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Research Article

Shrimp farming and mangroves: entities in conflict?

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ABSTRACT. This study quantifies the possible effects on mangrove forests from activities associated with shrimp farms operating in a shrimp farming development pole in northwestern Mexico. Remote sensing and Geographic Information Systems (GIS) were used, specifically ERDAS Imagine 10 and ArcGIS. Satellite image classification consisted of a statistical method by which, through a sampling of pixels, the rest of the pixels of the image were grouped into categories or classes. Two classification methods were used: supervised and unsupervised. The Normalized Difference Vegetation Index (NDVI) was computed using remote sensing data to monitor patterns of vegetation change. Results indicated a 1.8% increase in mangrove area and a 5.8% increase in mean NDVI values for the years considered (2013-2020). The results of this study are the first to show evidence that shrimp farming is not responsible for mangrove deforestation and that, by considering the original area of this plant community, its development, and health are not necessarily compromised by the presence of shrimp farms.

Keywords: wetlands; deforestation; coastal management; GIS; NDVI; Gulf of California

INTRODUCTION

The growth of aquaculture in coastal regions has increased the demand for land and water bodies, leading to extensive wetland reclamation in tropical areas (Lin et al. 2018). However, wetlands possess high productivity and nutrient retention capabilities, making them more productive than even the most fertile agricultural fields (Hammer& Bastian 2020). Therefore, we propose integrating shrimp farming and mangroves as part of landscape management scenarios. The European Landscape Convention defines landscape as "any part of the territory perceived by the population, the character of which is the result of the action and interaction of natural and human factors" (Déjeant-Pons 2006), emphasizing the necessity of an inclusive approach to management that considers both natural and human factors.

The advantages of mangroves and shrimp farming are indisputable, as each offers numerous benefits to individuals. Mangroves have been extensively studied and have been shown to provide a range of ecosystem services (Carvajal-Oses et al. 2019, Verhagen 2019). On the other hand, shrimp farming holds significant economic and nutritional advantages (Wirth et al. 2007, Tacon et al. 2020).

However, this aquaculture infrastructure has presented mangrove deforestation (Ahmed et al. 2018), which is an unsustainable practice as it leads to the destruction of mangrove forests and marshes (Páez-Osuna 2001, 2005, González-Ocampo et al. 2006).

Initial evaluations of mangroves (Ramírez-García et al. 1998) in the Mexican state of Nayarit from 1970 to 1993 estimated a 23% loss of mangrove forest covering 1065 ha. A comparable reduction was also reported for Sinaloa, Mexico (Ruiz & Berlanga 1999). However,

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these early studies highlighting the decline of mangroves did not provide visual evidence or other substantiation linking the loss of vegetation cover to the construction of aquaculture infrastructure.

Typically, a shrimp farm infrastructure includes an intake channel, which facilitates the inflow of seawater from a neighboring coastal lagoon system or, occasionally, from an oceanic source. Moreover, a reservoir or inner channel is typically designed to provide the necessary water volume for sustaining at least 10% of the daily pumping requirements before the water is directed to the earthen growing ponds. Eventually, the water is discharged back into the coastal lagoon system through a designated harvesting or discharge channel.

In Sinaloa, Mexico, approximately 40,000 ha of water surface area are allocated for aquaculture production. This expansive surface area corresponds to an estimated shrimp harvest of about 99,000 t, with an approximate market value of US$ 500 million (CONAPESCA 2018).

Our study aims to quantify the specific impact of shrimp farming construction, rather than shrimp farming operation, on mangrove areas. We establish a baseline mangrove area and compare it to the current area following the establishment of aquaculture facilities. By employing rigorous methodologies and spatial analysis techniques, our objective is to precisely assess the direct effects of shrimp farming infrastructure on mangrove loss or gain within the study area.

Our study aimed to test the hypothesis that establishing coastal shrimp farming infrastructure would result in mangrove deforestation. We utilized remote sensing and Geographic Information Systems (GIS) analyses to examine whether the alteration of mangrove areas was directly attributed to the construction of shrimp farms in a designated aquaculture farming development hub in northwestern Mexico.

MATERIALS AND METHODS

Study area

The study area is located in northern Sinaloa, Mexico, coordinates 25°36'N, 109°06'W. Within the Ramsar site number 107 on the national list and 2025 on the Ramsar list, known as "Lagunas de Santa María-Topolobampo-Ohuira". The original polygon representing the study area was obtained as a KML file from the webpage [http://www.conanp.gob.mx/conanp/dominios/ramsar/lsr.php]. However, due to the lack of provided geographic or Universal Transverse Mercator (UTM) coordinates on the webpage, we converted it into the DraWinG (dwg) format using Global Mapper v19.0 software. We extracted the UTM coordinates of the boundary between the shrimp farms and the mangrove vegetation from the delimited site. The resulting polygonal area encompassed 10,091.24 ha, with a northern distal part measuring 30,910 m in length (Fig. 1).

Landscape characterization

A land cover classification map of the study location was generated using LANDSAT satellite imagery, considering hectares of mangrove and non-mangrove vegetation. A supervised classification approach was employed to assess the accuracy of the classification. The confusion matrix was utilized to evaluate the classification accuracy by comparing the classified image with reference data. This matrix quantifies the degree of agreement between the classified image and the known reference data, enabling the calculation of various accuracy metrics. These metrics provide a scientific and technical measure of the classification's reliability and alignment with the ground truth data.

The study site comprises a mangrove forest, primarily characterized by the presence of three main mangrove species: black mangrove (*Avicennia germinans*), white mangrove (*Laguncularia racemosa*), and red mangrove (*Rhizophora mangle*). These species are considered of significant ecological importance and are subject to "Special Protection" status as per NOM-059-SEMARNAT-2010 (NOM-059-SEMARNAT, 2010; Official Mexican Standard 059 of the Secretariat of Environment and Natural Resources).

The shrimp farms are situated close to the mangrove forest. These shrimp farms have been established gradually, creating new infrastructure and modifying and rehabilitating existing ponds. The earliest satellite image records indicating the development of shrimp farming infrastructure date back to 1995.

The study area can be characterized as a flat plain with a gentle slope, typically classified as a "marsh" or flood zone. It is devoid of agricultural or livestock activities. Within this area, semi-intensive aquaculture practices are observed, with stocking densities below 12 ind m^{-2}. The ponds used for shrimp cultivation exhibit irregular shapes and vary in size from 2 to 10 ha.

Satellite imagery offers a rapid and extensive monitoring capability for data acquisition on a large scale (Samsuri et al. 2021). Following the methodology outlined by Nath et al. (2000), we identified the project requirements, specifically focusing on detecting lands-

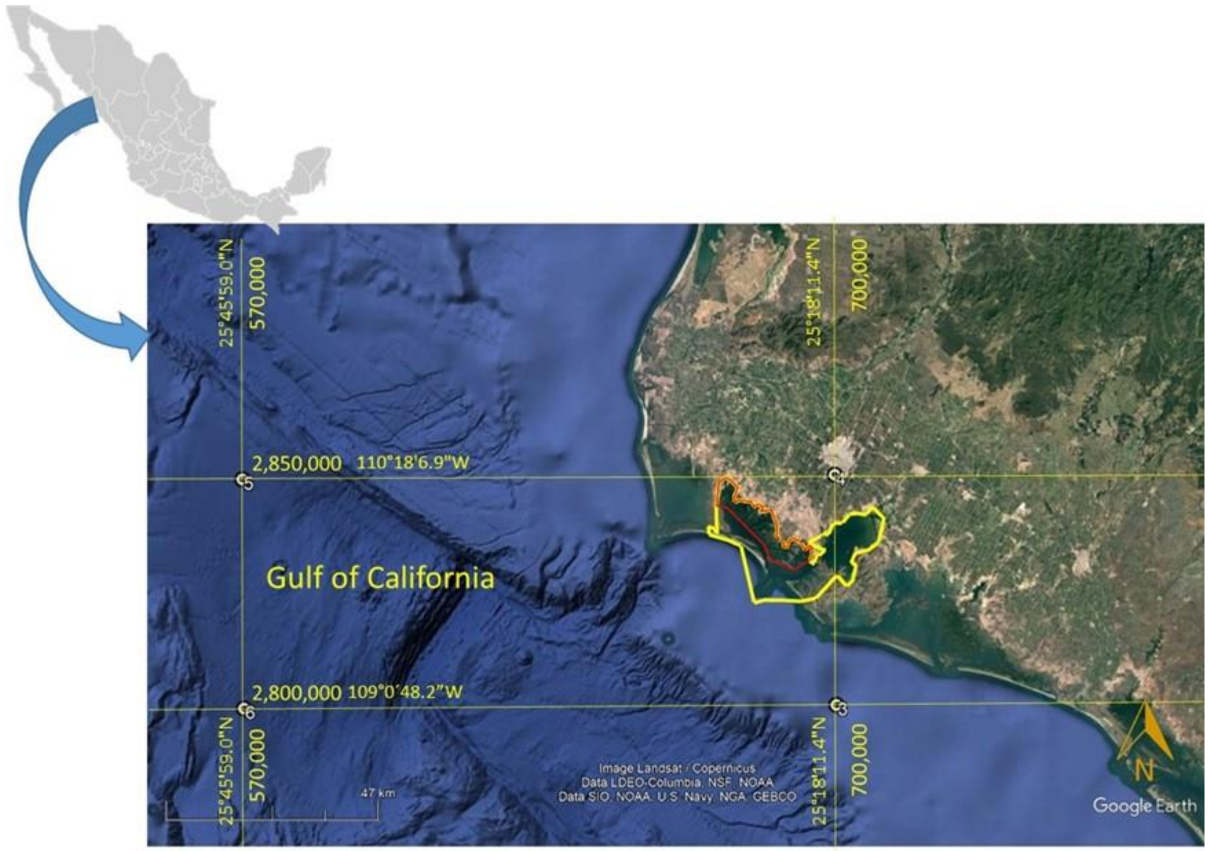

Figure 1. The figure illustrates the spatial extent of the study area, with the yellow line representing the polygon assigned to Ramsar Site number 107, officially recognized as "Lagunas de Santa María-Topolobampo-Ohuira" and listed as Ramsar Site number 2025 at both national and international levels. The red line represents the polygon under study, focusing specifically on the mangrove vegetation adjacent to shrimp aquaculture infrastructure within the Ramsar Site. The specific coordinates for both illustrations are provided as an attachment for easier reference while reading the text.

cape changes related to mangroves and aquaculture activities. The specifications were then formulated to capture these changes. Given the study's scope, we did not differentiate the reflectance values of individual mangrove species in the satellite imagery. Instead, we considered the entire mangrove forest a unified entity, as defined by Rützler & Feller (1988), encompassing plant species exhibiting morphological and physiological characteristics suitable for thriving in tidal marshes.

Giri et al. (2011) suggested that moderate-resolution data, such as Landsat, provide sufficient detail to capture the distribution and dynamics of mangrove forests. However, very small patches of mangroves, measuring less than 900-2700 m^2, may not be identifiable using this data. Therefore, our study utilized Landsat imagery and selected a 5000 ha (50,000,000 m^2) mangrove area for detailed examination.

Within the analytical framework, the specific research question focuses on understanding the relationship between the construction of aquaculture infrastructure and its impact on mangroves. The study aims to differentiate changes in vegetation cover specifically caused by the establishment of aquaculture infrastructure, excluding other potential factors not addressed in the literature review.

Band composition

Spectral bands from satellite images were obtained for the years 2013, and 2020 (Fig. 2). Table 1 presents the relevant details of the images, including acquisition year, satellite source, date, spatial resolution (in meters), resolution type, and corresponding identifier (ID). In our study, we utilized publicly accessible satellite imagery with a spatial resolution of 10 m, ensuring cost-free image acquisition.

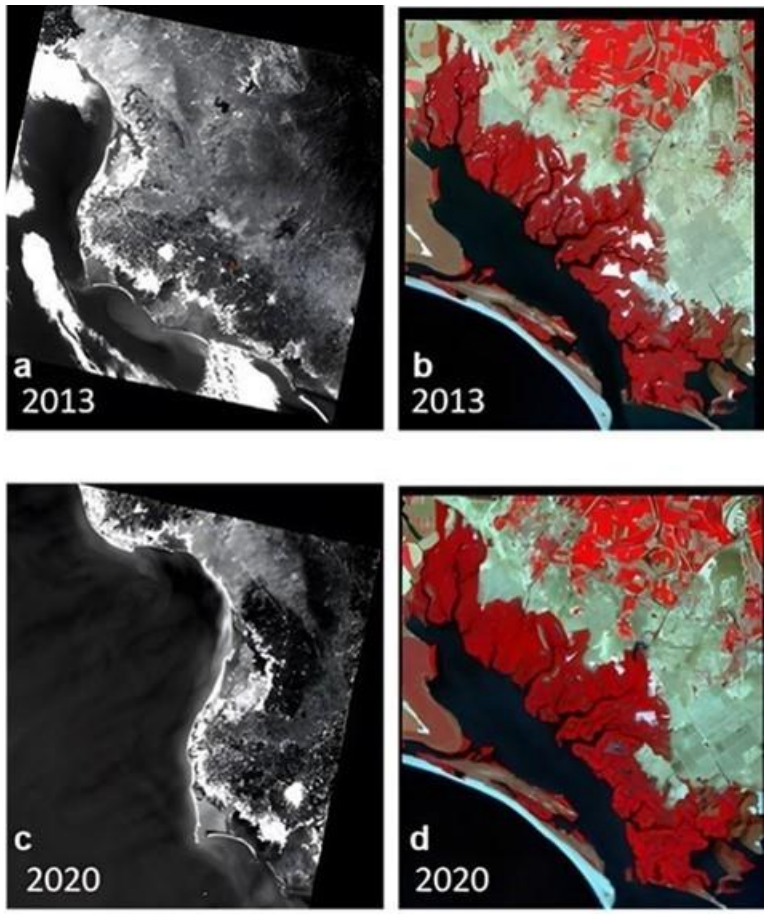

Figure 2. Satellite images were downloaded from Landsat 8 satellite. Two satellite images were used: a-b) from 2013, showing farms already operating before the Ramsar datasheet was presented, and c-d) from 2020, where farms were operating and built more recently. A mask or polygon was created by defining precise geospatial boundaries that enclosed the area of interest, excluding other regions irrelevant to the analysis. This mask overlaps the general image, restricting the analysis only to the area delimited by the polygon. This masking or clipping technique focuses solely on the region of interest, eliminating interference or noise from surrounding areas irrelevant to the study. This way, a more detailed and precise analysis can be performed in the specific area of interest.

Table 1. Landsat 8 product identifier for each of the two selected years.

Year	Image	Date	Spatial resolution (m)	Resolution type	ID
2013	Landsat 8	03/18/2013	10	Medium	LC08_L1TP_033042_20130318_20170310_01_T1
2020	Landsat 8	02/25/2020	10	Medium	LC08_L1TP_034042_20200225_20200313_01_T1

We employed an error matrix technique to identify vegetation and analyze changes around the aquaculture infrastructure to address potential limitations stemming from the image resolution. This approach allowed for accurate identification and analysis of vegetation cover changes, specifically related to the construction of aquaculture infrastructure, while accounting for any deficiencies in the image resolution.

Satellite image classification

Remote sensing and GIS software, including ERDAS Imagine 10 and ArcGIS, were employed in this study to locate relevant data sources, organize and manipulate input data, analyze data, and verify results.

The classification of satellite images involved a statistical approach, wherein a sample of pixels was used to assign the remaining pixels in the image to

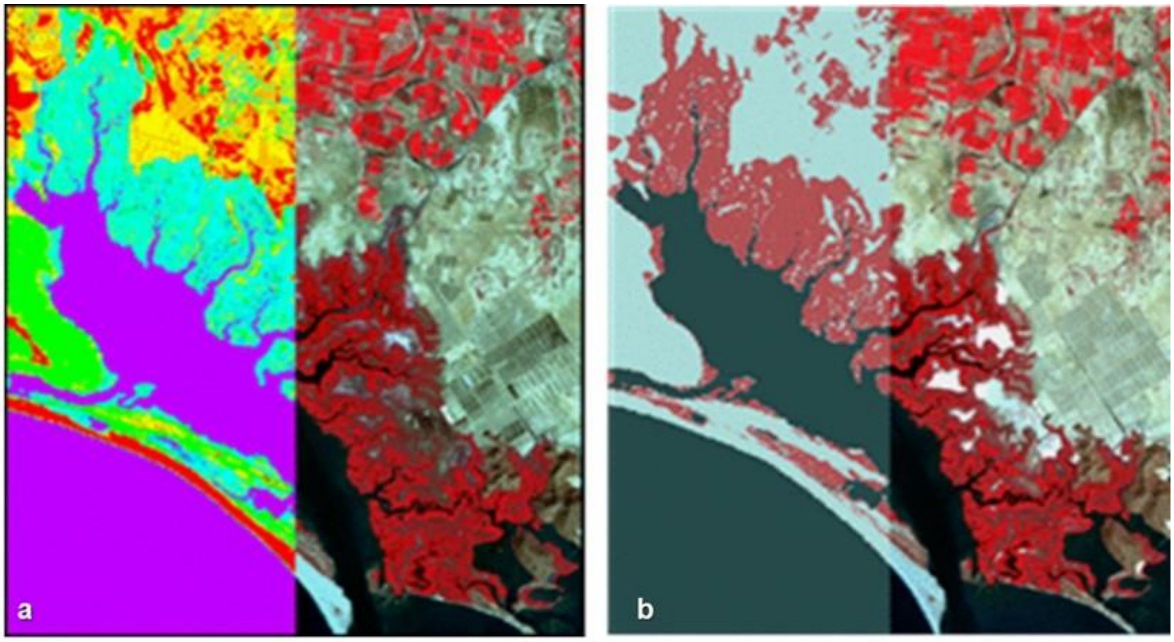

Figure 3. a) Unsupervised, and b) supervised classification, grouping the rest of the image pixels into categories or classes. Unsupervised classification involves grouping image pixels into clusters or classes based on their statistical properties without predefined training samples. It uses algorithms like clustering to identify patterns and similarities in the data analyzing pixel spectral characteristics to assign them to different classes. This method allowed predefined training samples or reference data to classify image pixels into specific categories or classes. Training samples represent known land cover types, and the algorithm learns from them to classify the remaining pixels. Thus, representative training samples associated with specific land cover classes were manually selected. The algorithm classified pixels based on their spectral similarity to the training samples.

specific categories or classes (Puebla & Gould 1994, Chuquichanca-Vara 2020). Two classification methods were applied: unsupervised and supervised classification (Fig. 3).

Georeferencing

Geographic coordinates and UTM coordinate systems were used to reference the farms within the study area, including ponds, water intakes, discharge channels, and other relevant features. The satellite system or map data based on WGA 84 ensured consistent referencing while maintaining a consistent north reference using the magnetic mode setting on the GPS devices (adapted from COFEPRIS 2009).

Field verification was conducted using a portable GPS Garmin GPSMAP 64x during three survey trips to the aquaculture development. Due to accessibility challenges, such as thick brush, not all previously identified points could be verified in the field. The field trips were carried out during the dry season to minimize access difficulties encountered during the rainy season.

Normalized Difference Vegetation Index (NDVI)

The Normalized Difference Vegetation Index (NDVI) is a ratio that quantifies the functional characteristics of active vegetation by comparing the reflectance of near-infrared (NIR) and red (Red-R) bands (Rodríguez-Moreno & Bullock 2013). The utilization of NDVI in remote sensing has proven highly valuable in monitoring changes in vegetation patterns (Nath 2014).

In this study, we considered natural factors to have minimal impact on changes in mangrove extent compared to the influence of aquaculture pond establishment for shrimp production. Therefore, land cover classification was performed using satellite images from 2013 before the current aquaculture development.

The resulting data were subjected to statistical analysis using the Student's *t*-test to determine whether there is a significant difference between the mean NDVI values of 2013 and 2020. We assumed a normal distribution of NDVI values and set the significance level (α) at $P = 0.05$.

Determination and distribution of the representative sample

A total of 104 points were generated to validate determinations for the "mangrove" and "non-mangrove" classes for years 2013 and 2020 (Fig. 4). Sampling points were generated using ArcGIS software, with an equidistant separability of 1000 m between each of them. This sample determination is referred to the number of sampling points used to estimate the reliability of the generated map. Although there is no standard setting for defining the optimal percentage of hit-and-miss observations, Congalton (2009) suggests choosing a minimum of 50 samples for each map class.

Points where the presence of mangrove and where the absence of mangrove was identified; in both cases, considering the accuracy of the author, as well as for the error of omission. The accuracy of the generated map was determined with an "Error Matrix," allowing us to estimate accuracy and errors (errors of omission and commission) associated with the generation of the map from the comparative crossing of the interpretation and the values of the classes assigned in the map (mangrove and non-mangrove) for each of the 104 validation points of years 2013 and 2020 (Tables 3-4).

Shrimp infrastructure

Referenced polygons of shrimp farms operating in the study area were obtained from satellite images, and these farms were grouped into blocks (Fig. 5). The site was divided into three blocks separated by marshes, with no mangrove vegetation in the lateral part that separates these blocks.

Considerations

We understand the importance of obtaining updated data and references. However, due to the nature of the study and the hypothesis being tested, we have included some earlier references from previous years that have guided the generalization and management of this potential conflict in the entities studied.

RESULTS

Shrimp infrastructure

Shrimp farms operating in the study area were grouped into blocks (Fig. 5). The site was divided into three blocks as described hereinafter:

Block 1 comprises farms located in the northernmost part, Block 2 corresponds to the infrastructure group in the central part of the study area, and Block 3 includes farms in the southernmost part. The selected area had a total surface of 2688.6 ha for shrimp ponds. The total surface of the incoming water channels was 161.084 ha, and 215.022 ha were considered for potential deforestation in the harvesting channels.

Three types of structures or infrastructure are considered for the operation of a shrimp farm, and all three are equally important. However, the ponds demand the greatest area, followed by the incoming water canal, reservoir, and harvesting canals. The ponds are made of earthen material with an irregular shape formed from lateral cuts in the land, which in this case comprised a total area of approximately 2688.6 ha.

The first structure in direct contact with seawater, where eventual mangrove deforestation occurs, is the incoming water canals, which refer to excavations and extensions for seawater to be pumped into the farm for the initial flooding of the pond and for maintaining pond water quality via water replacement. The calculated surface area for this infrastructure was 161.1 ha.

Harvesting canals, which ideally would have the same characteristics as the incoming water canal, were generally designed to be connected with existing natural canals flowing into the coastal lagoon system; therefore, their length and characteristics depended to a large extent on the geography of the site. The calculated surface area for this infrastructure was 215 ha.

Block 1. In this case, where the northern farms are located, the total area of incoming water canals is 360.7 ha, and the width of access to seawater is currently 34.93 m, showing an evident process of mangrove recolonization. This area has shown the least development or growth after the initial farms were completed. According to historical records from satellite images, the first recorded area was in 1998, with approximately 165 ha.

The mangrove recolonization process is associated with banks along the incoming water canals, presenting no deforestation events for pond construction or services in the observed years since construction.

Block 2. This block, which covers an area of 419 ha, is considered the central part of the studied area. The incoming water canal has an opening or mouth with an approximate width of 13.3 m for water access. It is the latest operational infrastructure area developed, with the first record of construction in 2017 and approximately 331 ha of operational infrastructure. It is considered the most recently developed site, and the banks of canals do not yet show evidence of mangrove colonization.

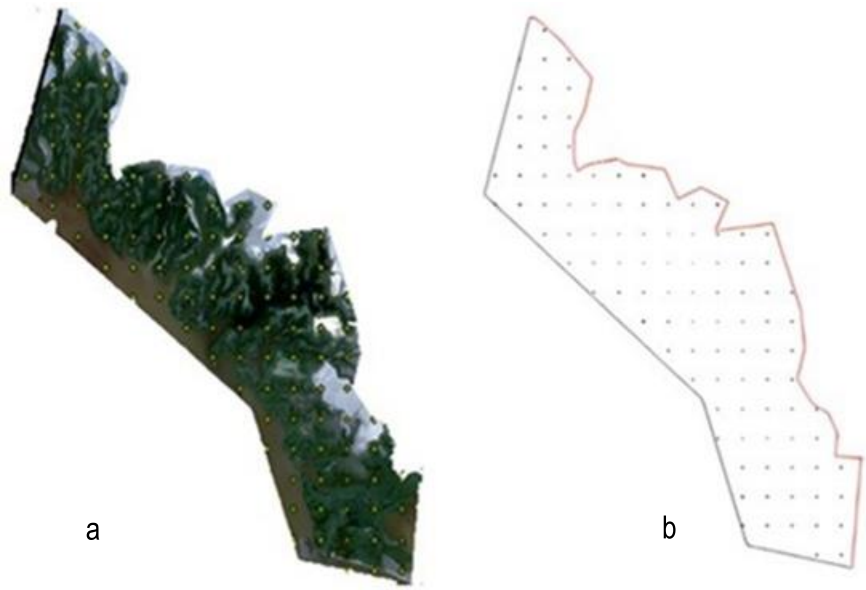

Figure 4. Distribution of the 104 validation points for the "mangrove" and "non-mangrove" classes in 2013 and 2020. a-b) As referenced points. The figure illustrates the spatial distribution of the 104 validation points representing the "mangrove" and "non-mangrove" classes for 2013 and 2020. These validation points serve as reference locations to assess the accuracy of the classification results. Figures a-b displays the specific locations of these points, indicating their distribution across the study area. The specific georeferenced locations of each identified point were recorded to indicate their precise distribution and enable validation by others for verification purposes. The "mangrove" category represents points where mangrove vegetation is present, while the "non-mangrove" category indicates the absence of such vegetation. By analyzing the distribution of these points, we can validate the efficiency and reliability of the classification process selected.

Table 2. Areas and surfaces identified for shrimp farming in the study site

	Block 1	Block 2	Block 3	Total
	ha	ha	ha	ha
Farms	276.40	330.50	2081.62	2688.6
Incoming water canals	41.70	55.82	63.54	161.1
Harvesting canals	42.50	32.65	139.84	215.0
Total	360.70	418.98	2284.99	3064.7

Block 3. This block is located in the distal southern part of the study area and is characterized as the one with the largest operational infrastructure. It was also the initial operational site where aquaculture activities began in 1995 with only 26 ha, and currently, it covers 2082 ha under operation. As the block with the largest operating surface area, its water intake requirements are greater than the previous two described blocks. Therefore, its incoming water canal has two intakes; the width of the first intake is 4.78 m, and the second is 15.15 m, with no major current changes. All calculated areas and surfaces are shown (Table 2).

Spatiotemporal detection of mangrove vegetation cover change

Spectral separability

We separated the subjects in the satellite image into different classes, distinguishing not mangrove vegetation areas and assigning them to mangrove, marsh, and estuary classes. We then proceeded with the separability of the bands and used Euclidean separability measurement to separate the subjects. After identifying the subjects, we interpreted them for the years 2013 and 2020, discriminating between the subjects of "Estuary" and "Marsh" and examining only "mangrove" and "non-mangrove" subjects.

Table 3. Error Matrix for each of the 104 validation points (2013).

Matrix of confusion 2013					
	Mangrove	Non-mangrove	Total	Accuracy of the producer (%)	Error of omission (%)
Map					
Mangrove	102	1	103	99	1
Non-mangrove	3	53	56	95	5
Total	105	54	159		
Accuracy of the producer (%)	97	98	97	Global precisión: 97	
Error of omission (%)	3	2			

Table 4. Error Matrix for each of the 104 validation points (2020).

Matrix of confusion 2020					
	Mangrove	Non-mangrove	Total	Accuracy of the producer (%)	Error of omission (%)
Map					
Mangrove	102	1	103	99	1
Non-mangrove	2	54	56	96	1
Total	104	55	159		
Accuracy of the producer (%)	98	98	98	Global Precision: 98	
Error of omission (%)	2	2			

Calculation of "mangrove" and "non-mangrove" areas

With the results obtained from the spectral analysis, the following surfaces were determined at a 97 and 98% confidence level, respectively:

• In 2013, the total mangrove vegetation was 5164.20 ha.

• In 2020, the total mangrove vegetation was 5255.19 ha.

The remote sensing calculations comparing 2013 and 2020 show a loss of 48.15 ha of mangrove vegetation and a gain of 142.47 ha, which may not necessarily correspond to the same areas. In the studied polygonal area, there is no evidence of deforestation associated with the construction or operation of shrimp farms during the evaluated years. The loss/gain of mangrove vegetation is scattered throughout the georeferenced polygonal area without a clear deforestation pattern. There was a 1.8% increase in mangrove vegetation in 2020 compared to 2013 (Fig. 6).

2013. The overall accuracy for the map of 2013 was 97%, while the user accuracy for the classes "mangrove" and "non-mangrove" were 99 and 95%, respectively. The recorded area of mangrove cover for 2013 was 5164 ha (Table 3).

2020. Overall accuracy for the 2020 map was 98%, while the user accuracy for the "mangrove" and "non-mangrove" classes were 99 and 96%, respectively. The area of mangrove cover recorded for 2020 was 5379 ha (Table 4).

An "Error Matrix" for the years 2013 and 2020 is presented in Tables 3-4, respectively, to support the accuracy of the generated map of the assigned classes ("mangrove" and "non-mangrove") for each of the 104 validation points. Deforested mangrove, directly associated with pond construction, was detected in blocks 2 and 3, totaling 0.903 ha.

In Block 2, the total vegetation area affected was observed at 0.0737 ha (682089 m E, 2843137 m N) and 0.1993 ha, for a total of 0.273 ha. In Block 3, a 0.63 ha (686963.00 m E 2835967.00 m N) affected area was identified. (Fig. 7).

Normalized Difference Vegetation Index (NDVI)

The same two satellite images were used to reduce spectral variation due to different images, and the respective bands were taken from 2013, which corresponded to the site before the construction of all current farms, and secondly, from 2020, corresponding to the actual time.

NDVI 2013. The average NDVI for 2013 was 0.3656250, with a maximum value of 0.4765410 and a minimum of 0.2082010 (standard deviation, SD = 0.0662032).

Figure 5. Shrimp production infrastructure includes intake canals (magenta), discharge/harvesting canals (green), and grow-out ponds. These components play crucial roles in regulating water flow, maintaining water quality, and providing controlled environments for shrimp rearing. Understanding their spatial arrangement and functionality is essential for effective shrimp farming and system management.

NDVI 2020. NDVI for 2020 was 0.3868160, with a maximum of 0.4794190 and a minimum of 0.1464210 (SD = 0.0697118).

One hundred four validation points were assigned to the "mangrove" and "non-mangrove" classes, with 48 and 56 points for 2013 and 49 and 55 points for 2020, respectively. The analysis showed an increase of 0.021191 units in NDVI value between 2013 and 2020. There was a significant difference in NDVI values between the period before the operation of shrimp farms and after their construction and operation (Fig. 8).

DISCUSSION

Historical development of infrastructure

Shrimp farming in Mexico, particularly in Sinaloa, has presented a complex undertaking encompassing both commercial and socio-environmental dimensions. Initially, inadequate adherence to environmental regulations was observed, necessitating subsequent corrective actions mandated by the environmental regulatory agency.

In the site under study, we have identified 10 shrimp farms actively engaged in aquaculture operations, with their environmental impact assessments approved after construction and operational infrastruc-ture. Following national legislation (DOF 2001), prior authorization from the Environmental Federal Authority is mandatory for the construction and operation of such facilities. Nevertheless, the timing of the actual construction activities does not consistently align with the issuance of initial construction authorizations.

The loss or gain of mangrove areas is influenced by various factors directly related to shrimp farming and other contextual drivers. Mangroves face global threats such as land conversion for agricultural or aquacultural purposes, coastal development, pollution, alterations in

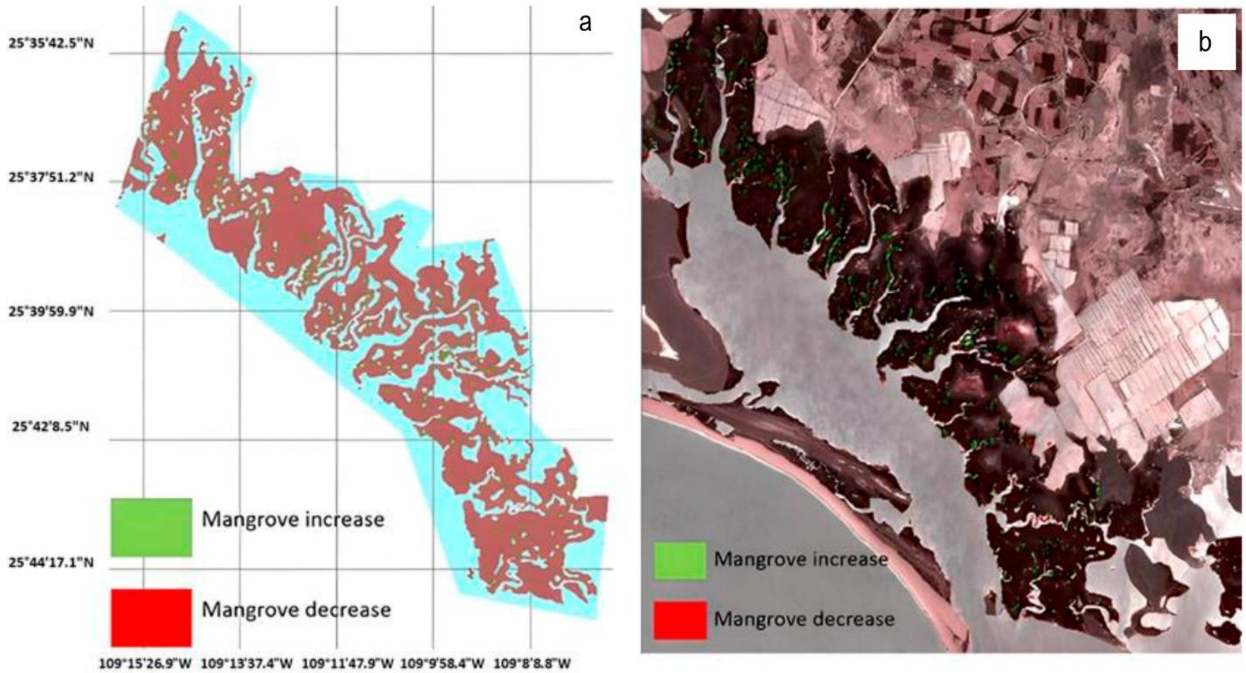

Figure 6. The calculation of "mangrove" and "non-mangrove" areas involved a rigorous process. Quality control measures were implemented to assess the accuracy of the final map generated for 2013-2020. The results are visually presented in a) cartographic map, representing the distribution and extent of the identified mangrove and non-mangrove areas. Additionally, b) a satellite image is utilized to visually depict the observed land cover classes and their spatial patterns. Combining these two visual representations allows for a comprehensive understanding of the mangrove ecosystem dynamics over the studied period.

hydrological regimes, climate change, and extreme weather events (Adams & Rajkaran 2021). In the present study, we establish a baseline by documenting the constructed areas of mangroves and shrimp farms, providing a foundation for further analysis and assessment.

While previous studies have quantified overall mangrove deforestation, limited efforts have been made to specifically measure the loss of mangroves resulting from the expansion of commercial aquaculture (Hamilton 2013). Our research aims to employ a robust methodology to assess the extent of aquaculture infrastructure linked to removing mangrove vegetation as a collective entity, diverging from traditional system evaluations, or proposing alternative remote sensing approaches.

Early studies on wetlands and shrimp farming primarily served as cautionary reports rather than providing conclusive evidence of the impact of mangrove deforestation in these specific locations (DUMAC 2000, Páez-Osuna 2001, Páez-Osuna et al. 2003, Castellanos-Navarrete & Jansen 2015).

Our research observed a 1.8% increase in mangrove cover between 2013 and 2020, a positive trend. However, it is important to acknowledge that shrimp farming can indirectly impact mangroves by altering hydrological patterns (Páez-Osuna et al. 2003). Furthermore, expanding shrimp aquaculture infrastructure can introduce new environmental pressures by modifying the coastal landscape, often establishing farms on bare soil and salt marsh areas, as Alonso-Pérez et al. (2003) demonstrated.

Our study reveals that mangrove cover was 5164 ha in 2013 and increased to 5379 ha in 2020, corroborating the findings of Ruiz-Luna et al. (2010), who assessed the distribution patterns, extent, and current condition of mangroves in northwest Mexico. Their study indicated that 75% of shrimp farming activities in the region were established on salt marshes, while less than 1% were constructed within mangrove areas.

The present study's findings indicate that establishing infrastructure for shrimp farming did not require removing mangrove vegetation. In contrast with early studies conducted in the 1990s, which reported that

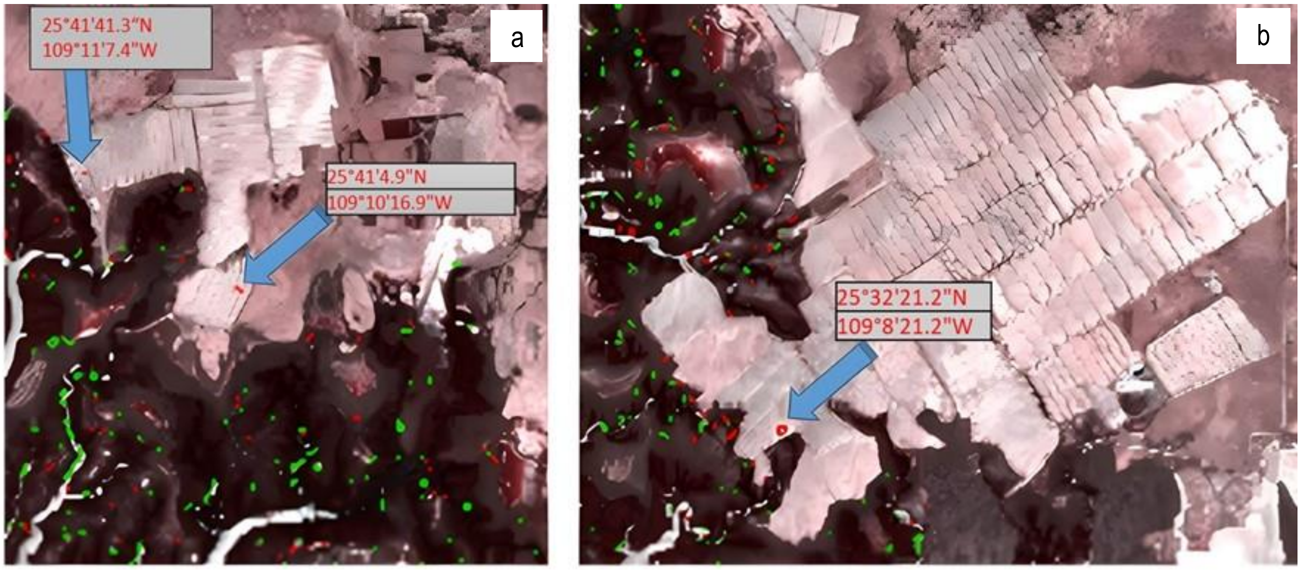

Figure 7. a) Block 2, and b) Block 3 exhibit specific deforested mangrove areas due to the construction of ponds for shrimp aquaculture.

over 20% of surveyed areas in Sinaloa and Nayarit states, Mexico, required mangrove clearance (Ramírez-García et al. 1998, Ruiz-Luna & Berlanga-Robles 1999).

Ramírez-García et al. (1998) warned rather than presenting concrete evidence when assessing deforestation in mangrove-covered regions. They acknowledged the need for land clearance for grazing, farming, and shrimp aquaculture among coastal communities but did not specifically quantify deforestation associated with aquaculture. They also recognized indirect causes of deforestation, such as road and infrastructure construction for tourism activities, natural phenomena like hurricanes and floods, and changes in river courses.

Ruiz-Luna & Berlanga-Robles (1999) estimated water surface coverage, vegetation classes, and land use in the Huizache-Caimanero Lagoon System. They reported an increase in mangrove area from 1220 to 1250 ha between 1990 and 1997, indicating a positive overall rate of change (2%). However, from 1973 to 1986, they observed a significant decrease in mangrove vegetation from 2310 to 1380 ha, even though shrimp farms had yet to be established. Hence, aquaculture could not be attributed to any deforestation during that time.

Since 2002, mangrove species have been designated as "subject to special protection" under Mexico's NOM-059-SEMARNAT-2010 (2010), making logging activities illegal at any time. Therefore, we assume that the mangrove forest has a uniform age. Although it consists of different species and densities, its coverage has increased in our study case by 1.8% between 2013 and 2020.

The degradation of mangroves necessitates urgent attention to appropriately implement adaptation strategies and coastal protection measures (Veettil et al. 2019). While various threats to mangroves have been widely identified, a systematic assessment of these changes remains understudied (Faridah-Hanum et al. 2019). However, our study employs NDVI estimation to consider that the presence and operation of shrimp farms at the site during the study period (2013-2020) have kept the condition and health of the mangrove strong.

In this case, the mean NDVI values have increased by 5.8% from 2013 to 2020, which contrasts with the findings of Thakur et al. (2021), who reported a decline in healthy forest cover and an increase in open patches/non-vegetative cover in the Sundarbans region of India, as indicated by mean NDVI values of 0.441 in 2000 and 0.229 in 2017.

The degradation of mangroves requires urgent attention to implement adaptation strategies and coastal protection measures at an adequate pace (Veettil et al. 2019). While Alatorre et al. (2016) suggested that arid mangroves in the Gulf of California are at risk due to shrimp farming development and climate change, the full extent of their impact on mangrove health remains unclear.

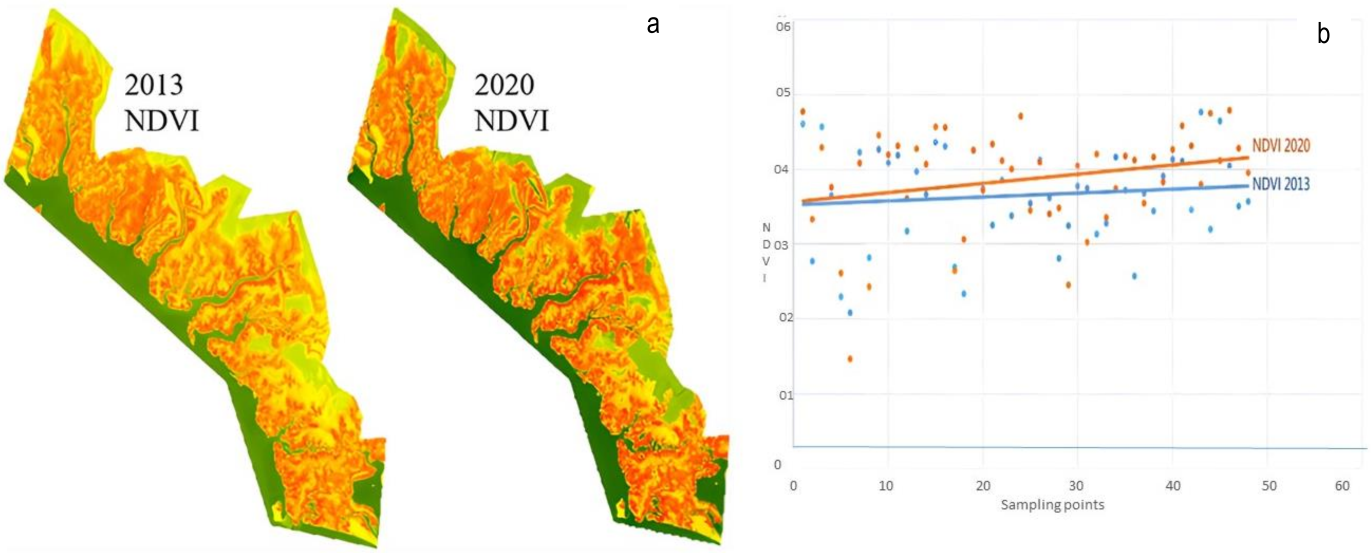

Figure 8. The figure graphically illustrates the Normalized Difference Vegetation Index (NDVI) obtained within the study polygon, represented on a scale ranging from -1 to 1. Negative values near -1 indicate areas devoid of vegetation or non-vegetated surfaces, including water bodies. Values near 0 indicate low vegetation or a mixture of vegetation and bare soil. Values approaching 1 indicate a high density of healthy vegetation. The highest NDVI values correspond to greater vegetation density and health, represented in varying shades of yellow-orange color, arbitrarily chosen by the authors to denote the mangrove vegetation status based on the color intensity generated by the analysis performed. The analysis results are shown with a) results projected onto a satellite image and b) graphed results.

The present study's scope does not allow direct correlation validation with the observed increase. However, the construction of shrimp ponds and farming operations has not negatively affected the current positive NDVI values of the mangrove.

In contrast to Faridah-Hanum et al. (2019) findings, the average NDVI values of 0.365 and 0.368 in the two years under review were similar. Still, no negative values were observed, indicating that the construction of shrimp farming infrastructure in the area does not compromise the sustainability of the mangrove and its services for present and future generations.

Our study provides scientifically relevant results for the harmonious development of shrimp farming activity. Our findings have the potential to challenge the widespread perception that pond construction and shrimp farming infrastructure contribute to mangrove deforestation in the studied landscape.

Dauber & Miyake (2016), in their discussion on guiding principles for commodity production landscapes, emphasized that management strategies that simultaneously address ecological and economic challenges still need to be discovered. However, a preliminary inventory is indispensable for comprehensively understanding landscape consistency and variability within a specific area (Cullotta & Barbera 2011). Our results serve as a valuable starting point, functioning as a preliminary inventory that, under an appropriate governance framework, can identify and promote the initiation of landscape management in the study area.

In Mexico, a substantial proportion of mangroves (68%) are concentrated within Ramsar sites, underscoring the need for conservation and management interventions, as highlighted by Acosta-Velázquez et al. (2009). This imperative remains valid. However, our study results demonstrate that the establishment and operation of aquaculture practices in the studied area have not negatively affected the original mangrove extents. It is crucial to maintain this trend by implementing a framework of conservation and responsible management practices that do not compromise the mangrove cover when initiating new aquaculture projects.

The study site encompasses an approximate production area of 3065 ha, with 87.7% allocated to grow-out ponds and 12.3% dedicated to water intake and discharge infrastructure. Through remote sensing analysis conducted for the years 2013 and 2020, no evidence of deforestation associated with the construction of shrimp farming infrastructure was observed.

The mangrove forest cover within the study site was estimated at 5164.20 ha in 2013 and 5255.19 ha in 2020, indicating a net increase of 90.99 ha over seven years. Although there was a loss of 48.15 ha of mangrove forest cover during this timeframe, offset by a gain of 142.47 ha, these changes do not exhibit a discernible pattern that can be attributed to the construction of aquaculture infrastructure. Furthermore, these modifications are dispersed throughout the study area. It is plausible that the altered areas are more closely associated with natural estuarine dynamics or seawater channels rather than activities occurring within the central core of the mangrove forest.

Environmental sustainability is a primary driver, necessitating adopting new approaches. Conventional aquaculture practices often engender adverse environmental consequences, including water pollution, excessive resource exploitation, and waste generation. The novel mentioned above approaches and technologies have been developed to minimize these impacts and engendering enhanced environmental sustainability. Notably, IMTA facilitates the integration of different species within a single system, enabling the utilization of waste produced by one species as a nutrient source for another. This approach effectively reduces the water's pollutant burden while promoting improved resource utilization efficiency (Biswas et al. 2020)

Optimizing resource efficiency represents a critical consideration in the context of aquaculture. The scarcity of resources such as optimal marine water and fish feed presents substantial challenges to sustainable aquaculture production. The new approaches aforementioned explicitly target resource efficiency maximization. For example, biofloc technology (BFT) capitalizes on utilizing microbial biomass generated by bacteria and other microorganisms to convert organic waste into valuable fish feed effectively. This innovative approach reduces reliance on external inputs and mitigates resource scarcity concerns (Emerenciano et al. 2013, Knowler et al. 2020).

Diversifying aquaculture production holds significant merit for enhancing overall system resilience. The approaches introduced facilitate the diversification of aquaculture production by integrating complementary practices. Marine aquaponics, for instance, seamlessly combines fish farming with hydroponics, enabling the utilization of fish waste as a nutrient source for cultivating plant-based food (Chu & Brown 2021). This integrated approach promotes sustainable fish production and contributes to the production of diversified, plant-based food sources within the system.

The concept of circular marine bioeconomy underscores the need for a holistic and sustainable utilization of aquatic resources within the aquaculture sector. Embracing a circular economy approach necessitates the conversion of waste into valuable resources and the reutilization of by-products across various sectors. By implementing this concept, the entire aquaculture value chain, from production to marketing and consumption, can operate more efficiently, sustainably, and interconnectedly (Yarnold et al. 2019, Yadav et al. 2020).

Therefore, we propose that shrimp farming conducted in wetlands, from a landscape perspective, should be included in future management plans as 'any part of the territory perceived by the population, whose character results from the action and interaction of natural and human factors' highlighting the potential for sustainable coexistence between aquaculture and mangrove ecosystems and underscores the importance of considering both ecological and socio-economic factors in conservation planning.

CONCLUSIONS

The coastal aquaculture developments in the study site are a well-recognized source of employment for the surrounding communities and a vital part of the productive chain without evidence of deforestation or mangrove degradation.

Results evidence that shrimp farming is not responsible for mangrove loss and its development and health are not necessarily compromised. Furthermore, the seawater used for shrimp growing operations could expand the natural mangrove area beyond the marsh and the constructed shrimp farms.

We do not consider it a constraint to assess mangrove deforestation as a whole, including discriminating against particular species (based on physiognomic differences) since our work presents a baseline of the situation before the construction and development of aquaculture infrastructure and the actual situation, which can be used for appropriate governance or management plans in conservation areas such as Ramsar sites.

Harmonic growth is necessary for shrimp aquaculture to respect regulatory ordinances and maintain the health of these environments. For a real governance approach, GIS technology must be oriented towards social, productive, and economic purposes and the scientific scope. In our case, it acts as an impartial arbitrator, indicating that shrimp aquaculture (in this site) has not been responsible for mangrove deforestation.

It is crucial to assess the current state of the mangroves and to evaluate the carrying capacity of the receiving water body as a vital factor in conjunction with decision-making processes. Water intake and discharge strategies have often lacked systematic consideration. It must be addressed as a determining factor for achieving sustainable aquaculture practices.

It is pertinent to determine the potential impact of shrimp farming operations on the local mangrove community, exploring the extent to which "the use of seawater for shrimp farming operations could expand the natural mangrove area" requiring additional, comprehensive analyses beyond the scope of this research.

Indeed, this study does not provide a universal justification for asserting the non-impact of shrimp pond construction on mangroves. Rather, it serves as a specific case study aimed at increasing the adoption of GIS in decision-making processes for achieving a harmonious and sustainable development of shrimp aquaculture.

The urgent need to achieve environmental sustainability, optimize resource utilization, and foster circularity within the sector is imperative for aquaculture farms to embrace novel approaches such as IMTA, BFT, marine aquaponics, and circular marine bioeconomy. These emerging methodologies provide promising pathways for transitioning towards a more sustainable and resilient aquaculture industry. Continued research, technological advancements, and practical implementation are crucial for realizing their full potential and driving the transformation toward a sustainable future for aquaculture.

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