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Article

Geospatial Simulation Model of Sustainable Mangrove Development Scenarios for the Years 2030 and 2050 in Marismas Nacionales, Mexico

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Abstract: Anthropogenic activities influence the loss of mangroves, increase natural phenomena such as hurricanes, tropical storms, and El Niño, and consequently increase concentrations of greenhouse gases such as CO₂, promoting climate change. There are strategies to reduce emissions from Deforestation and Forest Degradation, the Sustainable Development Goals, and the General Law on Climate Change to counteract these conditions. Therefore, this research aims to generate an integral simulation model of sustainable mangrove development scenarios for 2030 and 2050 through mitigation strategies, using geospatial techniques, multi-criteria evaluation, and generating a future surface demand model. The Marismas Nacionales study area is a mangrove ecosystem and an important carbon sink. The simulation model determined that the mangrove area in 2030 will be 77,555 hectares, with an estimated absorption of 358.95 Gg CO₂ e (equivalent). By 2050 there will be 86,476 ha, absorbing 400.24 Gg CO₂ e. This increase will be in disturbed mangrove areas and other wetlands. The sustainable simulation model and the surface demand model can be applied in any study area to increase, protect, and conserve mangroves to benefit the social, economic, and environmental sectors.

Keywords: mangrove; surface demand; sustainable; CO₂ absorption

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1. Introduction

In recent years, the climate has changed globally in response to anthropogenic activities, and as a result, the concentrations of greenhouse gases (GHG) in the atmosphere have increased, mainly CO₂, a pollutant that influences climate change [1]. Such anthropogenic climate change affects the environment, increasing natural phenomena such as rising or falling sea levels, El Niño, tropical storms, hurricanes, droughts, and temperature changes, impacting the mangroves. Moreover, such changes promote the phenomenon known as “Mangrove dieback” [2–10].

Regarding the increasing damage to the environment, more and more future scenarios are being used to predict what is possible to happen by perceiving how the dynamic processes in a geographic space will be [11,12], comparing the consequences of each of them [13,14], and allowing the creation of new alternatives [15] by describing and generating coherent images [16]. In addition, they can be used as an early warning system by showing the effects of future changes in land use and vegetation cover [14], providing helpful information for professionals and decision makers of programs and public policies in environmental management; for this reason, they suggest greater use of predictive models [17].

Some techniques have been used to model scenarios in mangroves using cellular automata and the factors of marginalization index, altitude, slopes, soil type, distances to roads, agricultural areas, human settlements, communication routes, water bodies, the edge or center of the polygon that presented changes [18], the Markov chain method with mapping from two different dates [19–22], and multi-criteria evaluation (MCE) with the factors of deforestation, distances to urban areas, and the Natural Protected Area, expansion of shrimp farms, and human settlements [21]. These scenarios obtained a loss of surface area. On the other hand, the studies mentioned above also used these last two techniques and the factors of distance to population centers and road density, acquiring information on the surface area increase [22]. Such works are used to acquire trend scenarios.

The study of individual-based models (FORMAN, KIWI, and MANGRO) use factors such as light, nutrients, salinity, and competition to obtain qualitative and quantitative knowledge that describe the life processes of mangroves such as establishment, growth, and mortality [23]. It should be noted that the technique suitable for generating sustainable scenarios is MCE by providing information on the optimal areas for mangrove development [12,24].

Mangroves are considered one of the most threatened habitats on Earth due to the loss of 3.6 million hectares of mangrove globally, during the years from 1980 to 2005 [25,26]. In Mexico, the loss has been 80,850 ha, and 17,140 ha has been disturbed from 1970 to 2015 [27,28]. Therefore, their long-term survival is at risk along with the essential ecological services that this ecosystem provides, such as the absorption of atmospheric CO₂ through the photosynthesis process [27,29–32].

Marismas Nacionales is located on the coastal strip of the States of Sinaloa and Nayarit of Mexico; it has a large area of mangroves that allows it to act as a relevant carbon sink. However, anthropogenic activities are carried out using natural resources in an unsustainable way. For this reason, it is considered an area of biological importance and in need of ecological recovery and protection [33].

In order to reduce the impacts associated with climate change and land-use change, the 17 Sustainable Development Goals (SDGs) have been implemented to balance environmental, economic, and social sustainability [34]. Mexico was the first developing country to present its commitment to mitigate and adapt to climate change by reducing GHGs and short-lived pollutants in 2015 at the plenary session of the United Nations [35].

The Mexican government created a National Strategy to Reduce Emissions from Deforestation and Forest Degradation (ENAREDD+, for it is acronym in Spanish), establishing the goal of reducing 22% of GHG emissions by 2030 and 51% of black carbon from forest fires, achieving a net-zero deforestation rate, in addition to increasing the area of sustainably managed forests and promoting natural and induced regeneration of resources and forest conservation with the consequent increase in carbon stocks [35].

Mexico plans to mitigate climate change by reducing the 4.9% of GHG emissions from the Land Use, Land-Use Change, and Forestry (LULUCF) sector and absorbing approximately 26% of GHG emissions in Mexico through forests [35], particularly mangroves, which are important carbon reservoirs [31,36–38]. The ENAREDD+ is aligned to meet the goals of national environmental legislation, mainly in the General Law of Climate Change (LGCC, for it is acronym in Spanish), which establishes that to contribute to the mitigation of GHG emissions, 30% of these gases must be reduced by the year 2020 and 50% by the year 2050 in comparison to the emissions generated in 2000 [39,40].

Based on the above, a comprehensive geospatial simulation model for the future was generated with the objective of obtaining a sustainable development of the mangrove forest for the years 2030 and 2050, through the behavior that this vegetation cover has presented over the years (1981–2005 and 2005–2015), following the guidelines of the SDGs, the LGCC, and ENAREDD+ and applying Geographic Information Technologies.

2. Materials and Methods

The present study area is called Marismas Nacionales (MN) and extends along the coast of the Pacific Ocean of Mexico, with an area of 220,000 ha distributed in 8 municipalities, 1 belonging to the state of Sinaloa and 7 to the state of Nayarit [33]. According to the 2015 population census, 56,349 people are living in these municipalities [41]. On the other hand, this territorial extension is home to 99 endemic species and 73 near extinction [42], of which include the mangrove species *Rhizophora mangle*, *Avicennia germinans*, *Laguncularia racemosa*, and *Conocarpus erectus* (colloquial names as red mangrove, black mangrove, white mangrove, and button mangrove, respectively) [43,44]. The climate of this study area is warm and subhumid with a temperature greater than 22 °C [33]. Therefore, according to its great environmental importance, it has been decreed as a Ramsar site No. 732 since 1995, as well as being recognized as a Natural Protected Area, Marismas Nacionales Biosphere Reserve, Nayarit in 2010 [45]. Before that, this area had already been declared as an important area for bird conservation in 1998 (Figure 1).

Over the years, aquaculture, forestry [46,47], agricultural, tourism, ecotourism, and mining activities have been carried out [45,48], taking advantage of natural resources to the degree of being cataloged by CONABIO as a site with biological importance and in need of ecological protection and recovery [33,49].

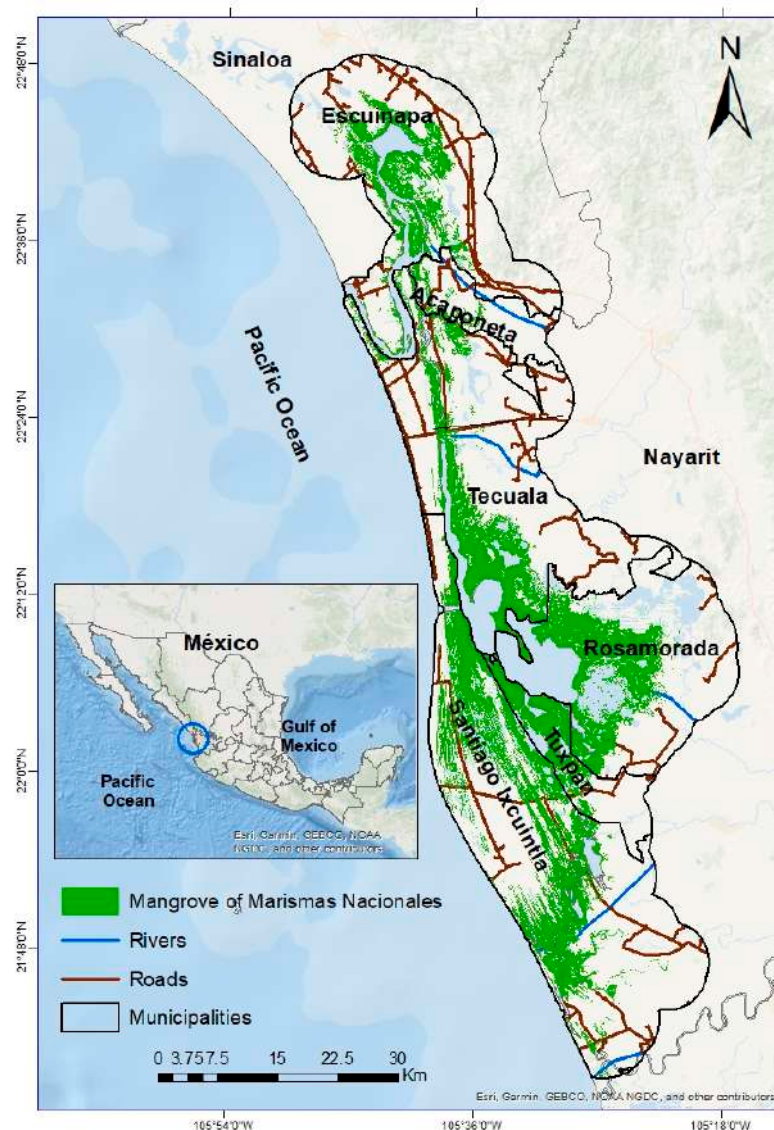


Figure 1. Marismas Nacionales study area.

2.1. Data

The cartography published by CONABIO of land-use and vegetation of the coastal zone associated with mangroves was acquired of the years 1981, 2005, and 2015 at a scale of 1:50,000; this official cartography was elaborated utilizing an interdependent classification method [50], which presents a geostatistical validation percentage of 93% and is classified into 8 categories as indicated in Table 1 [28,50]:

Table 1. Categories of the cartography “Land-use and vegetation of the coastal zone associated with mangroves”.

Category	Description
Mangrove	<i>Rhizophora mangle</i> , <i>Avicennia germinans</i> , <i>Laguncularia racemosa</i> , and <i>Conocarpus erectus</i>
Disturbed mangrove	Dead or regenerating mangrove
Anthropic development	Villages, aquaculture ponds, shrimp farms, salt mines, roads and highways, and hydraulic infrastructure works that include channels
Livestock-agricultural	Rainfed and irrigated agriculture, pastures for livestock activity, anthropic cover for food production, and resting agricultural areas
Low deciduous and medium sub-deciduous forest	Tropical deciduous forest, tropical thorny deciduous forest, and medium sub-deciduous forest
Without vegetation	Eroded areas without apparent vegetation, coastal sand dunes, and beaches
Other wetlands	Hydrophytic vegetation: popal, tular, reed beds, and flooded grasslands
Water	Bays, estuaries, lagoons, rivers, dams, and cenotes

The variables used for this modeling were selected considering the objective of the scenario through a literature review and consultation with experts through a survey on the factors that cause deforestation and degradation of the mangrove forest in MN. Thus, with respect to data availability, raster, vector, and alphanumeric information were collected from different governmental institutions, as shown in Table 2.

Table 2. Variables used for factor modeling.

Data	Scale/Resolution and Format	Source
Edaphology (2001)	1:1,000,000 Vector	[50]
Land use and vegetation map of the coastal zone associated with mangrove forests, North Pacific Region. (2005, 2015)	1:2,500,000 Vector	[50]
Population by locality (2010)	Number of population Numeric	[50]
Communication routes (2019)	1:50,000 Vector	[51]
Hydrography (2008)	1:4,000,000 Vector	[50]

2.2. Methods

Based on the mapping of land-use and vegetation cover changes for the periods from 1981–2005 and from 2005–2015, the mangrove cover to be simulated was defined, and the Multi-Criteria Evaluation (MCE) method was used to design a sustainable geospatial model of the mangrove forest from the last evaluated date (2015), qualitatively describing the future scenarios and calculating the surface demand for the years 2030 and 2050, through structural guidelines that allow the implementation of techniques ranging from the search and selection of factors.

2.2.1. Qualitative Description of the Sustainable Scenarios of the Mangrove Forest

The expected scenarios will present the conservation and increase of mangrove forest area naturally and through reforestation and restoration programs that will develop in disturbed mangrove areas, in optimal areas of other wetlands, as well as in areas recoverable from livestock-agricultural land use, in the proximity of anthropic development, and low deciduous and medium sub-deciduous forest that allow for the growth and development of these plants.

This retreat of non-forest soils will make it possible to maintain anthropic development such as agricultural and livestock activities in a sustainable way in areas where they do not cause habitat fragmentation within the special use of the subzone established in the sub-zoning map of the Management Plan for the Marismas Nacionales, Nayarit, Biosphere Reserve, Nayarit.

On the other hand, the scenarios will allow for the creation of mitigation strategies so that productive activities, the union of human resources, and social work are carried out together under a vision focused on reducing vulnerability and increasing the resilience of the mangrove forest by reducing atmospheric CO₂ emissions, following the guidelines of the SDGs, the LGCC, and the ENAREDD+ to increase and conserve this forest, minimize the environmental impact, and improve the quality of life of the population and the economy of the region.

2.2.2. Mangrove Forest Surface Demand Model in MN

The surface demand was generated to simulate the behavior of the forest area in the future, that is, to estimate the mangrove area that will be covered in the years 2030 and 2050 based on the area of the year 2015, using the area gain exhibited during the dates 1981–2005 and 2005–2015, to which the respective annual rate (rg) was estimated. An average of the rates (Mrg) was performed, obtaining the annual value of gain per year, which was multiplied by the number of years between the dates to be evaluated, as follows:

$$rg = 1 - \left(\frac{G}{A_1} \right)^{1/t} \quad (1)$$

where rg is the rate of change of annual area gain, G corresponds to the area gain between two dates, A_1 refers to the area at date 1, and t is the number of years between the two dates. Equation (2) is calculated as follows:

$$Mrg = \frac{\sum_{i=1}^N rgi}{N} \quad (2)$$

where Mrg is the average rate of gain, $\sum_{i=1}^N rgi$ corresponds to the sum of data corresponding to the rate of gain, and N is the number of data. Finally, Equation (3) is calculated as follows:

$$SD = (M(rg) \times t) + A1 \quad (3)$$

where SD is the surface demand.

2.2.3. Factors and Restrictions

The edaphology variables, land-use, and vegetation, hydrography, road networks, and localities were used to model the factors influencing the generation of the mangrove forest model in MN (Table 2).

These factors were modeled using geospatial techniques, such as spatialization, rasterization, reclassification, distance calculation, and map algebra; subsequently, the importance value of each factor was estimated using the Saaty matrix. Finally, the factors and their respective weights were integrated using the Weighted Linear Sum (WLS) to obtain the suitability map of the mangrove forest in MN.

The importance value of each factor was assigned utilizing a bibliographic analysis and an opinion survey applied to experts in the field (academics, government, private sector, non-governmental organizations, fishing sector of the study area [52]) on “The causes of deforestation and degradation of the mangrove forest in MN”, as proposed by the authors of [53].

It is important to mention that Saaty’s Analytical Hierarchy Method (AHM) was applied to the optimal soil factor to establish the level of importance [54], that is, the soil where the mangrove can best develop. Likewise, this procedure was carried out for the factor of proximity to localities where population ranges were generated, and due to the alphanumeric information that represents them, they provide socioeconomic data.

These factors are shown in Table 3, which describes their importance in the simulation model and how their interaction allows us to obtain the areas with the greatest aptitude to increase the mangrove area in future years.

Table 3. Factors of the spatial simulation model of the sustainable mangrove forest.

Variables	Factors	Description
Edaphology	Optimal Soils	The most suitable soils for the growth and development of the mangrove forest are weighted, taking the Solonchak gléyco soil type as a reference. Models of the areas to be restored or reforested with mangroves, fragmented by rainfed or irrigated agriculture and pastures dedicated to livestock activity. In addition, the proposed areas will be more successful if they are located further away from a livestock-agricultural areas and close to the existing mangrove.
	Inverse proximity to livestock-agricultural areas	
	Proximity to low deciduous and medium sub-deciduous forest	Shows how the mangrove forest can expand to areas of low and medium jungles as long as conditions are optimal, allowing the growth and development of the mangrove forest.
Land use and vegetation	Proximity to existing mangrove 2015	Models mangrove development contiguously to existing mangrove areas, reducing mangrove fragmentation, i.e., the closer the proposed areas to be reforested or restored are to the existing mangrove, the more successful the growth and development of these plants will be.
	Disturbed mangrove areas	Indicates the optimal areas that favor the increase of the mangrove forest since it can regenerate naturally or carry out reforestation or restoration programs.
Hydrography	Proximity to rivers	Indicates that the areas closest to the rivers provide optimal conditions for the growth and development of the mangrove forest.

Road network	Remoteness from highways and roads	Models the farthest distance from highways and roads, obtaining the best surfaces that allow the growth and development of mangroves through reforestation or restoration programs.
Localities	Weighted proximity to localities	Models mangrove conservation at a greater distance from the localities, creates the ideal areas for the growth and development of the mangrove forest, establishes the areas with the lowest population, and shows us where the largest economically active population and the lowest marginalization are located.

After weighing the factors, they were normalized in the Idrisi selva software through the fuzzy logic function (fuzzy) using the scale of 0–255 and the monotonic increasing and decreasing linear functions according to the behavior of the factor, i.e., the factors of inverse proximity. In addition, the factors of remoteness to highways and roads were normalized by applying the linear decreasing function [12].

As a restriction of the simulation model, some factors were considered to avoid carrying out any transformation. It should be noted that these maps are binary represented with values of 0 where the interactions of the model factors are restricted, and 1 indicates the areas where the activity takes place.

2.2.4. Scenarios

Once the suitability map was obtained, the most suitable pixels corresponding to the surface demand obtained for the 2030 scenario were selected. This made it possible to obtain a mangrove map for the year 2030, which was also used to update the land-use and vegetation map. To generate the 2050 scenario, it was necessary to model the mangrove factors, disturbed mangrove, and other wetlands factors, which were updated in the 2030 scenario.

Once these factors were modeled, the suitability map was obtained, integrating the corresponding factors and employing the weighted linear summation that is based on adding the derivation of multiplying each element of the raster for each of the normalized factors by the established importance value for each factor [12]. Finally, the most suitable pixels corresponding to the surface demand were selected to generate the 2050 sustainable scenario.

2.2.5. Sustainability Indicators

Land-Use Change Indicator

With the 2030 and 2050 mangrove scenarios, indicators were estimated using map algebra, comparing the maps obtained in the 2030 mangrove scenarios with the 2015 land-use and vegetation cover base map. Similarly, the 2030 scenario was compared with the 2050 scenario.

For this purpose, the matrix of changes [55] obtained in both processes was used, which was analyzed to know the dynamics of the mangrove in the future in MN, obtaining the corresponding gains (G), losses (L), and rate of surface gain (rg) [49] modified from the FAO equation [56] as follows:

$$G = S_c - P \quad (4)$$

$$L = S_l - P \quad (5)$$

$$rg = 1 - \left(1 - \frac{G}{A_1}\right)^{1/t} \quad (6)$$

where S_c is the summation of the column in question, P is the value of the main diagonal of the column in question, S_i is the summation of the row in question, and A_1 is the area at date 1.

CO₂ Indicator Estimate

To estimate CO₂, the absorption factor (AF) was obtained, which refers to the gain or loss of carbon in a period of time associated with the activity data (AD), which are the changes in the use of soil and vegetation in an area defined for a period, as established in the Guide to Good Practices for the Land Use, Land Use Change, and Forestry sector (GPG-LULUCF) prepared by the Intergovernmental Panel on Climate Change (IPCC) [57].

In the present study, the mangrove AF was acquired through the data reported by the National Inventory of Greenhouse Gas and Compound Emissions (INEGI, Mexico) [58], which allow for estimating CO₂ at a local or regional level, and the AD were obtained through the changes in the mangrove area in the future in MN for the periods 2015–2030 and 2030–2050, following the equation stipulated by the IPCC guidelines [57,58]:

$$A = AF \times AD \quad (7)$$

The methodology used is described in detail in [49].

3. Results

3.1. Change Detection

The mapping of the land-use and vegetation cover in 2005 and 2015 showed the area of mangrove forest in MN in such a way that, in 2005, 74,047 ha was conserved, corresponding to 24.93% of the study area. In 2015, there was 70,864 ha (23.86%), as we can see in the following Figure 2.

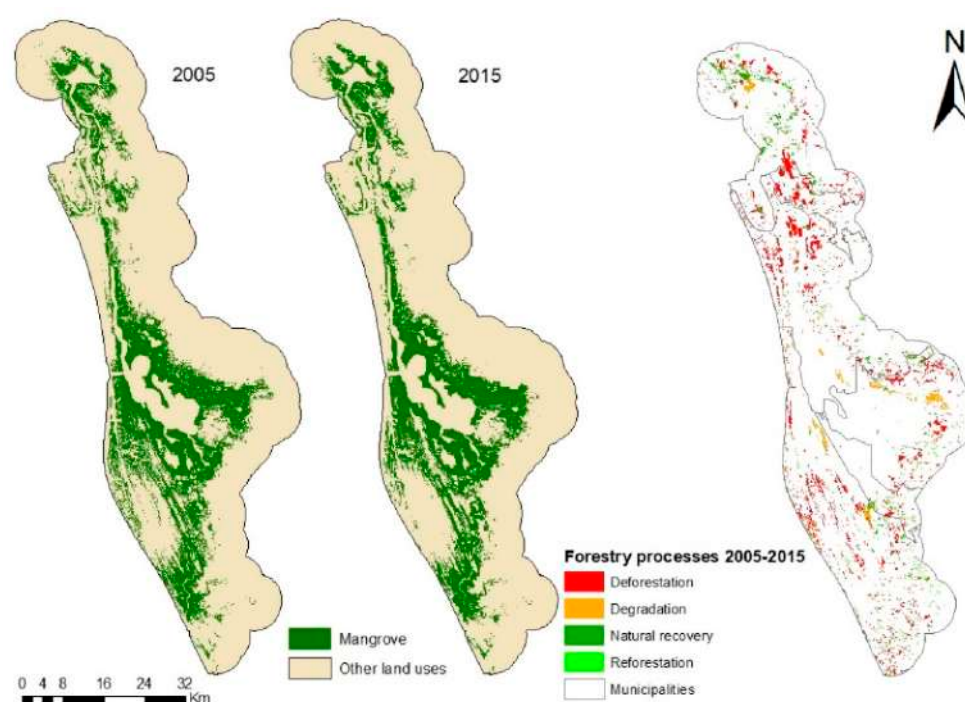


Figure 2. Maps of mangrove forest cover and forest processes by deforestation, degradation, natural recovery, and reforestation in Marismas Nacionales during 2005–2015.

In addition, changes were detected in the forestry processes of the mangrove forest, showing the deforestation of 3514 ha during the years 2005–2015; there was also a degradation of 3484 ha. However, there was an increase in forest area as 3355 ha were recovered naturally, and 117 ha recovered through reforestation programs implemented in MN (Figure 2).

3.2. Demand Surface of the Mangrove Forest Sustainable Model

The future behavior of the mangrove forest was acquired from the value obtained from the average gain rate of the last evaluated period (2005–2015), which was 446.08, multiplied by the number of years to be known. That is, to know the surface that the mangrove forest will occupy in 2030, it was multiplied by 15, which is the number of years between 2015 and 2030.

Obtaining a gain of 6691 ha that were added to the base year surface allowed the mangrove forest to reach a surface coverage of 77,555 ha. In this way, the surface demand in 2050 will be 86,476 ha, with an area increase of 8921 ha, representing an annual rate increase of 254.90 (Table 4, Figure 3).

Table 4. Mangrove forest surface demand for the years 2030 and 2050 in Marismas Nacionales.

Period	Year	Surface (ha)	Gain (ha)	Annual Rate of Gain (ha)
1981–2005 2005–2015	1981	80,071		
	2005	74,047.00	7479.00	311.63
	2015	70,864.00	2689.00	268.90
Future periods	Year	Estimated surface (ha)	Future land demand	Annual future rate
2015–2030	2030	77,555	6691	446.08
2030–2050	2050	86,476	8921	254.90

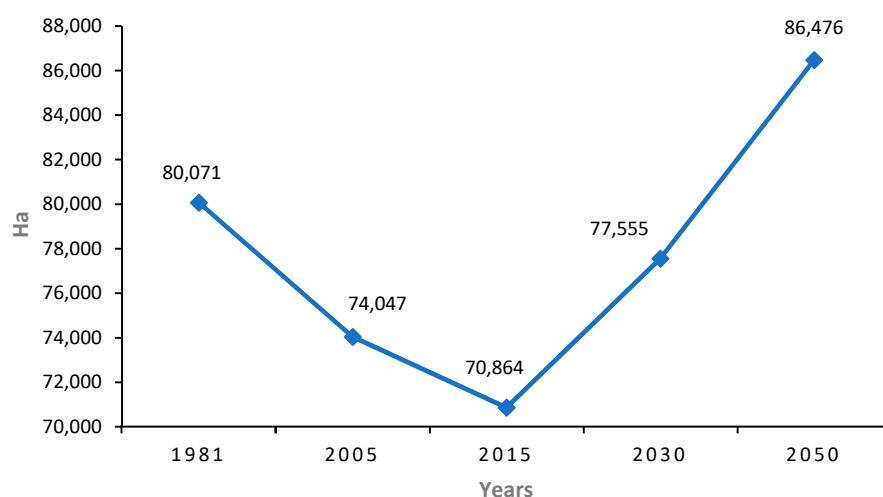


Figure 3. Surface demand for the years 2030 and 2050.

This increase in mangrove vegetation cover for the years 2030 and 2050 benefits the guidelines of the SDGs, the ENAREDD+, and the LGCC, which aim to conserve and increase the forest area and, at the same time, increase the absorption of atmospheric CO₂ through the photosynthesis process, contributing to the mitigation of climate change.

3.3. Weighting of Factors

The survey of causal factors of deforestation and degradation of the mangrove forest, as well as the literature review, allowed for the assignment of the importance value of each factor, so that first a weighting of factors was performed, using Saaty's (AHM), as can be observed in the pairwise comparison matrix in Tables 5–7.

Table 5. Saaty's pairwise comparison matrix for optimum soils.

Reclassification According to the Degree of Suitability		Saaty's Pairwise Comparison Matrix					
Soils	Importance value	3	4	6	8	9	Weight
Eutric Cambisol	3	1					0.10
Haplic Feozem	4	1.33	1				0.13
Eutric Fluvisol	6	2.00	1.50	1			0.20
Eutric Regosol	8	2.67	2.00	1.33	1		0.27
Gleyic Solonchak	9	3.00	2.25	1.50	1.13	1	0.30
						Σ	1

Table 6. Saaty's pairwise comparison matrix for population-weighted localities.

Reclassification According to the Degree of Suitability		Saaty's Pairwise Comparison Matrix					
Weighting of localities	Importance value	1	2	4	6	8	Weight
Locality from 2500–4999	1	1					0.04
Locality from 1000–2499	2	2	1				0.10
Locality from 500–999	4	4	2	1			0.19
Locality from 250–499	6	6	3	1.5	1		0.29
Locality from 1–249	8	8	4	2	1.3	1	0.38
						Σ	1

Table 7. Saaty's pairwise comparison matrix for the factors of the model.

Suitability of Factor		Saaty's Matrix									
Model factors	Importance value	1	2	3	6	6	7	8	8	9	Final weight
Optimum soils	1	1									0.02
Inverse proximity to livestock-agricultural areas	2	2	1								0.04
Proximity to low deciduous and medium sub-deciduous forest	3	3	1.5	1							0.06
Weighted proximity to localities	6	6	3	2	1						0.12
Remoteness to highways and roads	6	6	3	2	1	1					0.12
Proximity to other wetlands	7	7	3.50	2.33	1.17	1.17	1				0.14
Proximity to rivers	8	8	4	2.67	1.33	1.33	1.14	1			0.16
Proximity to existent mangrove	8	8	4	2.67	1.33	1.33	1.14	1	1		0.16
Areas near disturbed mangrove	9	9	4.50	3	1.50	1.50	1.29	1.13	1.13	1	0.18
										Σ	1

3.4. Normalization of Modeled Factors

Subsequently, the factors normalized using the linear increasing and linear decreasing function using fuzzy logic, with a scale of 0 as the minimum value and 255 as the maximum normalized value for all factors (Figure 4).

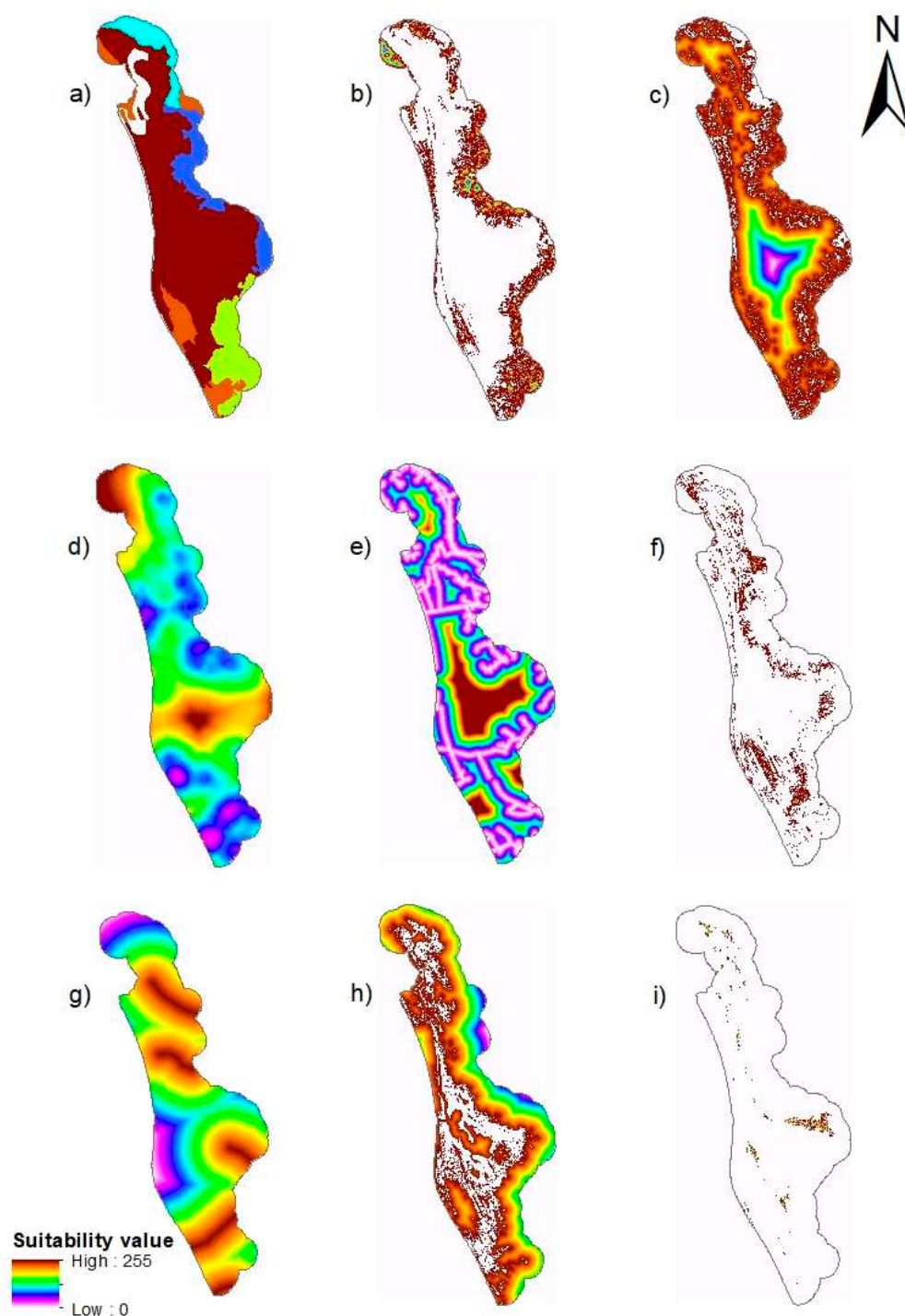


Figure 4. Normalized factors of the sustainable mangrove model for the years 2030 and 2050. (a) Optimum soils, (b) Inverse proximity to livestock-agricultural areas, (c) Proximity to low deciduous and medium sub-deciduous forest, (d) Weighted proximity to localities, (e) Remoteness to highways and roads, (f) Proximity to other wetlands, (g) Proximity to rivers, (h) Proximity to existent mangrove, (i) Areas near to disturbed mangrove.

Concerning the factors that presented changes in the 2030 scenario, the existing mangrove, disturbed mangrove, and other wetlands were modeled geospatially to generate the 2050 scenario, as shown in Figure 5.

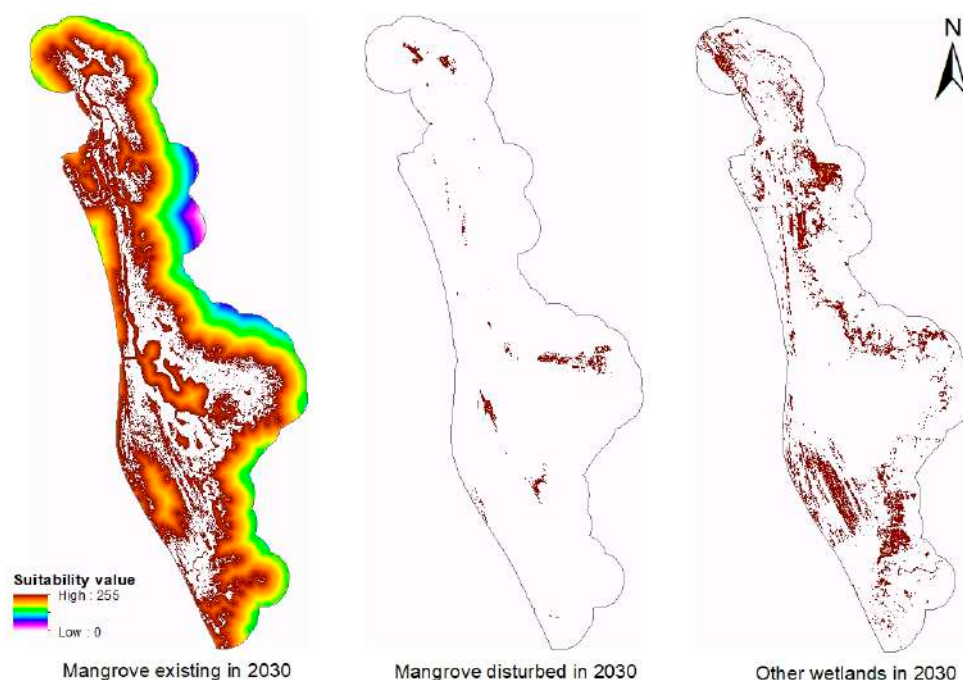


Figure 5. Factors modeled the base year 2030 and normalized to simulate the 2050 scenario of the sustainable mangrove model.

3.5. Restrictions

The base layer of the study area was used, giving it the value of 1 as the area to be simulated where the interaction of the model factors can be carried out and for the rest the value of 0, the factors of rivers, bodies of water, low deciduous and medium sub-deciduous forest, and anthropic development were assigned a value of 0, while the rest of the maps were set to a value of 1 (Figure 6).

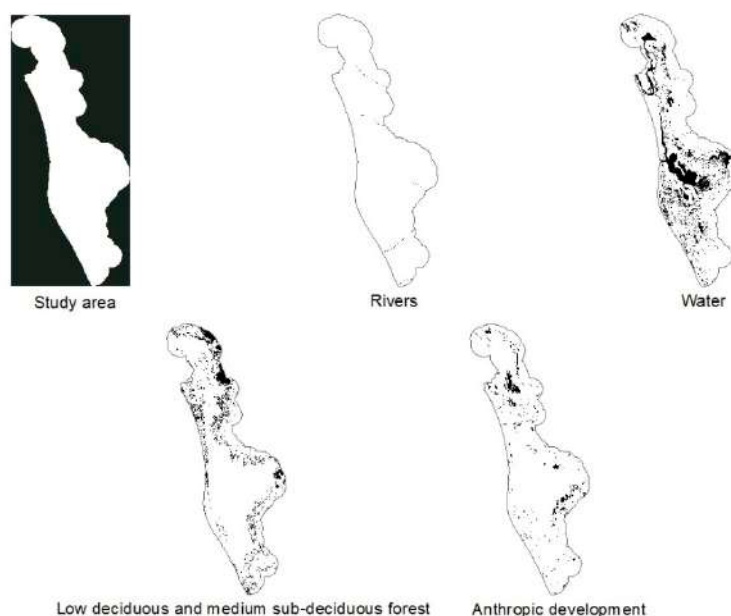


Figure 6. Constraints of the mangrove sustainability model for the years 2030 and 2050.

3.6. Map of Suitability

In this process, the weighted linear summation was applied, obtaining the most suitable pixels for the model objective, and therefore the suitability map of the 2030 and 2050 scenarios, in which we can see where the mangrove forest will develop. In this sense, the interactions presented by the factors in the model allowed us to define the areas where the mangrove forest will regenerate naturally or through reforestation or restoration programs, while also showing the less optimal pixels, meaning those with a lower value indicating that, in those areas, there is minimum suitability for the mangrove forest to develop (Figure 7).

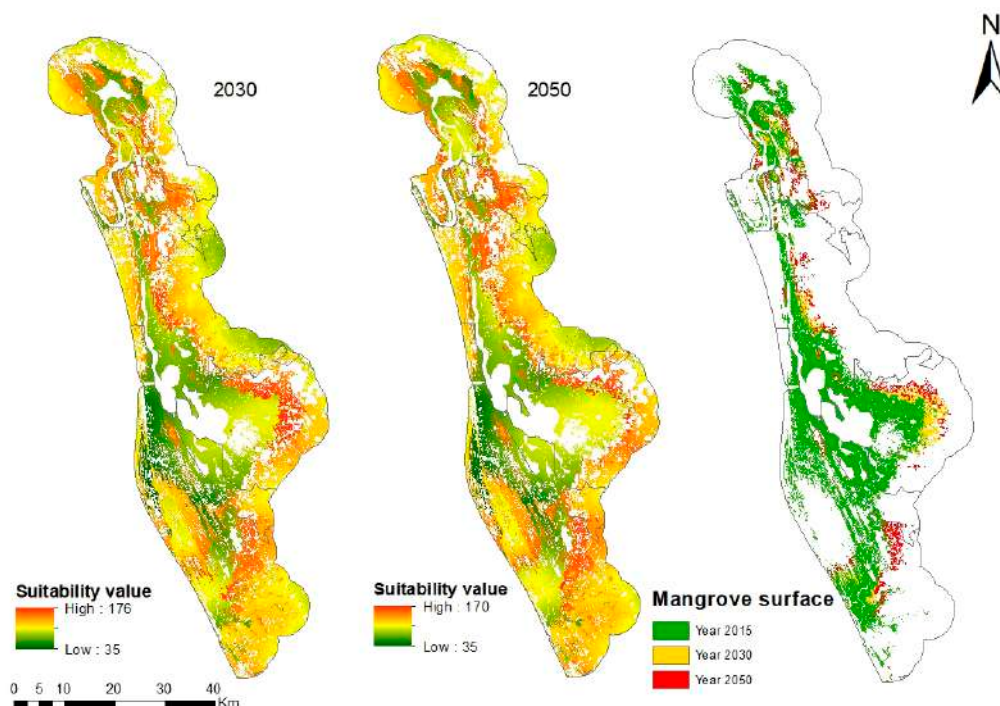


Figure 7. Suitability map for the model of a sustainable future of the mangrove forest in Marismas Nacionales.

3.7. Sustainability Indicators

3.7.1. Change Indicators

After obtaining the geospatial simulation model, the land-use and vegetation cover in future years were analyzed. Figure 7 shows the indicators of change for the year 2030, where we can see that the increase in mangrove cover will occur in the coverage of other wetlands, with a transition of 4337 ha, and in areas of disturbed mangrove with 2354 ha, presenting an annual rate of gain of 0.59%. Concerning the 2050 scenario, the mangrove cover will continue to increase in the aforementioned vegetation covers with 6598 ha and 2323 ha, respectively, at a rate of gain of 0.73% (Table 8).

Table 8. Indicators of sustainable changes in the Marismas Nacionales mangrove forest for 2015–2030 and 2030–2050.

Period	Category	Gain (Ha)	Loss (Ha)	Rate of Annual Gain (%)
2015–2030	Mangrove	6691	0	0.59
	Disturbed mangrove	0	2354	0
	Other wetlands	0	4337	0
2030–2050	Mangrove	8921	0	0.73
	Disturbed mangrove	0	2323	0
	Other wetlands	0	6598	0

Thus, this increase in mangrove forest area will occur mainly in areas close to mangrove forests and areas where this forest has been disturbed during the years 1981 to 2015; this will be possible by implementing reforestation or restoration programs in areas that have been deforested or degraded by agricultural and livestock activities. The increase in mangroves will occur mainly in the municipality of Rosamorada, in the area cataloged for exploitation in the management plan for the Protected Natural Area Marismas Nacionales, Nayarit Biosphere Reserve.

Moreover, it will increase naturally in degraded mangrove areas where environmental factors caused this forestry process near rivers, allowing for a better development by providing fresh water and at the same time decreasing salt concentrations. The same will occur where there are small populations of 1 to 249 inhabitants, in areas with a larger economically active population, and less marginalization, the conservation of the forest and less exploitation of natural resources.

Meanwhile, in areas where the construction of canals and roads has modified the hydrological flow, hydrological restoration programs should be implemented to distribute water in areas where mangroves have been lost or degraded due to water scarcity.

3.7.2. CO₂ Estimation Indicator

The increase in mangrove area that will occur in future years will allow for an increase in the absorption of atmospheric CO₂ through the photosynthesis process so that for the years 2015 to 2030, the estimate will be 358.95 Gg of CO₂ e with a surface area of 77,555 ha, and by 2050, there will be an absorption of 400.24 Gg of CO₂ e as the mangrove will expand to 86,476 ha (Table 9).

Table 9. CO₂ absorption of the mangrove forest in Marismas Nacionales.

Period	Year	Surface (ha)	Absorption (Gg de CO ₂ e)
1981–2005	1981	80,071	370.59
	2005	74,047.00	342.71
	2015	70,864.00	327.98
2015–2030	2030	77,555	358.95
2030–2050	2050	86,476	400.24

Following the goals of this strategy, the reduction of degraded mangrove areas will be implemented out through mitigation strategies. In addition to this, the surface demand model contributes to the ENAREDD+ by increasing the forest and absorbing atmospheric CO₂ since Mexico's global commitment is to reduce 22% of GHGs by 2030 and 51% by 2050.

Therefore, it is important to follow the guidelines of this strategy because it contributes to meeting the goal established in the LGCC of reducing GHGs by 30% by 2020 and 50% by 2050 compared to 2000 emissions. In addition, these national goals contribute to

the commitment made by Mexico in 2015 during the plenary session of the United Nations to comply with the 17 SDGs to stop climate change and its implications that affect humanity.

3.7.3. Mitigation Strategies

The suitability map shows the optimal and strategic places to perform the increase of mangrove area, that is, in the Solonchak gleyic soil type, as it is optimal for the growth and development of this forest so that the interactions of the factors used in the sustainable model that interacted in this soil reveal the strategic sites.

In this way, the areas close to the category of anthropic development located in the type of soil mentioned above and close to mangrove areas are suitable surfaces to implement reforestation or restoration programs if the site is in bad ecological condition.

On the other hand, in the land-use category of anthropic development, solid waste management must be implemented, mainly wastewater management in drains near the mangrove, to improve environmental conditions by reducing physiological stress in plants. At the same time, avoiding affecting the fauna that inhabit this landscape is necessary, as much of the fish, crustaceans, and mollusks are used for local or regional consumption and these actions will avoid generating a public health problem.

In addition, solid waste management must be done in the aquaculture ponds and must comply with the Environmental Impact Management done before installing the aquaculture production areas. It is also very important to install sanitary landfills in the municipalities in the study area to meet the population needs without directly affecting the ecological landscape in MN.

For its part, the construction of roads and highways should not obstruct the hydrological flow; this expansion of infrastructure can be done far from the mangrove surface. In addition, it is important to note that the construction of canals should contribute to the distribution of water on mangrove surfaces so that the sediments extracted in the construction should not be placed on the edges of the canals as this interrupts the flow of water towards the interior surfaces. Furthermore, these sediments can be dragged by the hydrological flow, increasing the soil height in particular areas, limiting the growth and development of the mangrove.

Livestock-agricultural activities can continue to be implemented as long as they are done sustainably, identifying and controlling the use of active and inactive parcels, implementing technologies that promote the quality of renewable resources through ecological techniques for agricultural production, biofertilizers, and biological pest control. In addition, it is necessary to reduce the use of agrochemicals and improve management techniques and sustainable livestock production.

Regarding low deciduous and medium sub-deciduous forests, they should be conserved because these areas absorb large quantities of atmospheric CO₂ through photosynthesis; and the mangrove forest can expand near this forest area. This could be possible if natural phenomena continue to increase because these areas provide optimal conditions for its growth and development compared to the soils around these vegetation covers, such as anthropic development or livestock-agricultural use.

Continuing with the mitigation strategies, it is important to create environmental awareness in the communities of MN, implementing more environmental education classes for the population that lives in the localities near these areas, as well as in the Mexican educational system so that everybody can learn about the environmental and socio-economic benefits that mangroves provide and thus protect, conserve, and increase such forests.

This knowledge should be implemented primarily in localities with a high level of marginalization such as Escuinapa, Acaponeta, Tecuala, and Santiago Ixcuintla. In localities with a low economically active populations such as Santiago Ixcuintla, Acaponeta, and Escuinapa, the population living in these places tends to acquire natural resources in

a non-sustainable way more frequently as they have a lack of education, as well as low economic income.

We can argue that reforestation programs can be developed in other wetlands because they are located in optimal soil to grow and develop mangroves and areas very close to these forests.

In reference to the disturbed mangrove areas, it is necessary to implement reforestation programs on the limits of these areas and restoration programs inside them, as they present deterioration as hypersaline soil and desertification due to the lack of hydrological flow, modifying the ideal environment for the mangrove to develop.

For such reasons, hydrological restoration should be conducted within the disturbed patches in order to create channels that distribute water and thus allow for the entry of mangrove seeds to grow naturally; with this hydrological flow, reforestation and restoration programs can be performed within the disturbed patches, increasing the surface area of these forests.

It should be noted that the reforestation mentioned above, and restoration programs should involve the local population in their implementation since they provide employment and, therefore, an economic income, at the same time raising awareness about the importance of conserving and increasing mangrove forests.

4. Discussion

Deforestation and degradation of the mangrove forest promoted by anthropogenic activities and consequent changes in land-use and vegetation cover generate environmental problems, such as increased natural phenomena, loss of biodiversity, and impact on the social and economic sectors [59]. Consequently, they promote climate change as it has manifested over the years in MN, presenting a forest loss of 13,503 ha during 1981–2005 and 5672 ha between 2005 and 2015.

This decrease in the surface of the mangrove forest has also occurred in other places, which is alarming because different researchers have observed that there is a tendency for this forest cover to decrease in future years [32]. This was observed in the study carried out in Térraba-Sierpe, Costa Rica, where the mangrove forest will continue to decline due to higher wave energy and rising sea levels [60].

In Oaxaca, Mexico, agricultural activities, road construction, and tourism infrastructure will reduce 635 ha of mangrove forest by 2025 [18], just as the socioecological system deforests this forest in Huaylá-Machala, Ecuador [61].

The researchers mentioned above agree that the sustainability of the coastal ecosystem must be improved, in addition to developing planning actions, conducting programs to mitigate the impact of natural resources, as well as providing tools for the management and implementation of public policies intended to protect, conserve, and increase the mangrove forest.

The increase in mangrove forest surface will lead to environmental, social, and economic improvement, reduce CO₂ (the main greenhouse gas), mitigate climate change, and achieve the 2030 SDGs.

Regarding the mangrove surface demand model for the year 2030 with an increase of 6691 ha and 2050 with 8921 ha, it contributes satisfactorily by presenting a little more than the area evaluated in the first year of 80,071 ha. Thus, by combining the surface demand model with the factors used in the mangrove sustainability model, the optimal sites for the growth and development of this forest were obtained.

In this sense, the sustainable surface demand model of the mangrove forest satisfactorily meets the guidelines of the SDG 2030, which were adapted to put an end to poverty, protect the planet, and ensure the prosperity of people by the year 2030. It also meets what stipulated in the LGCC, which establishes that to contribute to climate change mitigation, Mexico must reduce GHG emissions 30% by 2020 and 50% by 2050 compared to the emissions generated in 2000.

It also contributes to the national REDD+ strategy that encourages the reduction of deforestation and forest degradation and the increase of these to absorb GHG emissions, proposing to reduce 22% of such emissions by 2030 and reach a 0% deforestation rate. That is why the future land use demand was integrated with a deforestation rate of 0.

Finally, it is necessary to clarify that other studies only analyze the future trend of the mangrove forest based on changes in land-use and vegetation cover in the past [18,20,21,60] or they analyze the life processes of each mangrove individual, such as establishment, growth, and mortality [23]. In contrast, the study presented in this article develops a complete analysis that goes from the dynamics of spatiotemporal land use in the past, the design of a demand model, the generation of a geospatial model using MCE techniques, the design of sustainable scenarios for 2030 and 2050, and the estimation of sustainability indicators.

5. Conclusions

The future sustainable mangrove forest model and the demand surface model can be applied in any study area to increase the forest area and protect and conserve the goods and services provided by mangroves following the guidelines of the SDGs, the LGCC, and the REDD+ strategy.

In addition, implementing the set of mitigation strategies favors the future development of these models, benefits sustainability indicators by increasing the absorption of atmospheric CO₂ through photosynthesis, and complies with the national REDD+ strategy to achieve 0% deforestation by 2030 and 2050.

These strategies also benefit the social sector, protect against the impact of natural phenomena, generate economic income for the local and regional population, and creates sustainable reforestation and restoration work activities. The mangrove forest offers refuge, food, and space for reproduction to the fauna that coexists in the landscape. At the same time, it benefits the environment and contributes to climate change mitigation.

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