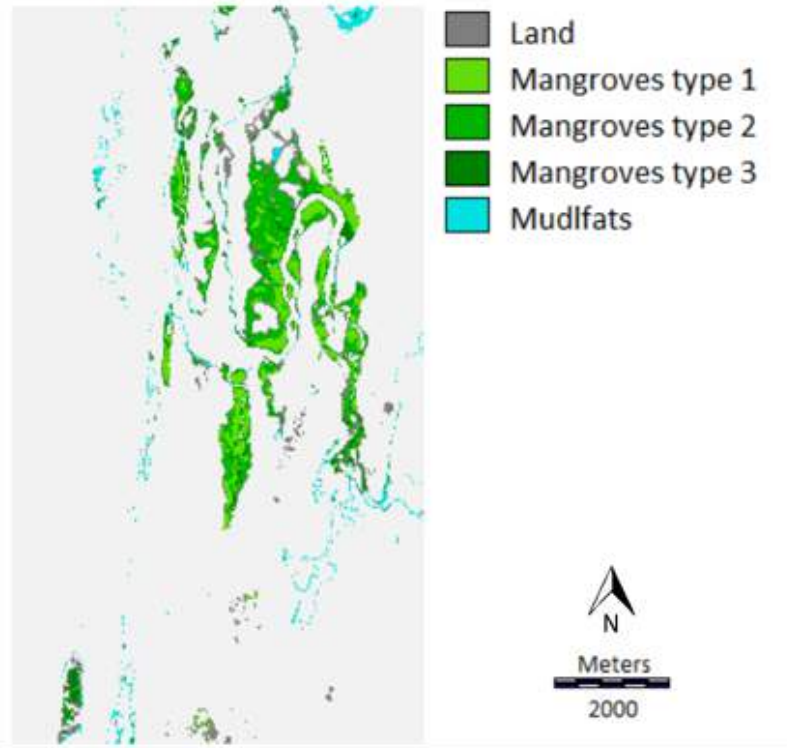
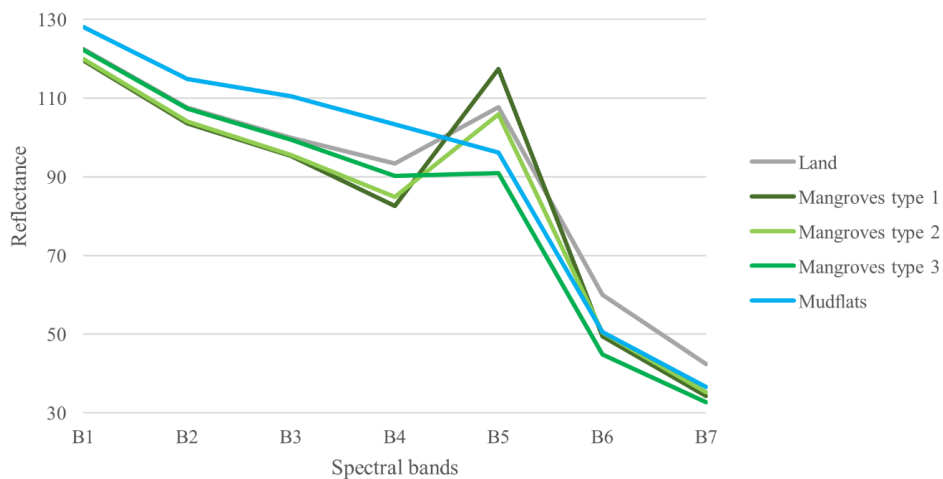


Figure 3 - Radiometric curves defining five classes stacked in the first mangroves cluster (Senegal River mouth site, Senegal, 2017, Landsat 8 OLI sensor)



- 24 Accuracy assessment based on ground truth could only be conducted for Benin, Senegal (Landsat), and Philippines' (Sentinel-2) sites. Ground verification of 40 points (10 points per class) for each site was done for the land cover classes. In the other sites, we therefore used images from Google Earth© to estimate an error rate in the

classification. The Kappa coefficients from the error matrix are presented in table 4. Table 4 show that the accuracy is satisfying on Both Sentinel and Landsat with very similar indexes.

Table 4 - Kappa coefficients from error matrix

Sites	Type of environment	Kappa coefficient of classes	Overall Kappa
Mono River mouth	Water	0.99	0.97
	Mangroves	0.96	
	Land	0.97	
Saloum delta	Water	0.99	0.93
	Mangroves	0.88	
	Mudflats	0.90	
	Land	0.96	
Senegal River mouth	Water	1	0.95
	Mangroves	0.95	
	Mudflats	0.89	
	Land	0.96	
Cuajiniquil	Water	1	0.96
	Mangroves	0.94	
	Mudflats	0.91	
	Land	0.99	
Chomes	Water	0.99	0.96
	Mangroves	0.92	
	Mudflats	0.96	
	Land	0.98	
Tambaliza	Water	0.98	0.95
	Mangroves	0.92	
	Mudflats	0.95	
	Land	0.96	

Results

- 25 For the African sites, a map of pre-restoration changes is first presented along with a table of changes in cover observed between the two periods. For all sites, a map of post-restoration changes is presented, along with a table with changes in hectares for each class and a table with percent and areal changes in mangrove cover. For sites where the exact location of restoration could be identified, we present a zoom on the restoration site with listing the percent and areal cover changes in mangroves. Comparisons of overall sites versus restored areas done here are useful to better differentiate natural regeneration from the direct effects of restoration.
- 26 For all the sites, the evolution of the mudflats is linked to the tidal coefficients (which varies the height of water on the surface), the tidal coefficients are presented in appendix table 2.

Mono River mouth, Benin

- 27 At the study site, the extent of mangrove cover approaches that of continental plant formations; hence, the class of mudflats devoid of mangroves is absent. Due to the inability to pinpoint the precise location of the restoration effort, we opted for a broader area that assuredly encompasses the project zone, as per the information supplied by the French Global Environment Facility (FFEM).
- 28 Examining the map depicting land and water cover alterations from 1988 to 2017, which is illustrated in Figure 4, a distinct diminution in mangrove coverage is evident. This contraction is prominent across the study region, especially to the north of the estuary. The documented decline is 23% (equating to a loss of 174.33 hectares) over 29 years, signifying an annual rate of decrease of 0.8%.
- 29 Turning to the post-restoration period, the map illustrating changes from 2017 to 2021, shown in Figure 5, reveals a considerable expansion in mangrove cover, a trend consistent across the study area. The observed augmentation is 39% (an increase of 228.24 hectares) in a span of merely 4 years, which translates to an impressive annual growth rate of 7.8%. Intriguingly, the mangrove coverage recuperated in these 4 years surpasses what was lost in the preceding 29 years.

Figure 4 - Detected changes in land and water cover for Mono River mouth site between 1988 and 2017 (Landsat 8 OLI sensor)

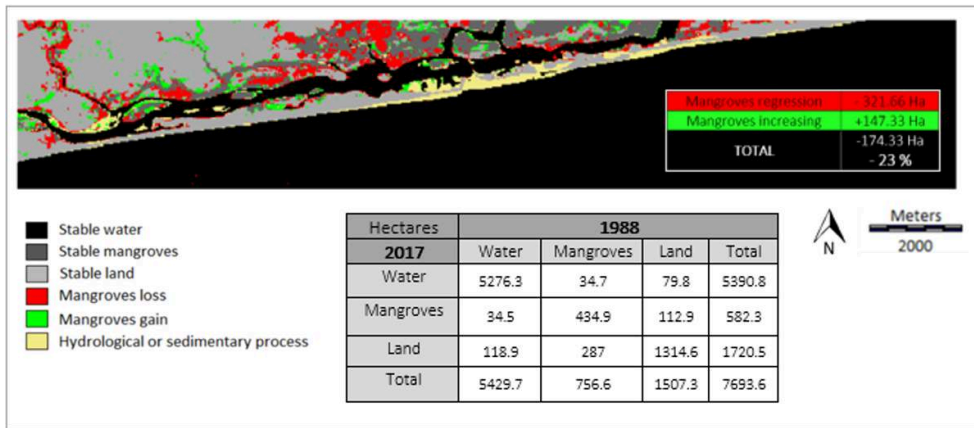
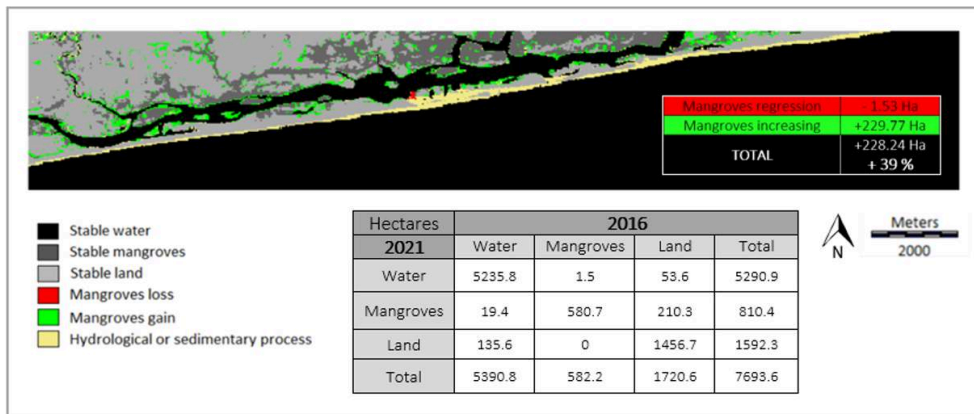


Figure 5 - Detected changes in land and water cover for Mono river mouth site between 2016 and 2021 (Landsat 8 OLI sensor)



Saloum Delta, Senegal

- 30 Figure 6 reveals that over the past 30 years, the mangroves of the western part of the Saloum Delta have undergone significant fluctuations, with pronounced periods of regression—specifically a decrease of 910.7 hectares, mainly observable in front of the Sangomar spit. Concurrently, there has been a uniform increase in cover of about 898.6 hectares along the upper edges of the mangrove clusters. Remarkably, after 29 years, the total mangrove cover has remained nearly constant with a negligible net change of -0.15%, despite the shifts in the geographical footprint of the mangrove forests over time.
- 31 The mapping of changes in land and water cover from 2017 to 2021, as depicted in Figure 7, demonstrates an expansion in the mangrove coverage across the study area. This growth has been consistent throughout, with an overall increase rate of 5.2% (equating to 431 hectares) in five years, or an estimated annual growth rate of 1%. Notably, within the restoration area, the rise in mangrove cover has been less pronounced, about threefold lower than in the entire area, with a 1.59% increase (which translates to 8.28 hectares) over five years, or an annual growth rate of approximately 0.3%.

Figure 6 - Detected changes in land and water cover for Saloum Delta site between 1988 and 2017 (Landsat 8 OLI sensor)

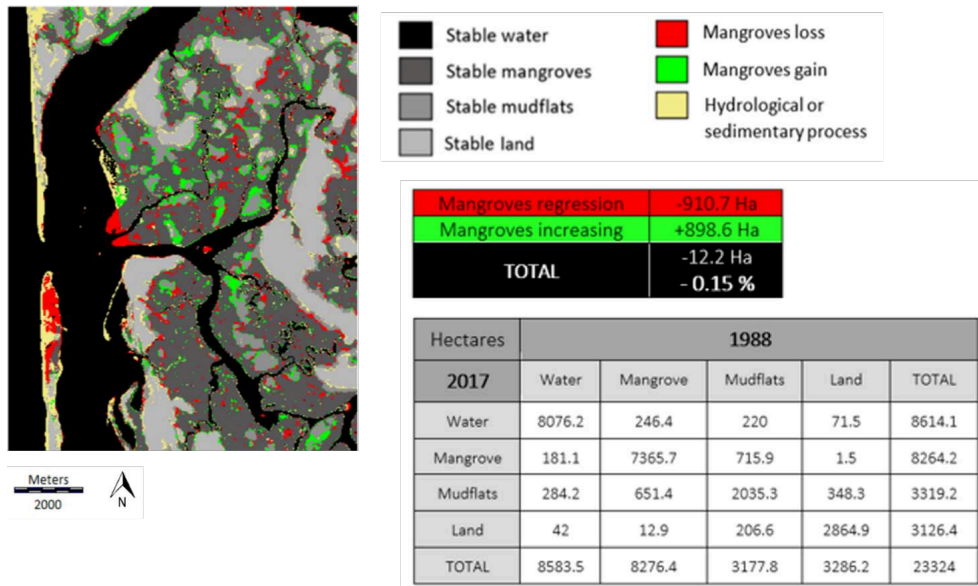
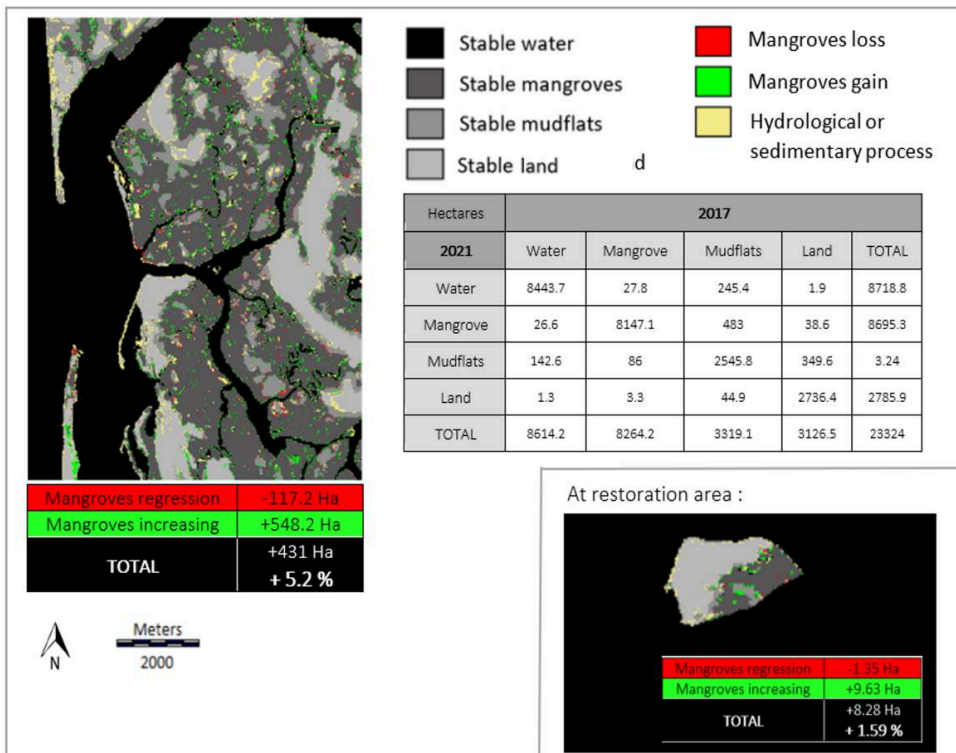


Figure 7 - Detected changes in land and water cover for Saloum Delta site between 2017 and 2021 (Landsat 8 OLI sensor)



Senegal River mouth, Senegal

32 In the land and water cover change map for the period between 1988 and 2017, shown in Figure 8, a notable regression of mangroves at the Saint-Louis River mouth sites was

recorded, amounting to a 28.5% decrease (representing a loss of 191.6 hectares) over 29 years. This equates to an approximate annual rate of loss of 1%. This decline was consistent across the entire study area.

- 33 Subsequently, the land and water cover change map between 2017 and 2021, as presented in Figure 9, indicates a 7.8% increase in mangrove cover, equivalent to an expansion of 32.5 hectares. This increase is primarily concentrated along the riverbanks of the Saint-Louis River mouth, adjacent to existing mangroves, corresponding to an annual rate of gain of approximately 1.56%. It is important to note that no increase in mangrove cover was detected at the actual site designated for restoration.

Figure 8 - Detected changes in land and water cover for Senegal River mouth site between 1988 and 2017 (Landsat 8 OLI sensor)

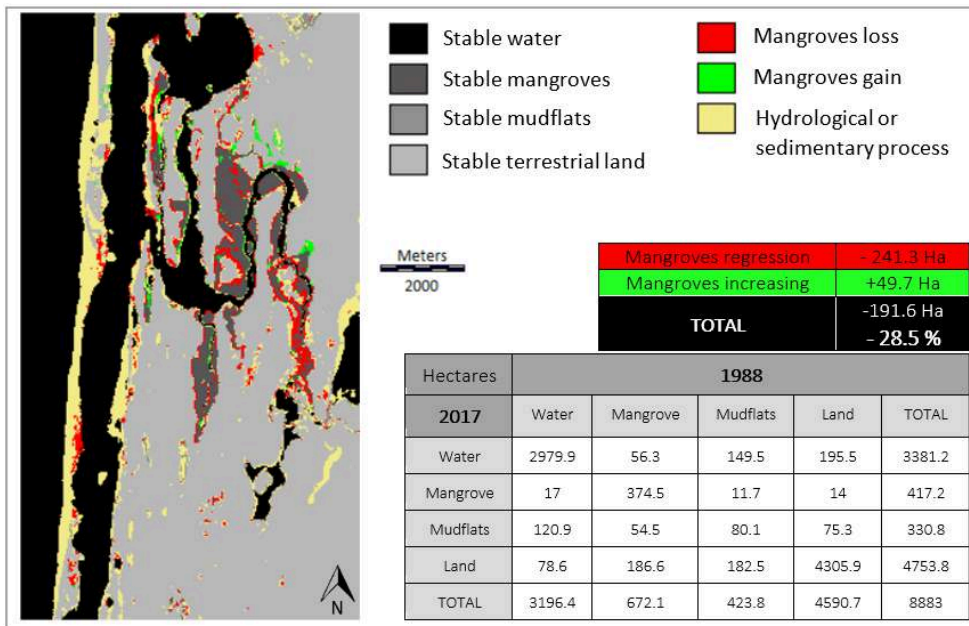
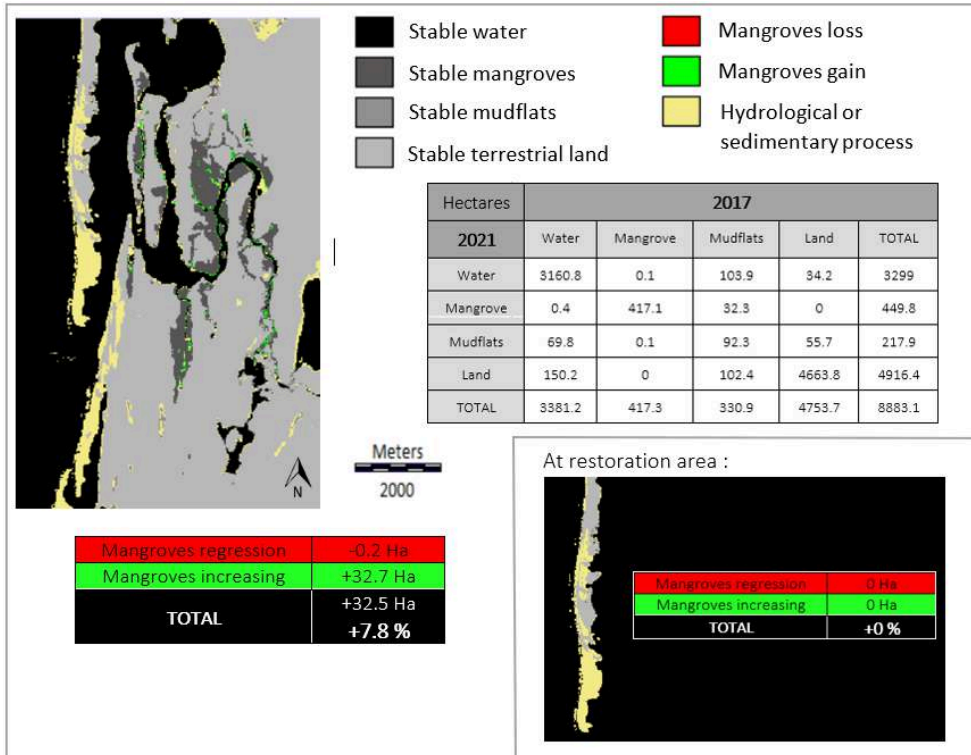


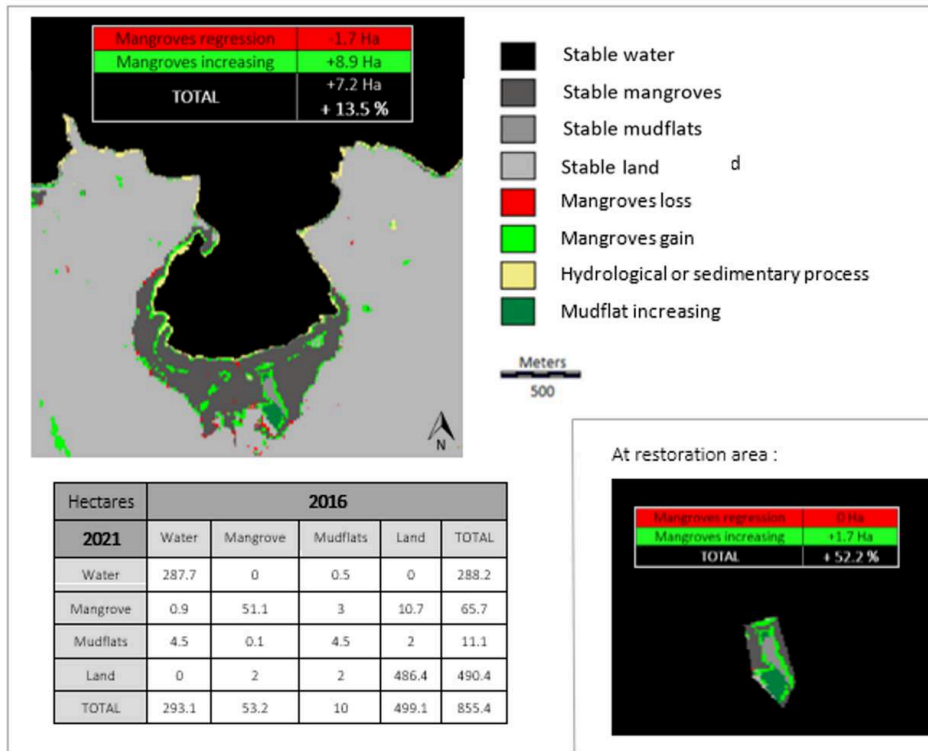
Figure 9 - Detected changes in land and water cover for Senegal River mouth site between 2017 and 2021 (Landsat 8 OLI sensor)



Cuajiniquil, Costa-Rica

- 34 On the map of detected changes in land and water cover between 2016 and 2021 presented in Figure 10, mangrove cover has increased by 13.5% (+7.2 Ha) all over the Cuajiniquil site, or an annual rate of gain of approximately 3%, and by 52.2% (+1.7 Ha) in the restoration area, or an annual rate of approximately 10%. There is also a strong sedimentary process in the restoration area driving the transformation of land into mudflats.

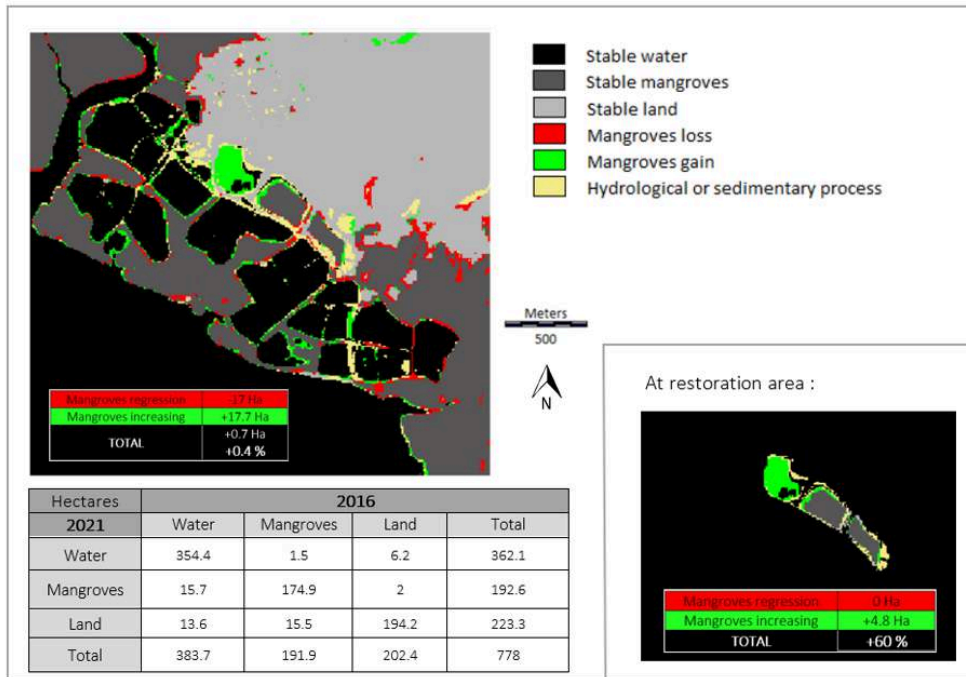
Figure 10 - Detected changes in land and water cover for Cuajiniquil site in Costa-Rica between 2016 and 2021 (Sentinel-2 sensor)



Chomes, Costa-Rica

- 35 For this site, mudflats without mangrove cover are covered by other plant formation (belonging to continental flora), consequently, the mudflat class does not appear.
- 36 On the map of detected changes in land and water cover between 2016 and 2021 presented in Figure 11, the mangrove surface in the whole study area is mainly stable between 2016 and 2021 with a very slight increase of 0.4%. However, there are zones of increased cover around the periphery of the aquaculture basins and zones of decreased cover in the eastern zone of the map. On the other hand, a clear improvement in mangrove cover is observed in the restoration area, with an increase of 60% (+4.8 Ha) in 5 years, i.e., an annual increase rate of 12%.

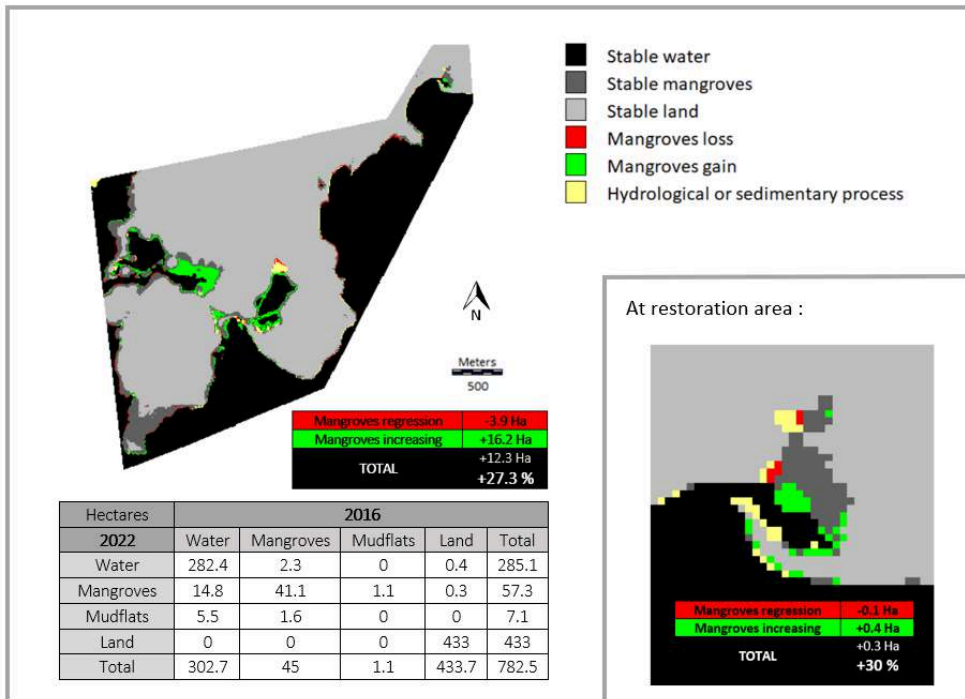
Figure 11 - Detected changes in land and water cover for Chomes site in Costa-Rica between 2016 and 2021 (Sentinel-2 sensor)



Tambaliza, Philippines

- 37 On the map of detected changes in land and water cover between 2016 and 2021 presented in Figure 12, the mangrove area has increased by 27.3% (+12.3 Ha) in 6 years, this increase is not homogeneous and is present in the form of 3 patches of progression of the pre-existing mangrove. Each of these patches is distributed in abandoned marine farms, respectively 2 larger ones in the south of the map and one smaller one in the north of the map, which corresponds to the mangrove restoration site. The increase observed at the restoration site is roughly the same as at the regional level with an increase in mangrove cover of 30% (+ 0.3 Ha) in 6 years, i.e., an annual increase rate of 5%.

Figure 12 - Detected changes in land and water cover for Tambaliza site in Philippines between 2016 and 2022 (Sentinel-2 sensor)



Discussion & Conclusion

38 First, in order to synthesize our results, table 5 shows the level of mangroves changes post-restoration using a simplified scale. For each project, we will discuss the potential reasons for their success and/or failure according to the ecological context of each site and a bibliography study. Finally, we will try to draw lessons from these different projects.

Table 5 - Changes in mangrove cover for the sites analysed in this report

Sites	Post-restoration changes throughout the area	Post-restoration changes in the restoration area
Benin: Mono river mouth	Very good	Little improvement
Senegal: Saloum Delta	Little improvement	No change
Senegal: Senegal river mouth	Little improvement	No change
Costa Rica: Cuajiniquil	Good	Very good
Costa Rica: Chomes	No change	Very good

Philippines: Tambaliza	Good	Good
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(No change: < 2%; Little improvement: 2-10%; Good: 10-30%; Very good: > 30%)

Results interpretation by site

Mono River mouth, Benin

- 39 Regrettably, the precise location of the restoration site remains unknown to the project owners, hindering the ability to conclusively attribute observed improvements to either restoration actions or natural recovery. Despite this, the uniform and homogeneous increase in mangroves across the entire site suggests that the phenomenon may be due to natural regeneration rather than project-induced actions.

Saloum Delta, Senegal

- 40 Increases in mangrove cover in the upper fringe, as documented by Andrieu *et al.* (2020) and Lombard & Andrieu (2021), were attributed to spontaneous regeneration following the recovery of rainfall in West Africa. This phenomenon explains the observed increase in mangrove cover since 2017. However, the enhanced cover within the restoration area is four times less than the overall increase in mangrove cover, indicating that the regeneration is primarily natural. As noted by Andrieu *et al.* (2020), the project did not significantly contribute to the fortification of the mangrove cover.

Senegal River mouth, Senegal

- 41 Mangrove cover exhibited a consistent increase and homogeneity across the site. There was no concentrated regeneration at the designated restoration site, suggesting a naturally occurring phenomenon influenced by increased rainfall since 1998, as documented by Andrieu *et al.* (2020) across Senegal. This aligns with observations in other regions where the project did not significantly contribute to enhancing or fortifying the spontaneous regeneration of mangroves.

Cuajiniquil, Costa-Rica

- 42 The regeneration in the restoration area was observed to be four times higher compared to the remaining site, indicating the effectiveness of the restoration efforts. Additionally, the emergence of a mudflat area to the south of the restoration site, likely associated with irrigation channels, was noted. This emergence was unrelated to tidal effects. The restoration efforts have proven effective; however, continued monitoring over the subsequent years is imperative to observe the complete recovery of mangroves at this site.

Chomes, Costa-Rica

- 43 Mangrove cover within these abandoned ponds has experienced significant natural growth; a phenomenon not observed elsewhere. These ponds were initially chosen as restoration sites due to early signs of re-vegetation. Consequently, this site serves as a

compelling illustration of the spontaneous and significant natural regeneration occurring in abandoned aquaculture ponds without human intervention.

Tambaliza, Philippines

- 44 The observed increase in mangrove cover at the restoration site is likely associated with the broader regional trend of mangrove expansion, indicating a pre-existing natural regeneration dynamic. The restoration actions appear to have facilitated and complemented the ongoing natural regeneration process already underway in the area.

General interpretation

- 45 First and foremost, this work shows that mangrove restoration actions are not always the primary driving force behind the recovery of vegetation cover. In several cases studied, the natural regeneration of mangroves appears to have played a predominant role in vegetation recovery, underscoring the importance of understanding the inherent ecological processes and resilience dynamics of mangroves (FAO, 2023). Climatic variations, particularly increased precipitation following periods of drought (1960s to the early 1990s), seem to have had a significant impact on mangrove regeneration, as observed in the Saloum Delta and at the mouth of the Senegal River. This highlights the need to consider macro-environmental factors in the planning and evaluation of restoration projects.
- 46 Secondly, human-led restoration efforts in mangrove environments have demonstrated various levels of success, with some areas showing significant signs of regeneration, particularly where specific ecological deficits have been addressed through targeted interventions. For example, in Cuajiniquil, Costa Rica, focused restoration practices have substantially enhanced mangrove recovery beyond natural trends, emphasizing the potential of well-planned human actions supported by thorough physico-chemical assessments. These interventions often aim to restore natural hydrological and edaphic conditions, which are crucial for the recovery of these ecosystems. Similarly, restoration efforts in former aquaculture ponds or abandoned salt pans have shown pronounced signs of success, suggesting these as favorable sites for future projects. These findings align with broader research indicating that hydrology is a critical factor in effective mangrove restoration (Lewis, 2005), and are further supported by studies highlighting the positive outcomes of restoring hydraulic connections alongside mangrove replanting (Flores-Verdugo *et al.*, 2007; Flores-Verdugo & Agraz-Hernández, 2006). The targeted restoration of previously degraded areas, when tailored to the unique conditions and historical impacts of the ecosystem, not only revives ecological functions but also offers vital insights into the management and recovery of similar ecosystems globally. This pattern of recovery underscores the complexity of interactions within mangrove ecosystems and the need for ongoing, detailed monitoring to evaluate the long-term effects of restoration interventions, especially those altering sediment dynamics which may present challenges discernible only over extended periods.

Limits

Satellite images

- 47 The combination of Landsat and Sentinel-2 needs to be discussed as a possible limitation of this study. In terms of spatial resolution, what can be sensed in a 30-meter pixel is not very different from what can be sensed in a 10-meter pixel (where part of the data is pansharpened from a previous 20-meter pixel). At both resolutions, small tree patches are sensed, but small plants are not. The main hiatus in spatial resolution is with very high-resolution sensors (below 1 meter), where individual plants are sensed rather than just plant formations. In terms of spectral resolution, Sentinel-2 offers more bands for multispectral analysis, making a raw analysis of spectral indexes less robust. The chosen method (clustering) is based on the separability of classes on the multispectral data scatterplot, not on a comparison of spectral indexes. According to a detailed comparison study by Mandanici and Bitelli (2016), although there are minor spectral and radiometric differences between the two satellite sensors, their corresponding bands generally show high correlation coefficients, suggesting they can be effectively combined for monitoring applications. This finding supports the use of both Landsat 8 and Sentinel-2 data in a unified classification method across different restoration sites, provided that consistent data preprocessing is applied to minimize potential biases (Mandanici & Bitelli, 2016). Therefore, despite the inherent differences in sensor technology, the consistent application of classification methodologies ensures reliable and comparable results in mangrove coverage assessments across multiple sites. The three African sites show very little to no increase at the very local scale and short timescale of the project. This might be explained by conceptual flaws in these projects. For example, both Senegalese sites had a direct objective on sedimentation, expecting an indirect effect on the mangrove. Another explanation might be a lesser detection of minor mangrove patches that might have been detected with Sentinel-2 but not with Landsat. However, Landsat has been successfully used on the Saloum Delta for change detection over a slightly longer timescale (Andrieu, 2018).

Comparisons of sites spread over several world regions

- 48 The comparison of mangrove restoration sites across various world regions poses significant challenges that may impact the generalizability of findings. Environmental and socio-economic variations across different geographic areas can introduce biases in interpreting results, making it difficult to draw broad conclusions. For instance, the ecological conditions such as soil type, salinity levels, and water quality differ markedly between regions like Southeast Asia and Central America, affecting the growth rates and survival of planted mangroves (Alongi, 2002; Bosire *et al.*, 2008). Socio-economic factors such as the availability of funding, community engagement, and local governance also play crucial roles in the success of restoration projects and can vary widely between sites (Barbier *et al.*, 2011; Walters, 2005). Moreover, the historical use of land and previous environmental degradation levels can affect the initial conditions of restoration sites, potentially skewing outcomes (Lewis, 2009). These variations necessitate a cautious approach when comparing sites and suggest that while general patterns can be observed, specific site conditions and local factors must always be considered in the interpretation of restoration success. However, these general interpretations are nonetheless essential, as comprehensive studies on mangrove

restoration are scarce. Despite geographical differences, mangroves exhibit similarities globally, which underscores the need for a global approach. Yet, this must be complemented by local strategies to effectively implement or evaluate mangrove restoration projects, ensuring that both universal and site-specific factors are adequately addressed.

- 49 Finally, while the primary focus of this research was to evaluate the success of mangrove restoration projects through biophysical and spatial assessments using remote sensing, acknowledging a social approach could provide valuable insights. Assessing past human drivers of change, gauging local awareness regarding mangrove protection and management, and understanding the community's confidence in participating in ecosystem restoration efforts would enrich the overall understanding of the restoration context.

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ABSTRACTS

Mangrove restoration projects have multiplied in last decades, but many have failed, and monitoring is often lacking. This paper aims at monitoring six projects in Benin, Senegal, Costa Rica, and the Philippines using remote sensing to evaluate the effectiveness of the studied restoration measures in terms of increase of mangroves cover. An unsupervised staked classification was performed to discriminate the land cover into four classes: water, dryland, mudflats, and mangroves. Projects combining hydrological restoration and mangrove replanting are the most effective and former aquaculture ponds or salt pan show rapid and regeneration, even without active restoration.

Les projets de restauration des mangroves se sont multipliés au cours des dernières décennies, mais beaucoup ont échoué et le suivi fait souvent défaut. Cet article vise à suivre six projets au Bénin, au Sénégal, au Costa Rica et aux Philippines en utilisant la télédétection pour évaluer l'efficacité des mesures de restauration étudiées en termes d'augmentation de la couverture de mangroves. Une classification non-supervisée emboîtée a été effectuée pour distinguer l'occupation du sol en quatre classes : eau, terre ferme, vasières et mangroves. Les projets combinant la restauration hydrologique et la replantation de mangroves sont les plus efficaces et les anciens bassins d'aquaculture ou salines montrent une régénération rapide, même sans restauration active.

INDEX

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