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Spatial analysis of the impact of shrimp culture on the coastal wetlands on the Northern coast of Sinaloa, Mexico

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A B S T R A C T

In the Mexican coasts, as in many tropical and subtropical coastal areas, shrimp culture grew exponentially over the last three decades. This process has produced an intense debate on the economic benefits but also about the extent and intensity of the impact of this activity on the coastal ecosystems, particularly the effects of pond construction on mangrove areas and other coastal wetlands. For the Northern coast of Sinaloa (Northwest Mexico), a region where shrimp culture is actively practiced and reproduces most of the shrimp controlled production model in Mexico, a land cover change-detection analysis, with Landsat images, outputs that 75% of the shrimp farming in this region has been built on saltmarshes while less than 1% was constructed on mangrove areas. Through the estimation of landscape metrics for different scenarios (with and without shrimp culture infrastructure), we find that in addition to direct removal of saltmarshes, shrimp aquaculture has significantly modified the spatial patterns of coastal wetlands, retreating wetland borders and fragmenting their patches. These last impacts are mainly related with the development of the linear infrastructure associated with shrimp culture (drainage channels and roads), rather than the construction of the ponds. Present findings and other from similar studies done in Northwest Mexico; allow us to estimate that 60% of shrimp farming in Mexico impacted directly on saltmarshes, contrasting with the 3% of shrimp farms built on mangroves.

1. Introduction

During the past three decades, the shrimp culture industry has expanded exponentially on the tropical and subtropical coasts worldwide. According to FAO (2011), the annual production of cultivated shrimp increased from about 213 600 t in 1985, with a value of nearly one billion dollars, to 3 399 105 t in 2011, with a value of about 14 billion dollars. Mexico is not an exception, and the activity that began in the early 1970s, with annual yields less than 200 t, in 2008 recorded a production of about 130 000 t with a value of 486 million dollars.

Currently it is estimated that between 1 and 1.5 million hectares along the world's coasts are covered by some type of shrimp farm. This expansion has been accompanied by an intense debate concerning its environmental, economic and social impacts. The activity has caused, among other impacts, the loss of wetlands, increase of the nutrient load in coastal waters, introduction of exotic species, spread of diseases and overexploitation of the juveniles of native shrimp species (Boyd and Clay, 1998; Primavera, 2006).

Human activities that involve land cover and land use changes have a major impact on both the productivity and diversity of the coastal zone. It is estimated that during the 19th and 20th centuries, about 50% of coastal wetlands in the eastern United States were lost because of land cover changes (Kennish, 2001; Klemas, 2001). Therefore, both the inventory of wetlands in different spatial and temporal scales and the understanding of the causes and dynamics of land cover and land use changes are essential to reverse the negative trends and to establish strategies for the long-term management and protection of coastal wetlands and ecosystems (Alphan and Yilmaz, 2005; Yang and Liu, 2005a,b; Rebelo et al., 2009).

The land cover and land use changes caused by shrimp culture in the coastal zone have been analyzed using remote sensing (RS) and geographic information system (GIS) techniques by many authors (Alonso-Pérez, et al., 2003; Ali, 2005; Bélard et al., 2006; Berlanga-

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Robles and Ruiz-Luna, 2006; Jayanthi et al., 2006; Rajitha et al., 2007; Seto and Fragkias, 2007). This type of research usually describes and quantifies the total area of land cover and land use changes, with special emphasis on the removal of mangroves or other wetlands, but little attention is paid to the impact of shrimp culture on the spatial structure of coastal landscapes, thus this latter is the purpose of our study.

Traditional inventories of land cover and land use changes can be improved with the analysis of the modifications of the spatial arrangement of the landscape elements (Manson et al., 2003; Yang and Liu, 2005b; Gu et al., 2007). For this purpose landscape metrics, which provide information of the structural characteristics of landscape in quantified parameters, can be used. There is a wide variety of metrics based on the landscape geometry and the spatial arrangement of patches. Although some of them are strongly correlated and could generate redundant information, they can be useful to describe and monitor the complexity of the landscape structure, including the external impacts on it. Landscape metrics may also help to detect changes in patterns over a variety of spatial scales as a result of prior land use and management (McGarigal and Marks, 1995; Herzog et al., 2001; Liu and Cameron, 2001). Regarding that little information is available about the use of landscape metrics to evaluate the impact of shrimp culture and other man-made infrastructures on coastal wetlands, we used this approach to analyze the extent of the land cover changes generated by the expansion of shrimp culture, but in addition we also assessed the impacts on the spatial complexity and connectivity of the wetlands.

2. Study area

The study area is on the Northern coast of Sinaloa, Mexico, approximately between 25°N and 26°N, and 108°W and 109°W, facing the Gulf of California (Fig. 1). The region is characterized by the presence of large estuarine systems. The climate is very dry and warm with an average temperature of 24 °C. The warmest months are July to October and the coldest from November to March. The average annual rainfall is 330 mm. The main plant associations are

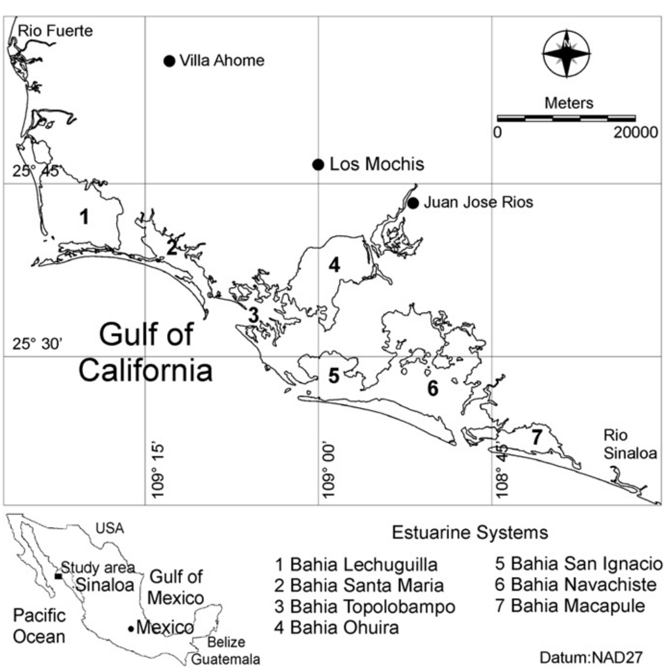

Fig. 1. Study area. Northern Sinaloa coast, Mexico.

the thorn forest–shrubland, low deciduous–tropical forest, halophytic vegetation and xerophytic scrubs.

The geographic characteristics of the Northern coast of Sinaloa made the development of a number of human activities possible. This area has been recently characterized by a high degree of economic development, considering that the valleys in the region contain the most technologically developed and productive agricultural fields in Mexico. In addition, the coastal plain in this region has the highest concentration of shrimp farms in the country. The main cultivated species is the white shrimp (*Litopenaeus vannamei*), with most farms using a semi-intensive system.

3. Material and methods

A spatio-temporal analysis was made in two steps using criteria similar to those used by Manson et al. (2003), Liu et al. (2003) and Gu et al. (2007). First a land cover and land use change-detection analysis was done and then the changes in the spatial structure of the wetlands were evaluated using landscape metrics.

3.1. Detection of land cover and land use changes

In the first step, a post-classification change-detection method was used (Yang and Liu, 2005a; Berlanga-Robles et al., 2010; Berlanga-Robles and Ruiz-Luna, 2006, 2007, 2011). A change-detection matrix was then constructed from thematic maps derived from classification of Landsat images (path-row 33–42 and 34–42) from 1986 (MSS), 1992 (TM), 2000 (ETM+) to 2005 (TM). A map to represent the landscape before the development of shrimp culture was created by the classification of the 1986 images with four categories of wetlands, an ocean surface class and a general class for all the terrestrial covers (Table 1). The images were classified with the Isocluster algorithm and the output with 30 clusters was improved with a decision tree to get the final result. The Isocluster output map, a digital-elevation model (DEM) and land use vector data were used to build a decision tree with eight nodes to derive a six-class map. The DEM was compiled from the data of the North American Landscape Characterization program of the US Geological Survey at a resolution of 60 m. The land use vector data

Table 1
Wetland classes of the Northern Sinaloa coast, Mexico obtained by classification with a decision tree of the Landsat MSS image from 1986 and ancillary data.

ID	Class	Description
1	Coastal lagoons	Wetlands and deep water habitat of estuarine-subtidal type, usually partially enclosed by land. The substrate is permanently flooded with tidal waters and the ocean water is occasionally diluted by freshwater of rivers and runoff. Includes bays, estuaries and coastal lagoons.
2	Saltmarsh	Estuarine intertidal wetlands. Plains temporarily flooded by tides and occasionally by freshwater runoff. Includes saltmarsh without or with vegetal cover.
3	Mangrove	Estuarine shrub-forest wetlands. Intertidal areas dominated by woody vegetation including monospecific or multispecific vegetation assemblages of four mangrove species: white mangrove (*Laguncularia racemosa*), red mangrove (*Rhizophora mangle*), black mangrove (*Avicennia germinans*) and buttonwood (*Conocarpus erectus*).
4	Sand beach	Unconsolidated shore wetlands. Areas exposed and flooded by tides with unconsolidated substrate dominated by sand, lacking vegetation except for pioneering plants. Includes landforms such as beaches and bars.
5	Terrestrial covers	Substrates dominated by dry faces. Land covers and land uses that include dry forest, xerophyte shrubs, agriculture, cities and villages and bare substratum.
6	Ocean	The open ocean overlying the continental shelf and its associated high-energy coastline.

were digitized from the land use and vegetation map Los Mochis, G12-9, at a 1:250 000 scale, produced by the National Institute of Statistics and Geography (INEGI).

The accuracy of the map was evaluated by an error matrix indicating the total accuracy and an estimate of the Kappa coefficient (K′) (Congalton and Green, 1999). The test points were selected by a stratified random sampling, defining the number of test points for each class of wetland according to their proportionality in the landscape. In addition, based on the sample sizes of the wetland classes, nearly 400 additional points for the terrestrial-cover class were also selected. The reference data for the matrix were obtained from the land use and vegetation map Los Mochis, G12-9 (1:250 000). In parallel, the shrimp farm polygons were digitized from the false-color composites of Landsat TM images of 1992, 2000 and 2005. For the most recent year, the procedure was improved with the aid of field data taken with a GPS receiver (with accuracy better than 15 m at a 95% confidence level) and the inspection of Google Earth images of higher spatial resolution. Polygons for each year were rasterized at a resolution of a 60 m pixel size and overlaid on the thematic map of 1986 to generate a change-detection matrix.

3.2. Assessment of spatial complexity and connectivity with landscape metrics

Three scenarios were analyzed in the second step:

Scenario 1 (S1): Coastal landscape before shrimp culture development (1986).
Scenario 2 (S2): Coastal landscape transformed by shrimp culture (2005). This was represented by the wetland thematic map of 1986 (S1) with the addition of the polygons of shrimp farms of 2005.
Scenario 3 (S3): Coastal landscape transformed by shrimp culture and linear facilities (hydraulic channels and roads). The vector data of channels and roads produced by INEGI at a 1:250 000 scale and updated with ground data were rasterized and added to the map of S2.

For each scenario, landscape metrics at the class and the landscape levels were calculated with the four-cell neighborhood rule and a minimum patch size of four pixels. Landscape metrics were calculated assuming a landscape-mosaic model in which the wetland classes were considered as "true" patches, whereas ocean water and terrestrial covers were considered as the external background (with negative value) and excluded from the analysis. In Scenarios S2 and S3, shrimp farms, hydraulic channels and roads were considered as interior background (positive value) and included only to calculate the total area of the landscape. Subsequently, the wetland classes were grouped into a single class and the landscape metrics were assessed at the landscape level under a biogeographic-island landscape model, in which a single class of patches is considered and analyzed analogously to oceanic islands surrounded by an ecologically neutral matrix.

The metrics calculated were class area and total area (CA and TA), number of patches (NP), larger patch index (LPI), perimeter-area fractal dimension (PARAFRAC), division index (DIVISION), effective mesh size (MESH) and splitting index (SPLIT). The DIVISION, MESH and SPLIT are metrics to assess the landscape fragmentation based on the cumulative-patch-area distribution. The simultaneous use of these metrics, although they might be somewhat redundant, could be useful because of the different interpretations and scales involved. These metrics were designed to be used in binary maps in biogeographic-island models, but the software FRAGSTATS 3.3 allows their evaluation at the level of class in mosaic models, with the characteristic of being insensitive to the data resolution and to the inclusion of numerous small patches in the analysis (Jaeger, 2000; Neel et al., 2004).

A comprehensive explanation of all metrics estimated is available in McGarigal and Marks (1995) and Jaeger (2000). The IDRISI-Andes software was used for editing the satellite images and the ancillary data, the unsupervised classification (with Isocluster), the accuracy assessment, the digitalization of the shrimp farms and the edition of the scenarios. The software ENVI 4.3 was used for the classification by the decision-tree method and FRAGSTATS 3.3 was used for the estimation of landscape metrics.

4. Results

Through the proposed classification procedure (Isocluster-decision tree), a thematic map of the wetlands was produced with an accuracy of 84% of the 1990 test points (Fig. 2). The estimate of the Kappa coefficient (K′) was 0.8, which defines a classification with substantial agreement with the observed data (Congalton and Green, 1999). The coastal lagoon class was classified with a producer's accuracy of 97% and an user's accuracy of 99%; the saltmarsh obtained 80% and 84%, respectively, mangrove 82% and 95%, sandy beaches with 84% and 100%, and terrestrial covers with 89 and 72%.

The shrimp farm polygons of the other dates were added to the 1986 classification (Fig. 3) to generate the change-detection matrix (Table 2), which allowed us to determine the period when shrimp culture had the highest expansion rate in the study area and to detect the changes in the land cover. The impact on the spatial patterns of the wetlands was therefore cumulatively assessed between 1986 and 2005. Calculations showed that in 1992 nearly 1200 ha of ponds were in the region and by 2000 the pond surface area increased near to 6400 ha, reaching about 10 000 ha by 2005 (Table 2). The peak of the expansion in the area was between 2000 and 2005 at a growth rate >700 ha year^{-1}. The land cover changes caused by shrimp culture from 1986 to 2005 were estimated by adding the pond surfaces for each date and this sub total was then subtracted from the surface of the ponds lost and without land cover changes. The results indicate that about 75% of the shrimp

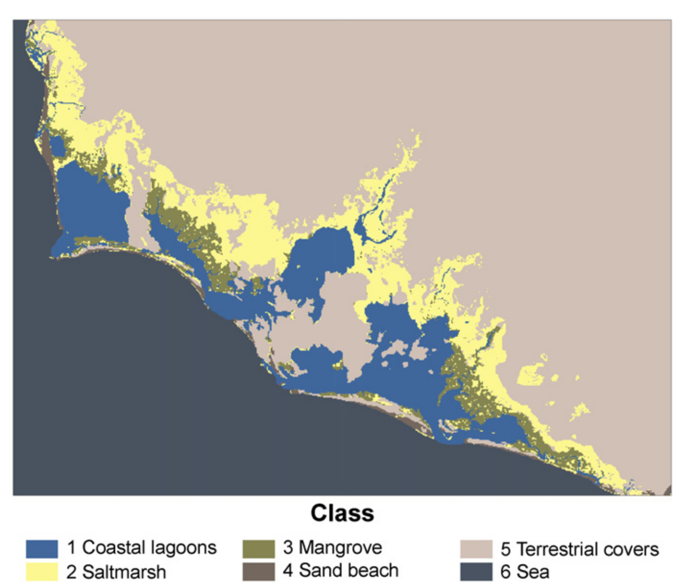

Fig. 2. Map of coastal wetland distribution in Northern Sinaloa (Mexico) before the development of the regional shrimp culture. Produced by classification (decision-tree method) of a Landsat MSS scene (1986). Overall accuracy = 84%.

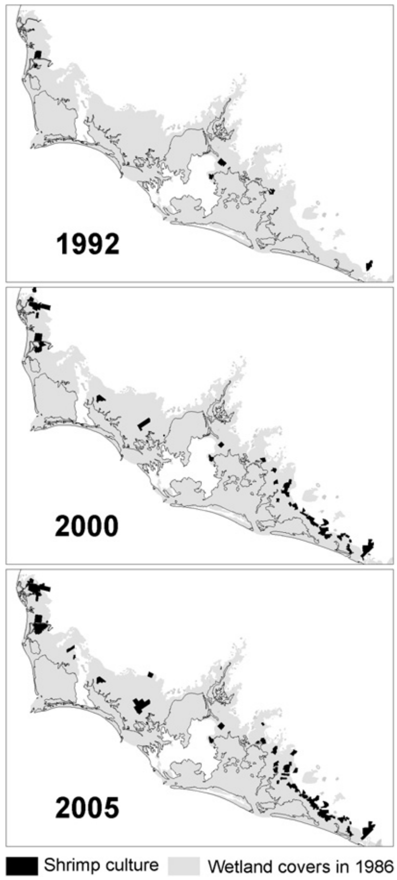

Fig. 3. Development of shrimp culture in the Northern Sinaloa coast (1992 to 2005). Polygons from the shrimp farms were digitized by interpretation of Landsat TM and ETM+ false-color images.

farms were constructed on saltmarsh and the remaining 25% were developed mainly over the terrestrial cover class.

For the 1986 landscape (S1), the natural wetland area was 160 000 ha, of which 41% was coastal lagoons, a percentage similar to that of saltmarsh, 14% was mangrove and 3% was sand beach (Table 3).

The landscape metrics for the coastal lagoon, mangrove and sand beach classes were constant for the three scenarios, because these classes were not affected by the establishment of ponds, hydraulic channels and roads. In contrast, the saltmarsh class, where most of the pond facilities detected in 2005 were established, had changes in landscape metrics in the different scenarios such as the decrease of the class area, an increase in the number of patches and a reduction of complexity and connectivity of patches (Table 3).

In S2, the building of nearly 10 000 ha of ponds caused the loss of 11% of the saltmarsh present in 1986 (S1). For scenario S3, nearly 340 km of linear infrastructure, including channels and roads, were built over the wetlands in the region. The area of such facilities was overestimated, because the conversion of vector data to raster format let the lines with a fixed width of 60 m (the size of the pixel) remain, which is greater than the real width of the channels and roads in the study area (<30 m at the widest). With this technical limitation in mind, we estimated that the building of these linear facilities was a loss of roughly 2000 ha of saltmarsh. Overall, the ponds and linear facilities in S3 resulted in a decrease of 14% of the saltmarsh present in S1 (Table 3).

The PARAFRAC for saltmarsh remained constant between the scenarios S1 and S2, but declined in scenario S3 (Table 3), which suggests a trend of the patches to adopt less complex shapes when the wetlands were affected by shrimp farms and linear facilities. The slope between the natural logarithms of the area and the perimeter of patches estimated for S1 was significantly different from the value of S3 ($F = 24.7$, Dunnet test $(q) = 5.3$, $P < 0.05$).

The comparison of the patchiness-related values of landscape metrics in the extreme scenarios (S1 and S3) showed that the overall impact of shrimp farms and linear facilities on the saltmarsh resulted in an increase of the number of patches and the decrease in the largest patch index (LPI) by 90%. The mode of the natural logarithm of the area of patches in S3 showed significant differences with modes of the other two scenarios (Mood's median-test statistic $= 26.91$, $P < 0.01$).

The patch-size distribution of saltmarsh in all the scenarios was dominated by small patches, such that 90% of these comprised less than 10% of the total area of this class (Fig. 4A). This distribution gives the landscape a low degree of coherence, which is defined by Jaeger (2000) as the probability that two animals located in different areas within a region come into contact. The metrics DIVISION, MESH and SPLIT were designed on the basis of such probability. According to the estimated values of these metrics, the connectivity of patches decreased, this was not clearly seen in the values of DIVISION because this metric was affected by the dominance of small patches in all scenarios. However, it was clearly reflected in the values of the effective mesh size (MESH), which decreased from 9% of the total saltmarsh area in S1 to only 2% in S3 (Table 3).

Even though three of the four wetland classes did not show the impact of shrimp farms and linear facilities, the impact on the saltmarsh was evident in the values of the landscape metrics assessed at the landscape level (Table 3). The values of the PARAFRAC index decreased, showing significant differences in the slopes of the linear regressions of the natural logarithms of the area and the perimeter of patches ($F = 15.3$, $q = 4.4$, $P < 0.05$). Similar to that which occurred to the saltmarsh class, the patch-size distribution was dominated by small patches in all scenarios (Fig. 4B), but the distribution of S3 was significantly different from that in S1

Table 2
Land cover changes caused by shrimp culture in Northern coastal Sinaloa, Mexico. Surface in hectares.

	Year	Subsidiary cover						Total
		Coastal lagoons	Saltmarsh	Mangrove	Sand beach	Terrestrial covers	Shrimp culture	
Shrimp culture	1992	0	931	1	0	284	0	1217
	2000	6	4166	13	0	1308	896	6388
	2005	5	2811	16	0	904	6213	9949
Sub total		11	7908	30	0	2496	7109	17554
Ponds loss		0	467	3	0	26	0	−496
Ponds without changes		0	0	0	0	0	7109	−7109
Total change	ha	12	7441	26	0	2470	0	9949
1986–2005	%	0.1	75	0.3	0	25	0	

Table 3
Landscape metric of natural wetland classes of the Northern Sinaloa coast, México estimated with a mosaic-landscape model for three shrimp culture impact scenarios; S1 without shrimp culture impacts, S2 with shrimp culture impacts, and S3 with shrimp culture and linear facilities (hydrologic channels and roads) impacts.

Metric	Class								
	Coastal lagoons			Saltmarsh			Mangrove		
	S1	S2	S3	S1	S2	S3	S1	S2	S3
CA/TA	66 950	66 939	66 910	66 951	59 477	57 456	21 983	21 958	21 873
PLAND	41.4	40.8	40. 8	41.4	36.3	35.0	13.6	13.4	13.3
NP	127	126	126	623	677	874	329	328	342
LPI	19.34	19.1	19.1	13.6	12.7	5.3	4. 0	3.9	2.1
PARAFRAC	1.37	1.37	1.36	1.40	1.40	1.32	1.37	1.37	1.36
DIVISION	0.94	0.94	0.94	0.96	0.97	1.00	1.00	1.00	1.00
MESH	9360	9219	9151	5928	4330	827	441	434	243
SPLIT	17	18	18	27	38	198	366	378	676

Metric	Class								
	Sand beach			Landscape level[a]			Wetlands[b]		
	S1	S2	S3	S1	S2	S3	S1	S2	S3
CA/TA	5144	5144	5143	161586	164056	164056	161586	164056	164056
PLAND	3.2	3.1	3.1	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
NP	33	33	33	1112	1164	1375	105	123	275
LPI	0.7	0.7	0.7	19.3	19.1	19.1	98.3	92.2	46.1
PARAFRAC	1.38	1.38	1.38	1.38	1.38	1.34	1.36	1.35	1.29
DIVISION	1.00	1.00	1.00	0.90	0.91	0.94	0.03	0.15	0.65
MESH	21	20	20	15749	14003	10241	156039	139313	57047
SPLIT	7863	8105	8107	10	12	16	1	1	3

Notes: Maps' resolution: 60 m, CA/TA: Class area/Total area (ha), PLAND: Percentage of landscape, NP: Number of Patches, LPI: Largest patch index, PARAFRAC: Perimeter-area fractal dimension, DIVISION: Landscape division index, MESH: Effective mesh size, SPLIT: Splitting index.
[a] Includes all natural wetland classes in a mosaic-landscape model.
[b] All natural wetlands combined into one class in a biogeographic-island landscape model.

and S2 (Mood's median-test statistic = 17.66, $P < 0.01$). The MESH index decreased from 10% of the total surface area in S1 to 6% in S3.

By analyzing wetlands as a single class in a biogeographic-island model, the landscape metrics showed significant changes between S1 and S3 (Table 3). The number of patches nearly tripled and the LPI was halved. The slopes of the linear regressions used to calculate the PARAFRAC showed significant differences (F = 5.3, q = 2.6, $P < 0.05$). As before, there were significant differences between the medians of the natural logarithm of the patch-surface area (Mood's median-test statistic = 34.56, $P < 0.01$). In this case, the DIVISION was not sensitive to the dominance of small patches in the patch-size distribution (Fig. 4C) and the impacts caused by the expansion of shrimp farms and linear facilities could be detected. This metric increased from nearly zero (landscape without fragmentation) in S1 to 0.15 in S2 and 0.65 in S3. Again, the landscape metric that best reflected the impact of the shrimp culture on wetlands was the MESH, which decreased almost 17 000 ha from S1 to S2, and almost 100 000 ha from S1 to S3. The MESH represented 97% of total area in S1, whereas in S2 it fell to 85% and to 35% in S3.

5. Discussion

In the Northern coast of Sinaloa from 1986 until 2005 the shrimp culture activity grew from zero to 10 000 ha, which is 15% of the ponds in Mexico (Appendix). The shrimp farm facilities in the region were established mainly on saltmarshes. This happened because of the advantages offered by this land cover for the building and operation of shrimp farms; saltmarshes are flat land (slope $<2°$) with Solonchak and Vertisol soils, both having fine textures and low infiltration rates that make them ideal for building shrimp ponds. The water supply and drainage is facilitated by the nearness of the coastal lagoons and altitudes lower than 2 m above sea level. The accessibility is easier than that for other wetlands, particularly mangroves. In addition, saltmarshes have assigned a low economic value because these lands are not suitable for traditional agriculture practices and the laws protecting these wetlands are limited and ambiguous. In Mexico there is little knowledge on their ecological functions and services.

The changes in land cover caused by shrimp culture in Northern Sinaloa are similar to those recently recorded by several authors in other coastal landscapes in Northwestern Mexico (Appendix). On average, 60% of the shrimp farms along the coast of the states of Nayarit and Sinaloa have been established on saltmarshes and only 3% on mangroves. This means a loss of 12% of the saltmarshes and 0.6% of the mangroves existing before the development of shrimp farming in both states.

Assuming that the above described are common patterns at country level, extrapolating them to the total shrimp farming extent in 2003 (Appendix), it is estimated that in Mexico nearly 39 000 ha of saltmarsh areas and around 2000 ha of mangroves could be replaced by shrimp culture facilities. This extrapolation did not include the Mexican states of Campeche, Yucatan, Quintana Roo and Chiapas, which together encompass 60% of the mangrove forests of the country (Acosta-Velázquez et al., 2009), but represent just around 1% of the shrimp pond area in Mexico by 2003 (CONAPESCA, 2004).

As in other parts of the world, the expansion of shrimp culture in Northern Sinaloa has resulted in the loss of wetlands, but unlike those places the most affected wetland type has been saltmarshes and mangroves in second term (Table 3). This pattern highly contrasts with the trends observed in other countries of America and Asia, particularly Bangladesh, Vietnam, Thailand, Ecuador and Honduras, where mangrove destruction has been documented in correlation with the expansion of shrimp aquaculture (Alongi, 2002; Barbier and Cox, 2004; Islam and Wahab, 2005; Bélard et al., 2006). It is estimated that between 20% and 40% of the total world's area occupied by shrimp culture was associated with mangrove deforestation (Primavera, 2006).

Other studies evaluating the impact of shrimp culture have focused on pollution and loss of biodiversity, besides mangrove area reduction. However, little attention has been given to the

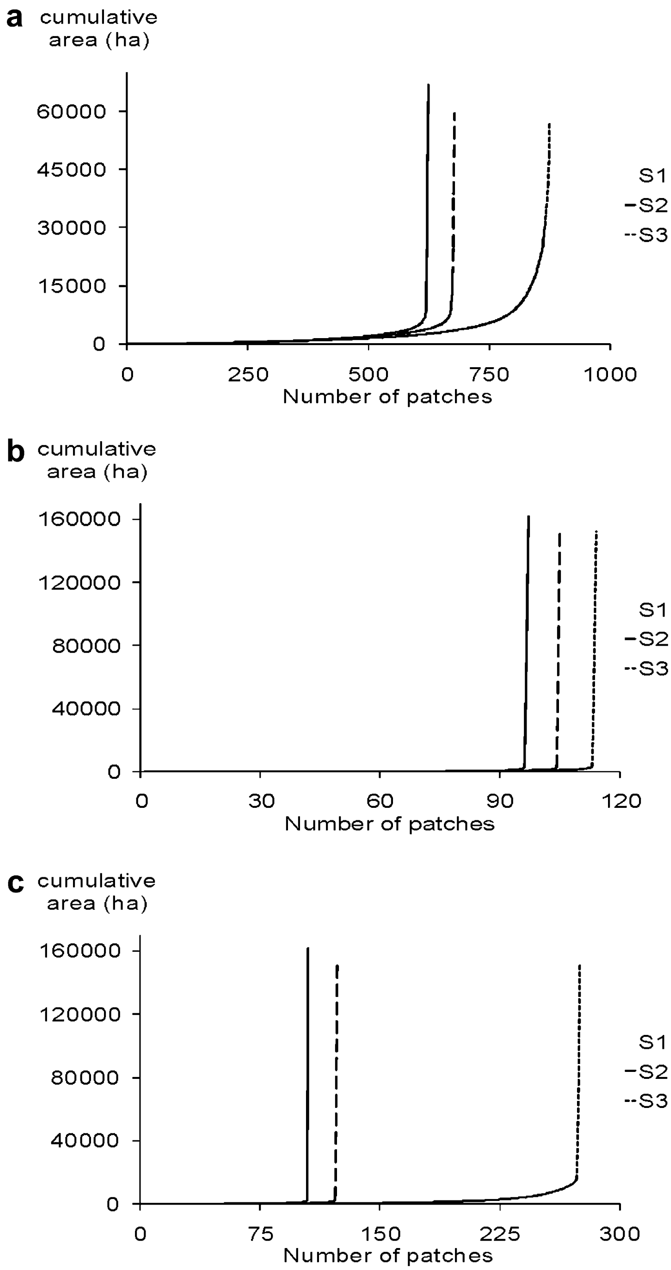

Fig. 4. Patch-size distributions for the coastal wetlands in Northern Sinaloa in three shrimp culture impact scenarios; S1 without shrimp culture impacts, S2 with shrimp culture impacts, and S3 with shrimp culture and linear facility (hydrologic channels and roads) impacts. A) Saltmarsh class B) Landscape level, and C) Wetlands. Landscape level includes all the natural wetland classes in a mosaic-landscape model. In C all wetland classes were combined into a single class in a biogeographic-island landscape model.

impact of this activity on the landscape. Shrimp culture in Northern Sinaloa has generated a mosaic characterized by the loss of natural wetlands, the retreat of wetland borders and the wetland fragmentation. These are trends recorded by analyzing landscape metrics.

Among those, PARAFRAC is a metric that can be used to define the spatial properties of wetlands and to assess the impact of anthropogenic activities. The observed trends of this metric provide information about the irregularity of patch borders within the total wetland classes and in other specific classes, such as for saltmarsh. Our results are in agreement with those of Liu and Cameron (2001) about wetlands in Galveston Bay, USA. Those authors did not find significant differences in the PARAFRAC between undisturbed wetlands and wetlands with holes (gaps within the patches), but they found a significant decrease of this parameter as a function of the increase of the impact of roads and railroads. Our study did not find significant differences in the values of PARAFRAC when comparing undisturbed wetlands (S1) with wetlands "perforated" by shrimp farms (S2). But when we compared S1 with wetlands impacted by shrimp farms and linear facilities (S3), the PARAFRAC decreased significantly.

The landscape-fragmentation metrics are indicative of the breaking up of natural areas into smaller and more isolated units. In the fragmentation process, six change-phases are distinguished; perforation, incision, dissection, dissipation, shrinkage and attrition, which all may occur simultaneously (Jaeger, 2000). In the wetlands of Northern Sinaloa, a perforation phase may be caused by the building of shrimp culture facilities, and as phases of incision and dissection caused by the expansion of hydraulic channels and roads. Overall, shrimp farms and linear facilities have caused the fragmentation of wetlands by dissipation. In contrast with DIVISION, which was sensitive to the presence of numerous small patches in the landscape, the other two metrics based on the degree of coherence (MESH and SPLIT) were able to detect the process of the fragmentation of the wetlands caused by aquaculture infrastructure.

The impacts of shrimp culture extend well-beyond the simple changes of land cover, because the fragmentation of the saltmarshes, mainly by the linear facilities, modifies the flow of water in the intertidal zone, reducing the supply of sediments, and altering the equilibrium between the relative rates of vertical accretion and immersion that determine the stability in such environments (Turner and Rao, 1990; Kennish, 2001). Saltmarshes are one part of the tidal frame so that impacts on this may result from changes in the relative sea level or the tidal range (Adam, 2002). As noted by Laegdsgaard (2006), because of the interruption of the surface flows of water, the flooding time of saltmarshes could increase, causing mortality of halophytes that can only withstand short periods of immersion. Saltmarshes can provide a continuity of habitat with other adjacent tidal or intertidal environments. Because the retreat of the borders of wetlands and increasing in fragmentation, the availability and access to refuge zones decreases, as does the exchange of juveniles of several species of crustaceans, mollusks and fish between the wetlands and their deep water habitats, thus having repercussions in the productivity of fisheries (Adam, 2002; Haas et al., 2004; Vance et al., 2008).

The fragmentation creates barriers that are obstacles to the colonization processes and the general ecological functions of these environments. Thus, the planning of shrimp culture facilities within the perspective of wetland conservation must be based not only on the prevention of the deterioration of "charismatic" ecosystems, such as mangroves; these have been impacted but not in the same proportion that other land cover classes were. In addition, planning must include rules to minimize the impact of the shrimp culture and linear facilities on the overall coastal landscape. This is possible by building of bridges, fords and culverts to insure the connectivity between the different environmental units and through a reevaluation of the economic and ecologic role of the saltmarshes in the tropical, coastal landscapes.

In Mexico, the conservation and management policies for coastal wetlands have mainly focused on mangrove forests, paying little attention to other wetlands; even the official guidelines for the conservation and use of coastal wetlands (NOM-022-SEMARNAT-2003) only protect mangrove communities directly, just applying precautionary principles to other wetlands, on which it is possible to construct farm facilities, particularly on saltmarshes, without legal problems as it could happen on mangroves.

In addition, the impact assessment of shrimp farming, due to land use changes, weighs only direct removal of mangroves, minimizing other aspects related to landscape health, such as wetland patches continuity, essential factor required to maintain the water and matter fluxes along the coastal landscapes. Such impacts are common even when regulations indicate that land use and land cover changes associated with shrimp farm construction must guarantee the integrity of the hydrologic flow and avoid any structures disrupting the dynamics and ecological integrity of coastal wetlands.

Regarding the terms included in the NOM-022-SEMARNAT-2003, the shrimp farming facilities in some regions of Mexico (*i.e.* Sonora) have been considered as part of a sustainable activity, because they were built on land covers other than mangroves, particularly on saltmarshes (González et al., 2003). In a similar way, only based on some estimates of the saltmarshes extent, Páez-Osuna et al. (2003) have argued that in the Gulf of California there is a potential area of 236 000 ha for shrimp farm construction, without any other ecological or landscape considerations.

Present results demonstrate that the impact of shrimp culture in the study area and probably in Mexico, in terms of land use changes, goes beyond the removal of mangroves. This suggests that it must be considered in a holistic perspective, integrating all types of wetlands as components of a self-organized coastal system, where elements and subsystems are interacting and producing a special development that only can be assigned to the system as a whole. In this sense, the present study shows that saltmarshes removal and construction of ponds and linear infrastructure have clear effects on the connectivity of the coastal wetlands.

The use of landscape metrics does not necessarily provide information on the condition of ecosystems, because not always the relationship between spatial patterns, as measured by these indicators, and ecological processes is justified, or because the metrics fail to adequately reflect changes in the landscape (Lindenmayer et al., 2002; Li and Wu, 2004). Even so, empirical ecological studies in coastal wetlands and other wetland ecosystems suggest that some patch measurements (such as the size of wetlands) may be suitable as landscape indicators of ecological condition in coastal wetlands (Lopez et al., 2006).

Nevertheless, although in this study we inferred changes in the hydrological patterns of wetlands from the observed landscape metrics assessed in each scenario, it is not possible to define thresholds for management purposes because of the lack of data and a theoretical framework from which it could be possible to analyze the correlation between spatial patterns and ecological processes, weighing the processes response to changes in spatial patterns and scale.

Despite this, when a relationship between a spatial pattern and an ecological process is assumed, such as the connectivity of the patches with the mobility of species, or with the energy or matter fluxes through the landscape, the landscape metrics can provide enough information to determine trends of change and thus provide indirect indicators of the impact of human activities on those processes, to support decision-making concerning with management and conservation of the coastal environment.

In general, the landscape metrics by themselves do not provide enough information to design management strategies, but their intrinsic value lies in the possibility to compare changes within a landscape or among landscapes analyzed with the same spatial scale, as in the present work, rather than to set differences between different landscapes (Hargis et al., 1998). In addition to the information that can be obtained on changing trends in landscape conditions, the metrics can provide additional information on actions required to reverse impacts, the type of intervention needed and for the future assessment of the success of the interventions (Lopez et al., 2006). A more efficient integration of spatial perspective to management coastal plans requires the development of databases and the adoption of techniques that together strengthen the decision-making processes, particularly those involving large areas and requiring spatially explicit information.

6. Conclusions

The debate on the impacts of shrimp culture in Mexico has focused on the loss of mangroves and other coastal wetlands. Our results and other related studies indicate that even when mangrove systems have been altered by shrimp aquaculture, saltmarshes are the most affected wetlands. If present findings in Northern Sinaloa can be extrapolated at country level, around 60% of the shrimp ponds in the country could be built on this type of wetland, while only 3% of these facilities could be occupying mangrove areas. Moreover, the construction of ponds and linear infrastructure associated with the operation of shrimp farms, such as drainage channels and roads, has led to fragmentation and the retreat the borders of the saltmarshes.

The change-detection matrix, patch-size distributions and landscape metrics calculated in this study indicate that whereas the construction of ponds is the main factor causing the loss of habitat, the linear facilities have the highest impact factor for the complexity and connectivity of wetlands.

The fragmentation of saltmarshes is endangering the stability of the wetlands within the intertidal zone and the ecological functions and services of these environments. Thus the planning of shrimp culture facilities and their further expansion must include mechanisms that minimize the impact of hydrologic channels and roads, such as the building of bridges, fords and underground facilities, planned with the help of a spatial study of the landscape, together with the economic and ecological revaluation of the saltmarshes.

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Appendix. Extent and land cover changes of shrimp culture in Northwest Mexico.

Shrimp culture area (2003).

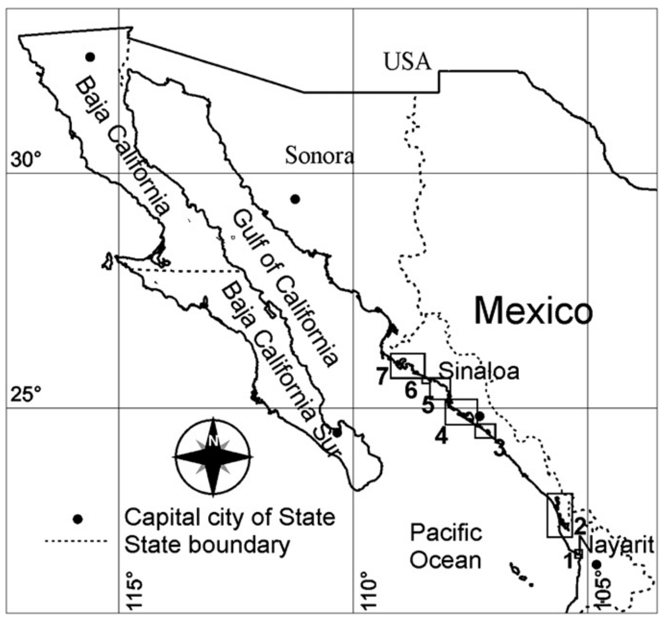
Estate	Area	
	ha	%
Nayarit	877	1
Sinaloa	48420	74
Sonora	13757	21
Baja California Sur	171	0.3
Baja California	550	1
Others	1310	2
Total	65085	

Source: CONAPESCA (2004).

Land cover changes due to shrimp culture in locations of Northwestern Mexico.

Place	Period	Subsidiary cover						Total
		Saltmarsh		Mangrove		Others		
		ha	%	ha	%	ha	%	ha
1 San Blas;	1973–2000	1102	58	230	12	568	30	1900
2 Teacapan-Agua Brava	1973–2000	938	29	102	3	2168	68	3208
3 Ceuta	1984–1999	442	39	8	1	698	61	1149
4 Altata-Ensenada de Pabellon	1984–1999	5644	89	54	1	646	10	6344
5 Bahia San Maria	1973–2005	2254	51	57	1	2090	48	4401
6 Guasave	1973–2000	4956	79	349	6	1004	16	6309
7 Northern Sinaloa coast	1986–2005	7441	75	26	0.3.	2482	25	9949
Average			60		3		37	

Sources: 1 Berlanga-Robles and Ruiz-Luna (2006); 2 Berlanga-Robles and Ruiz-Luna (2007); 3 Alonso-Pérez et al. (2003); 4 Lieberknecht (personal communication); 5 García (personal communication); 6 Martínez (personal communication); 7 this study.



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