

Land cover modification geoindicator applied in a tropical coastal environment

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Abstract: Environmental changes due to natural processes and anthropic modifications can be characterized by the degree of land cover modification and its environmental implications over time. The main goal of the present study was to propose and apply a land cover modification geoindicator in order to assess the environmental condition of the territory per landscape units. It was designed to interpret diffuse information and transform it into a synthetic indicator that will be useful for environmental managers. The geoindicator evaluation was performed through a multi-temporal analysis of medium resolution Landsat satellite images and their unsupervised classification according to the direction of land use transitions. A change detection analysis between image pairs from 1973, 1991 and 2001 was made to detect unaffected areas and the areas in which positive or negative land cover changes could be observed. The proposed methodology was applied in the coastal palustrine area; specifically, in the marine-terrestrial ecotone of Campeche, Mexico. Geoindicator values during the 1974-1991 and 1991-2001 periods were low, 46.5% and 40.9%, respectively, due to the intrinsic limitations of coastal wetlands for productive activities. Urban and suburban transition areas showed high degrees of modification of about 39.5% and 32.1% for the first and the second period, respectively. Moderate modification, 4.9% in the first period and 5.7% in the second, was observed in isolated landscape units with recovering vegetation. The proposed geoindicator showed physiognomic and functional evidence of affectation levels from human activities, regeneration patterns and alteration of the landscape structure, modulated by the historical-economic process in the studied area. *Rev. Biol. Trop.* 62 (3): 1111-1128. Epub 2014 September 01.

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Environmental geoindicators are measurements (magnitudes, frequencies, averages and trends) of natural and anthropic processes taking place above or near the Earth's surface, that denote significant environmental changes (catastrophic or gradual) that have occurred within a human lifespan (100 years or less). Berger and Iams (1996) considered how geoindicators are used to monitor and evaluate environmental changes and provide important references to support the explanation of stress factors induced by humans, nature or both. This allows the health of environments and their ecosystems to be assessed, including abiotic, biotic and anthropic elements, as opposed to statistics

from primary data, which are direct measurements of different parameters. In general, indicators represent an empirical model of reality, but are not reality itself (Hammond, Adriaanse, Rodenburg, Bryant, & Woodwatd, 1995).

Different types of environmental indicators are available (Hammond et al., 1995), ranging from ecological indicators which monitor biodiversity and ecological integrity, to sustainability indices with multiple objectives. Most indicators produce data based on targeted sampling, specific objectives and restricted areas, but do not consider their territorial setting or the related areas of influence. However, other indices provide concepts that are susceptible to



being territorially evaluated, such as those proposed by Cooper, Ramm, and Harrison (1994), Berger and Iams (1996), Dale and Beyeler (2001), Morton (2002) and Machado (2004). Cooper et al. (1994) focused their analysis on estuarine environments, and calculated a health index composed of a geomorphological base, water quality analyses, a biological quality assessment and an aesthetic value assessment. Later, Berger and Iams (1996) called for a meeting of natural science specialists, which led to the production of a guide of relevant indicators to show significant anthropic-natural environmental changes. In turn, Dale and Beyeler (2001) created an ecological index based on changes in the composition, structure and function of ecosystems at three levels of territorial organization, in relation to habitat fragmentation. Subsequently, building on the work of Berger and Iams (1996), Morton (2002) proposed geoindicators for tropical coastal environments characterized by the dynamics and importance of geomorphological changes that have occurred during the past few decades. More recently, theoretical contributions added the concepts of hemeroby (Kovarik, 1990; Hill, Roy, & Thompson, 2002), and of naturalness, proposed by Machado (2004); both concepts included a measurement of the human impact on the ecological state of ecosystems, on different perturbation scales at the site level.

In this paper, the procedures evaluating geoindicators were adapted to transitional ocean-continent coastal territories that were regulated by marine-terrestrial flooding regimes, and by the functional tension between oceanic and continental environments. According to Morton (2002), geoindicators that are used more frequently for environmental diagnosis in tropical coastal zones include the following: changes in the distribution and ecological integrity of coastal wetlands, change detection in coastal morphology, damage to coral reefs, alteration of sedimentary patterns, and biotic and abiotic changes associated with endogenous activity (neotectonics and volcanism).

The impact of human activity on the natural environment is a complex process with an

evident territorial expression that is linked to how the territory is appropriated by society, and results from the technological and economic levels of resource exploitation. The rhythm of these impacts, both in magnitude and persistence, determines the intensity of the effects and the possibility of nature's recovery, or the definitive loss of biological integrity and natural resources.

In order to identify and characterize the degree of environmental modification in their spatial-temporal context, changes in land cover were used as a dynamic indicator of landscape transformations over a given period of time. Vegetation cover is the result or synthesis of the ecological condition of the landscape, since it has a physiognomic expression that can be objectively delimited, and its degrees of perturbation can be quantified. The identification of environmental changes was based on the landscape ecological evaluation criteria used by Baudry (1984), Forman and Godron (1986), Oldeman (1990), Berger and Iams (1996), Etter (2001), Turner, Gardner, and O'Neill (2001) and Farina (2006).

Finally, this paper will show that while medium resolution satellite images allow for a precise comparison of environmental conditions of the territory at different time periods, they simultaneously facilitate the use of weighted numerical indicators for assessing both human impact and the ecological state of different land cover types. The land cover modification geoindicator proposed here is one of such assessment tool.

MATERIALS AND METHODS

Study area: The study area includes the South-Southwest coastal zone of the state of Campeche, Mexico; in particular, the wetlands of Terminos Lagoon, an important territory with actual and potential ecological and economic value. It is located between the settlements of Sabancuy and Atasta (19°N, 92°W). The study area covers a coastal belt 30km wide, and included both continental and subtidal environments. Toward the continent, the study

area extended up to 25km (perpendicular to the coastline), depending on the maximum level of marine-continental flooding (Fig. 1). Within this zone, the first 15km towards the ocean included the direct marine influence interface, mainly defined by the presence of palustrine plains of supratidal influence. The remaining 10km included wetlands that are ecologically and anthropically interconnected with the area of direct influence.

Identification and characterization of coastal landscapes: The system of landscape units in Terminos Lagoon has a continental interface composed of eight geosystems and nine geofacies. It comprises the terrestrial geosystems regulated by the flooding regimes on plains of different origins. The names given to the geosystems and geofacies (Fig. 2) describe significant functional characteristics and follow a landscape structural-systematic taxonomy based on a chorological, historical and genetic arrangement, originally proposed by Bertrand

(1968), Cowardin, Carter, Golet, and LaRoe (1992) and Zonneveld (1995). The chorological taxonomy is based on the regionalization principle of geographical space, in which the zone, domain and region represented upper fields, and, the interfaces, geosystems, geofacies and geotopes are on the lower organization levels. Interfaces can be differentiated according to their ecological functioning (marine or continental) and the nature of their components at the regional level. The geosystem corresponds to a well individualized territorial complex emphasizing its ensemble dynamics, and, the geofacies insists on the local physiognomy. If the geosystem includes the geographical complex and its dynamics, occupying areas of tens of meters to hundreds of square kilometers, the geofacies will reflect the features of the local ensemble, and will correspond to a homogeneous sector characterized by its own physiognomy, with a reduced spatial extension (from tens of meters to a few square kilometers).

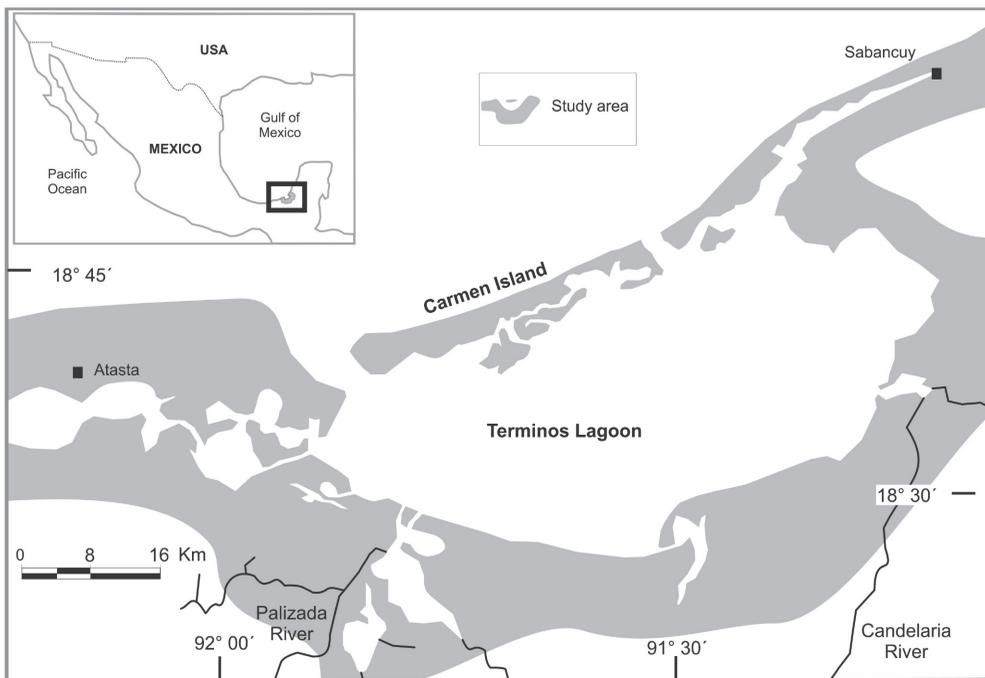


Fig. 1. Study area in the coastal zone of Campeche, Mexico.

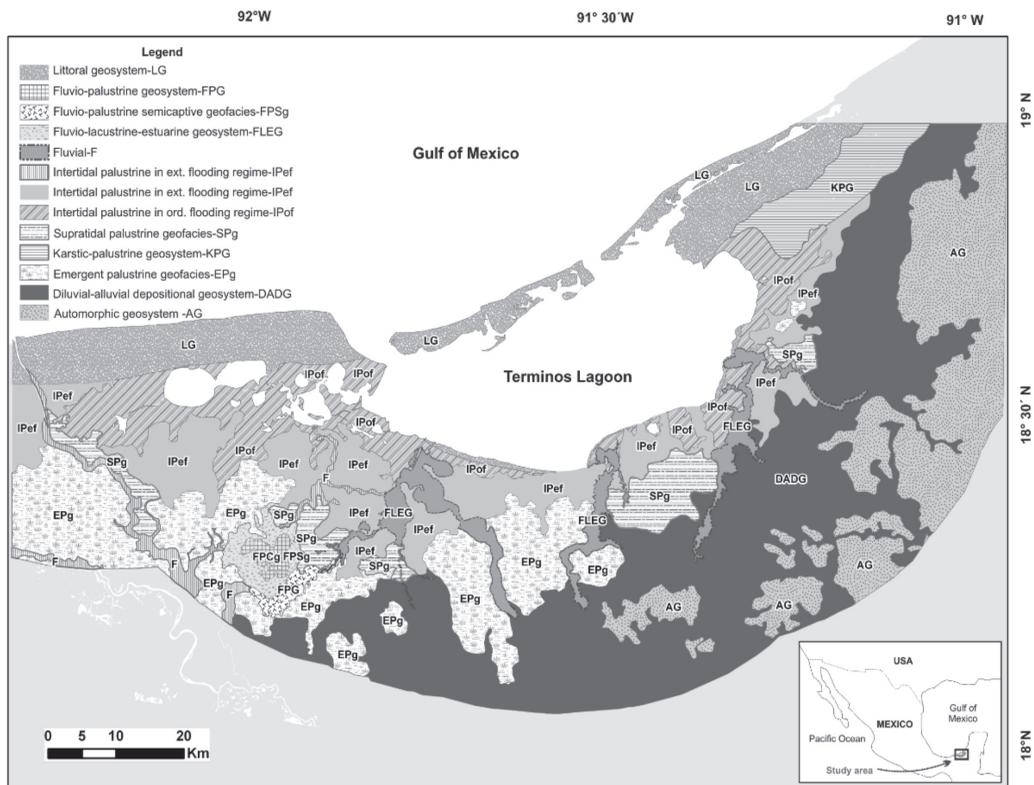


Fig. 2. Landscape units in the study area.

The land units are characterized as follows:

1. Littoral Geosystem (LG): This is a transitional landscape resulting from the functional tension between continental and marine environments. Relative influence is expressed by transitional aquatic, subaquatic and terrestrial sectors of varying extensions.
 - 1.a. Beach ridges littoral geofacie (BrLg): Marine-eolic undulating plains, formed by carbonate-siliceous-sand deposits. They are the result of the succession of aligned sandpits that have been partially stabilized by coastal vegetation. They form part of the marine, coastal and subaquatic morphology of zones and are characterized by abundant sedimentary materials and an intense longshore drift. Each topoform has a corresponding soil type: Calcaric

Regosol is found with beach ridges and Eutric Regosol with troughs. The vegetation cover can be differentiated morphologically and structurally into creeping and shrubby (*Coccoloba uvifera*, *Batis maritima* and *Ipomoea pes-caprae*), and arboreal (*Avicennia germinans* y *Conocarpus erectus*) species.

- 1.b. Barrier island littoral geofacies (BiLg): Subhorizontal marine-eolic plain formed by bar islets of subaerial carbonate-siliceous deposits. Bar islets are integrated in a continuum of narrow plains that tend to become stabilized by coastal vegetation. Calcaric Regosols are formed on these stabilized materials that are colonized by creeping plant species (*C. uvifera*, *B. maritima* and *I. pes-caprae*).
2. Palustrine geosystem (PG): Flooding cumulative plains formed by biogenic and

terrigenous sediments and plant debris. Due to the geologically recent sedimentary origin of the study area, its location over a marginal deltaic depression, and marine and terrestrial water inputs, this zone there has a natural predisposition for the formation of flooded plains. They are temporally or permanently flooded by tides, fluvial overflows or rainwater stagnation. Four main variants are recognized based on flooding regimes and the relationship with coastal-marine environments.

- 2.a. Intertidal palustrine in ordinary flooding regime geofacies (IPof): These subhorizontal marine-palustrine plains or flats (Reineck, 1972) are formed by biogenic structures, fine carbonate-siliceous and detritic materials, are permanently flooded by the average tidal level (0.42m). Hydromorphic soils are formed by the interstratified accumulation of sediments (Gleyic Solonchak and Eutric Gleysol) and are colonized by hydrophytic mangrove vegetation (*Rhizophora mangle* and *A. germinans*).
- 2.b. Intertidal palustrine geofacies in extraordinary flooding regime (IPef): These subhorizontal marine-palustrine plains are formed by fine carbonate-siliceous detritic materials and biogenic structures, and are flooded by the average water level between neap and spring tides during equinoxes (0.923m). Mollic and Vitric Gleysol hydromorphic soil types are formed on top of these materials, having a fine to medium texture derived from a mixture of sand and clay. Within this geofacies, emergent hydrophytic vegetation is dominant, and includes tule (*Typha dominguensis*) and reed thickets (*Phragmites australis*).
- 2.c. Supratidal palustrine geofacies (SPg): These subhorizontal marine-palustrine plains are formed by a complex of fine carbonate-siliceous and biogenic detritic materials, and are flooded by extraordinary tides (spring tides). This flooding is associated with the prism of water level ascent due to storm surges and saline

water intrusion during the hurricane season. Flooding invades low terrains in an interdigitated manner between 17 and 25km inland. In contrast with the previously described geofacies, the biomass of tule (*T. dominguensis*) and reed thickets (*P. australis*) is larger and more deeply rooted. Shrubby and arboreal elements of low tropical forests begin to colonize these landscape units.

- 2.d. Emergent palustrine geofacies (EPg): These subhorizontal palustrine plains (slopes of less than 2°) are formed by a complex of fine detritic siliceous and biogenic materials. Terrain flooding is regulated by rainfall accumulation and fluvial overflows where tidal influence is absent. Flooding generates hydromorphic and semi-hydromorphic Vertic and Mollic Gleysol soil types. Mesophytic vegetation from low and medium tropical subdeciduous forests grows on these plains. The most representative tree species of the tropical deciduous forest are *Annona glabra*, *Haematoxylum campechianum* and *Tabebuia rosea*, which form compact groves. *Bravaisia tubiflora*, an herbaceous species indicator of flooding in continental environments, is present in association with low and medium tropical forests.
3. Karstic-palustrine geosystem (KPG): This subhorizontal, slightly karstified structural plain is formed by marly limestone and is semi-permanently flooded. Semi-hydromorphic and hydromorphic Vertic and Eutric Gleysol soil types are predominant, as are savannoid grasses (*Paspalum notatum*, *Paspalum virgatum* and *Cyperus rotundus*) and trees (*Crescentia cujete* and *Curatella americana*).
4. Fluvio-palustrine geosystem (FPG): These subhorizontal fluvio-palustrine plains are formed by alluvial-biogenic deposits. This geosystem integrates different morphogenesis and dynamics. The lotic fluvial flow incorporates depressions that become permanent or temporary lentic reservoirs.

- 4.a. Fluvio-palustrine captive geofacies (FPCg): These subhorizontal fluvio-palustrine plains are formed by alluvio-biogenic deposits resulting from the chaotic array of palaeostreams that have lost their flow due to irregular ground settlements or to changes in the water stream direction. They are grouped in topographic zones below the depositional terraces and become temporary euryhaline lacustrine bodies. Fluvial hydrological connections have been lost either due to avulsion or to over-sedimentation of streambeds, not excluding extraordinary weather.
- 4.b. Fluvio-palustrine semi-captive geofacies (FPSg): These subhorizontal fluvio-palustrine plains are formed by alluvial-biogenic deposits from temporary communication between interchannel lakes and meanders that have an unstable configuration and temporary activity. In general, they are abandoned meanders or distributary channels in the process of stabilization that divagate over flooded plains and present water flow during the rainy season.
- 4.c. Active fluvio-palustrine geofacies (AFPg): These subhorizontal fluvio-palustrine floodplains are formed by alluvial-biogenic deposits and are built between meandering or braided rivers with longitudinal gradients of less than 1%. During overflow periods, water flow exceeds the levels, invading the floodplain and producing differential sedimentation. This process repeats in a seasonal cycle, generating a hydrosystem of interconnecting fluvial floodplains, intermittent watercourses and interchannel lakes. The smallest of these lakes tend to dry up and are gradually covered by the herbaceous species *P. notatum*, *P. virgatum* and *C. rotundus*.
5. Fluvio-lacustrine-estuarine geosystem (FLEG): This aquatic estuarine environment on fluvio-lacustrine plains is formed by alluvial-biogenic deposits with calcareous sands and calcareous crusts. It is a complex geoecosystem influenced by longitudinal, lateral and vertical hydrodynamic processes of seasonal drift. In the same hydrosystem, active interaction exists between fluvial, lacustrine and marine processes. In terms of relative intensity and types of interactions, three subzones may be differentiated: lower (mesohaline), middle (oligohaline) and higher (fresh). The associated riparian vegetation includes communities of medium tropical subdeciduous forest (*Inga vera*, *Lonchocarpus luteomaculatus*, *Machaerium falciforme*), tasistales (*Acoelorrhapha wrightii*).
6. Fluvial geosystem (FG): This is a fluvial bed on structural plains of consolidated calcareous materials and fluvio-diluvial deposits. The channel either follows the river bed or divagates to form an alluvial floodplain. The associated riparian vegetation includes communities of medium tropical subdeciduous forest (*I. vera*, *L. luteomaculatus*, *M. falciforme*), tasistales (*A. wrightii*) and savannoid elements (*C. cujete*).
7. Diluvial-alluvial depositional geosystem (DADG): These undulating diluvial-alluvial accumulative plains are formed by a complex of alluvial-diluvial deposits. They result from successive accumulation of layers of soil materials and small fragments which are removed by interfluvial sheet denudation and dragged downhill by gravity. They are characterized by the typical transitional morphology between low hills and fluvio-deltaic plains, where piedmont deposits coalesce with fine detritus from present fluvial overflow and from the overflow deposits of past intradel-taic floodplains. Due to the diversity of the geomorphological processes, ecotones exist between the Eutric Gleysol and Pelic Vertisol soil types. The associated vegetation includes communities of medium tropical subdeciduous forest (*I. vera*, *M. falciforme*), tasistales (*A. wrightii*) and savannoid elements (*C. cujete*).
8. Automorphic geosystem (AG): These are karstic tabular low hills with convex

geometry. They are semi-buried and alternate with low structural plains that have calcareous crusts. This geosystem disperses or infiltrates water rather than accumulating it, and thus remains unflooded, except in extraordinary flooding events. The dominance of denudation over accumulation processes develops automorphic, skeletal Rendzic Leptosol soil types. The vegetation cover in these areas consists of extensive low tropical subdeciduous forest and groves of medium tropical subdeciduous forest.

Geoinicator construction: The geoinicator of land cover modification is built one landscape unit at a time, because in terms of environmental diagnostics, the degrees of modification caused by anthropic activities are circumscribed to the functional realms of each landscape unit. Due to the different intensities and spatial and temporal distribution of the anthropic activities, the combination of the observed changes results in different degrees of modification expressed as changes in the vegetation cover, in comparison with the original state used as the reference point.

The land cover modification index described here is based on the concepts found in ecological theory of hemeroby and naturalness. Kovarik (1990) defines hemeroby as “the sum of the effects of past and present human activities on the current site conditions or vegetation which prevent the development to a final state.” Machado (2004) defines the loss of naturalness as the product of ecosystems that have been artificially altered, basically due to three often interrelated causes: the incorporation of new elements, the relocation or loss of its own elements, and the change in fluxes and dynamics, normally as a result of the input of additional energy.

The main evidence of change to the original morphological and functional conditions of the landscape due to anthropic perturbation includes: the replacement of climax stage vegetation by early stages, rejuvenation of lower trophic levels, reduction or loss of biodiversity,

alteration of regulatory mechanisms, habitat fragmentation, substitution of diffuse or curvilinear borders or frontiers by linear or geometrical borders, interruption or loss of connectivity, interruption or alteration of biogeochemical cycles, biomass reduction, introduction to the landscape of allochthonous or exotic elements, the increase in allochthonous (anthropogenic) energy, the time spans of modifications, partial or total loss of vertical porosity (increment in compacted or impermeable surfaces), and the status of resistance-resilience caused by these modifications. The temporal variations of natural and anthropic perturbations oscillate within an acceptable range of variation known as the condition of integrity (Fig. 3). When perturbations exceed their thresholds, ecosystems enter a critical state from which they hardly ever recover. In general, such variation thresholds are exceeded due to anthropic perturbations that inhibit resilience.

The degrees of modification are related to the moment in which perturbations begin, in the case of moderate modification. If the intensity of perturbation persists over time and reaches a critical level of intensity, a high degree of modification is reached. Finally, very high modification degrees are attained when the capacity for natural recovery is nullified due to the introduction of exotic species, the elimination of native species and the introduction of artificial energy.

The following procedures were used in the identification of the modification degrees per landscape unit:

- Delineation and characterization of landscape units that were systematically arranged according to the survey scale (1:100.000) and the morphological and functional elements,
- Identification of anthropic activities having an impact on the region and their relation to key indicators and modification degrees,
- Validation of the criteria and key indicators in a pilot area using satellite images and field work,

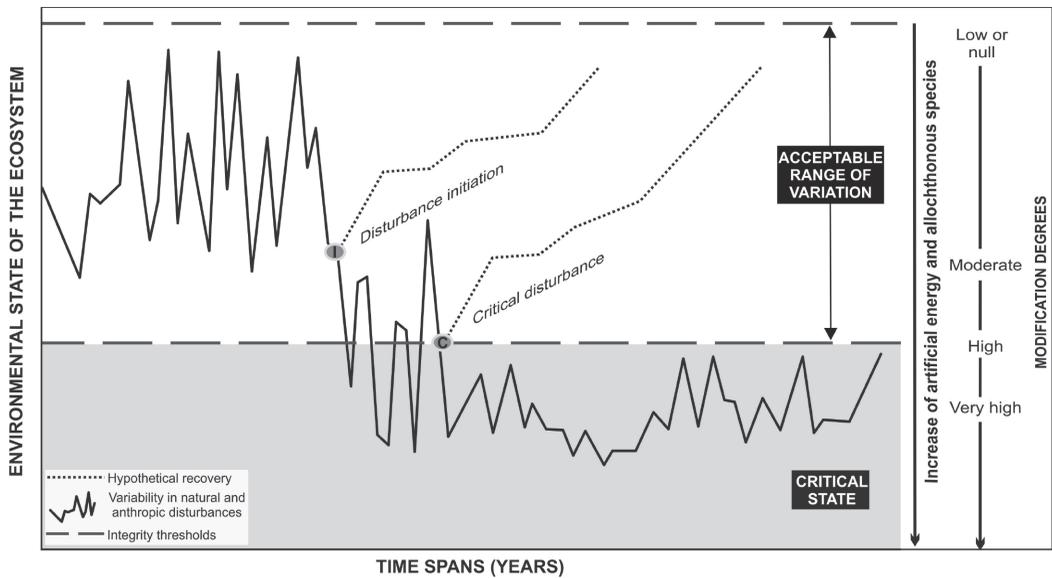


Fig. 3. Temporal oscillation in the environmental state of ecosystems and degrees of modification.

- General criteria application using a raster multi-temporal classification of medium resolution satellite images for all the study area. The raster formats for both dates were overlaid with conventionally determined numeric assignments in order to detect changes. Map Algebra in ArcGIS 9.x was used to perform spatial analysis by creating expressions in an algebraic language. With the Raster Calculator tool, is possible to create and run Map Algebra expressions that output a raster dataset.
- Generation of the modification geoindicator for each landscape unit through a multi-temporal comparison of modification degrees.
The identification of present anthropic activities and their temporal-spatial variations allows for the identification of their degree of modification and the permanence or retreat of the territory's ecological quality according to the following key indicators (Table 1).
In order to validate the degrees of modification on the pilot area, we clipped two Landsat TM images from two dates (1991

TABLE 1
Key indicators in land cover and modification degrees

Modification Degrees	Direction of land use transitions	
	Date of initial reference	Date of last record
Low	Original vegetation	Original vegetation
Moderate	Original vegetation preserved	Secondary tropical forests and pastures in recovery
	Original vegetation preserved	Agriculture and cattle raising
High	Secondary tropical forests and pastures in recovery	Agriculture and cattle raising
	Agriculture and cattle raising	Agriculture and cattle raising
Very High	Original or secondary vegetation	Suburban and urban areas
Retrosressive succession	All land covers except urban	Vegetation in different successional stages

and 2001) over a typical coastal and fluvio-palustrine environment that was representative of the study area. This area has a proposed degree of modification at the regional level and since 1964, the field campaigns have provided detailed data and recurrent monitoring of biotic and ecological factors. It was also selected for its ecological significance and relatively easy aquatic access through the coast, lakes and rivers.

Unsupervised classifications in spectral clusters were generated using the Isodata algorithm with between 5 and 40 classes, 3 iterations, 15% threshold and a minimum number of pixels in a class of 250. Thirteen classes were re-coded to an earlier date from 1991 and

a more recent one from 2001. Originally, 20 iterations were applied in the study area, looking to compensate the low radiometric resolution of the MSS image (6 bits and 64 levels) against the higher resolution of the TM (8 bits and 255 levels). However, after several evaluations and in order to make technically comparable all classifications, the number of classes was expanded and the iterations reduced to 3. Afterwards, the raster formats for both dates were overlaid with conventionally determined numeric assignments in order to detect changes in a final reclassified map of modification degrees (Fig. 4).

In order to verify the consistency of the modification keys for the entire study area in

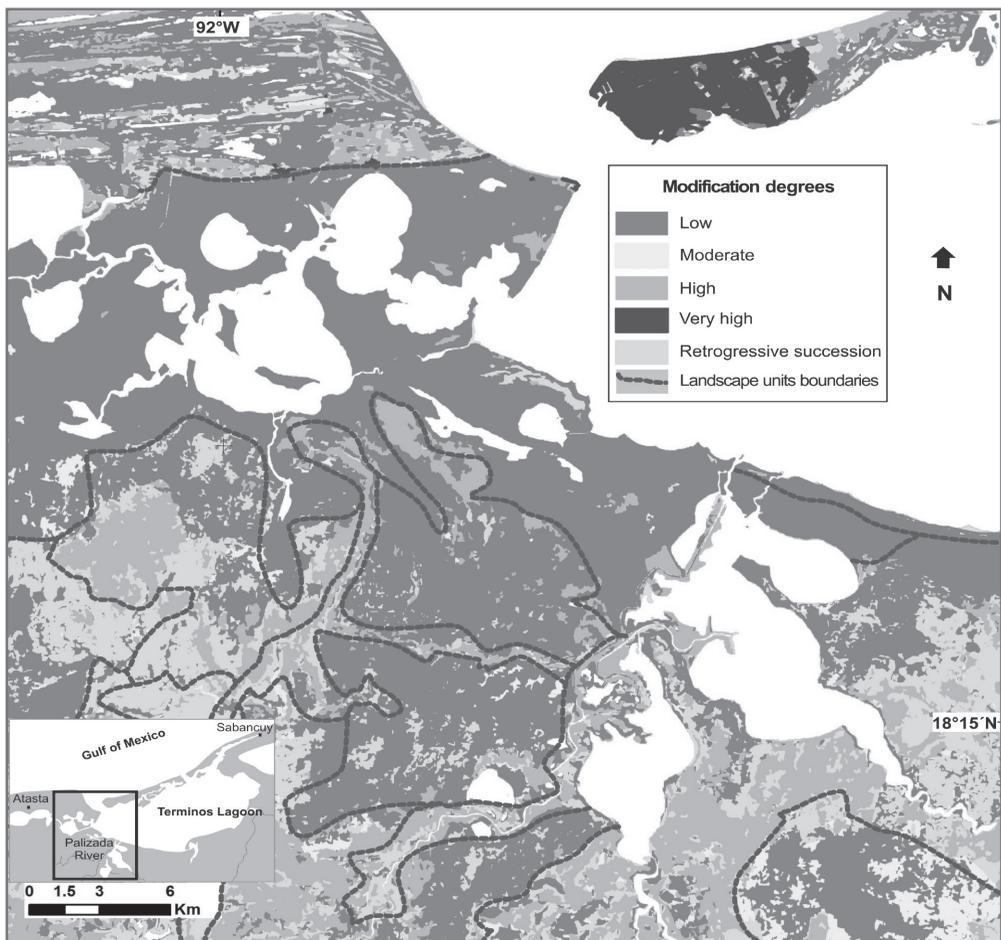


Fig. 4. Pilot area used to validate the degrees of modification.

the field, a stratified sampling was designed with 46 representative points. The verification was generated by the correspondence between the description of degrees of modification and the physiognomic characterization of successional stages, or modification of the vegetation cover. The detection of change was applied to the entire study area for two periods between three dates: 1974, 1991 and 2001, and its confidence was validated using ancillary cartography. For changes between 1974 and 1991, two types of sensors were used: Landsat MSS (Multispectral Scanner) and Landsat TM (Thematic Mapper); both have different spatial and spectral resolutions and geographic coverage. To overcome the incompatibility of the spatial resolution between images, the MSS image was resampled from 80 to 60m, and the TM image from 28.5 to 30m, using the nearest neighbor algorithm. With regard to settings related to the spatial resolution, resampling in meters were for both the MSS image and the TM images with less than a tenth of pixel, so that changes in terms of spatial resolution does not exceed more than one pixel. We also sought that the resampling would fit in exact multiples of 30 meters for reliable and comparable accounting of landscapes and corresponding areas between two images. The other objective was that when applying the low-pass filter, no abnormal or erratic pixels were obtained. As for the spectral resolution, for Landsat MSS four spectral bands were used, two of the visible channel and two near-infrared, and for Landsat TM three visible spectral bands, one near infrared and two mid-IR were used, excluding the thermal infrared. Afterward, a low-pass filter was applied to the unsupervised classifications in order to reduce the dispersion of information (salt and pepper effect). Clipping the 1991 classification to match the perimeter limits of the 1974 image solved the problem of incomplete image overlap from 1974 and 1991. Finally, to lighten the interpretation of data between the dates and to make the comparisons compatible, percentages were calculated from number of hectares with relative land cover by degree of modification. To validate the reliability of the

classification process, were applied the Kappa accuracy coefficient, this reached values of 0.71. This was not as high as ideal, but good enough especially for areas with high diversity of tropical continental (medium tropical subdeciduous forest and savannoid grasses) and sub-aquatic ecosystems (mangroves, tule, flooded tropical forests, among others). Although this coefficient is regularly used for classifications supervision, it was useful to compare the results of the original classification by type of coverage, with multiple field work checkpoints available, especially in the pilot area.

The correlation between the degrees of modification of the study area and the spatial range of each unit of coastal landscape is summarized the Geoindicator of Land Cover Modification Index. This geoindicator represents the level of perturbation circumscribed from spaces of relative functional homogeneity, in which each level of modification has a relative weight according to the area percentage it occupies, which is relative to the total area of each unit. Based on the criteria proposed by Oldeman (1990), Grant (1995), Kovarik (1990), Mateo and Ortiz (2001) and Machado (2004), and the criteria introduced in the present work, the adopted degrees of modification are described below (Table 2). The degrees of modification are based on three basic principles: the physiognomic expression of the ecological status of vegetation as an indicator of natural or human disturbance, human activities that could affect this status according to the technology level and the artificiality introduced of allochthonous elements of anthropic origin. Thus, each degree of modification reflects the levels of affectation experienced by the components and the original ecological dynamics, the compatibility or incompatibility of human activities with this dynamic, and the artificiality levels in the original landscapes. Strong anthropic pressure has generally led to the irreversible artificiality of its habitats.

The land cover modification geoindicator proposed here reflects the weighted value by relative area for each degree of modification, relative to the total area of the landscape unit;

TABLE 2
Landscape characterization and degrees of modification

Modification degrees	Landscape characterization
Low	Landscape units in biostasis (eco-units) of transitional or gradual borders. The original natural landscape is unaltered both in its physiognomy and in its functional relations, which maintain their dynamic equilibrium. High ecological value is present and economic activities are minimal, having a low impact on the natural environment.
Moderate	Landscape in aggradation (eco-units) of transitional or abrupt borders. Natural landscapes show significant but disperse and non-persistent transformation of the vegetation cover as a consequence of agricultural, cattle raising or forestry activities, as well as of rural and suburban settlements. Herbaceous, scrubby or arboreal vegetation appears; however, alterations of biogeochemical cycles and of flows and types of energy are not significant.
High	Landscape in innovation (eco-units) or degradation, of abrupt or very abrupt borders. Landscapes show persistent anthropic transformation with relicts of the original natural elements (individual or vegetation patches). Functional relations have been modified or adapted with specific anthropic purposes. Matter and energy inputs are largely artificial (agrochemicals, irrigation, mechanization, among other) as a result of a lengthy or inadequate agricultural and cattle raising activities. Human settlements are important modifiers of the landscape.
Very High	Original eco-units are absent. Artificial landscapes created by humans over a natural basis. The original dynamic equilibrium has been completely disturbed. Their functioning depends on large, artificially supplemented amounts of matter and energy. All or most natural elements have irreversibly disappeared.
Retregressive Succession	The landscape tends to establish a new status of ecological equilibrium from anthropic or natural perturbations, reincorporating or reestablishing some landscape elements. Presence of several successional stages (ages and strata) of plant re-colonization that do not restore the original condition of the landscape.

thus, readjusts the ecological importance on each surface disturbance and could help to explain changes in the internal functioning of each landscape unit over a period of time. It aids in locating more significant pressures, and thus optimizes the analysis of the threats affecting the ecological integrity by landscape unit. It also measures key ecological factors such as the territorial extent of the perturbation and its relative proportion in comparison with the environmental surroundings of the set of landscape units.

The geoinicator is applied to the continental interface of the coastal landscape due to the ease of monitoring visible changes in the landscape. It is based on the relative importance of degrees of modification and their transformation over time, variables which can only be monitored in terrestrial environments. It is calculated using the following equation, based on data gathered for each landscape unit and during a given time period:

$$MG = \frac{\sum CA_1(w_1) + CA_2(w_2) + CA_3(w_3) + CA_4(w_4) + CA_5(w_5)}{\sum^+ CA_{1,2,\dots,5}}$$

In which:

MG	Land cover modification geoinicator
CA _x	Area per class in hectares
	Weight of relative importance by degree of modification
w ₁	0.02 Low
w ₂	0.05 Moderate
w ₃	0.4 High
w ₄	0.5 Very High
w ₅	0.03 Retrogressive Succession
CA _{1,2,\dots,5}	Area per landscape unit

The weighting of the relative importance of the degrees of modification within the geoinicator aims at equalizing the unit as the maximum value, in order to maximize the importance of high and very high modifications

(usually in reduced areas), and to magnify the areas with low modifications. Thus, the modification geindicator should show an equilibrated relation between the surface area and the importance of the modification, classified into four levels: Low (0-0.25), Medium (0.26-0.50), High (0.51-0.75) and Very High (0.76-1.0).

RESULTS

The relative percentages of the changes in the vegetation cover are based on the succession of non-linear natural processes altered by human activity. Because of this, imprecision is registered within the complexity of the local environment, mostly due to the survey scale and the available information sources.

The results of the change detection (Table 3) show important percentages of low modification (of 46.5% between 1974 and 1991, and of 40.9% between 1991 and 2001) because mangrove, flooded tropical forests, tule vegetation and relict savannah areas are located within the limits of areas that have no productive potential for agriculture and cattle raising (Fig. 5 and Fig. 6). The second highest percentages of 39.5% (between 1974 and 1991) and 32.1% (between 1991 and 2001) correspond to a high degree of modification associated with persistent agriculture and cattle raising, at least during the past twenty years, invading areas of primary vegetation and secondary vegetation that are in a recovery process (secondary tropical forests and savannoid relicts).

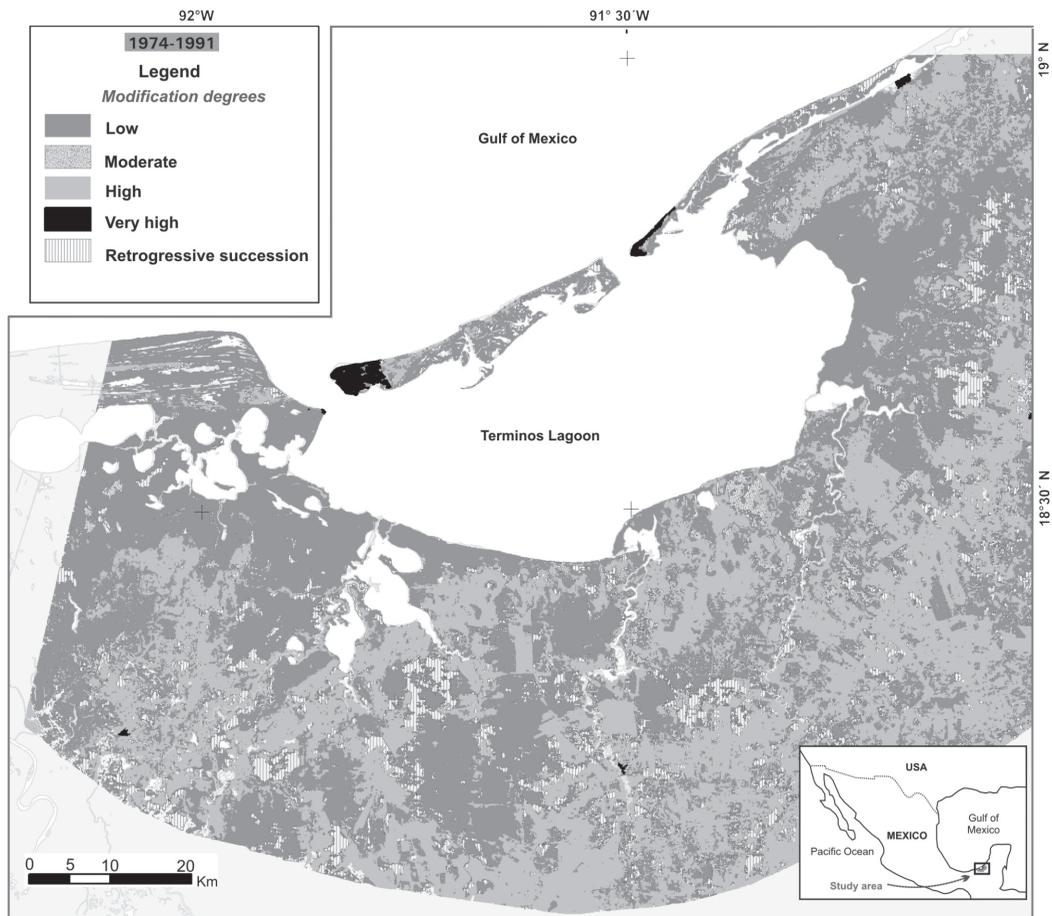


Fig. 5. Land cover modification index between 1974-1991.

TABLE 3

Land cover changes and land cover modification geoindicator in Terminos Lagoon, Campeche, between 1974 and 2001

	Change between 74-91		Change between 91-01	
	Ha	%	Ha	%
Low	31 7356.10	46.5	318 763.15	40.9
Moderate	33 570.02	4.9	44 088.63	5.7
High	269 563.38	39.5	249 932.37	32.1
Very High	2 021.18	0.4	4 299.64	0.7
Retrogressive succession	59 533.84	8.7	161 908.48	20.6
Total	682 044.52	100	778 992.27	100

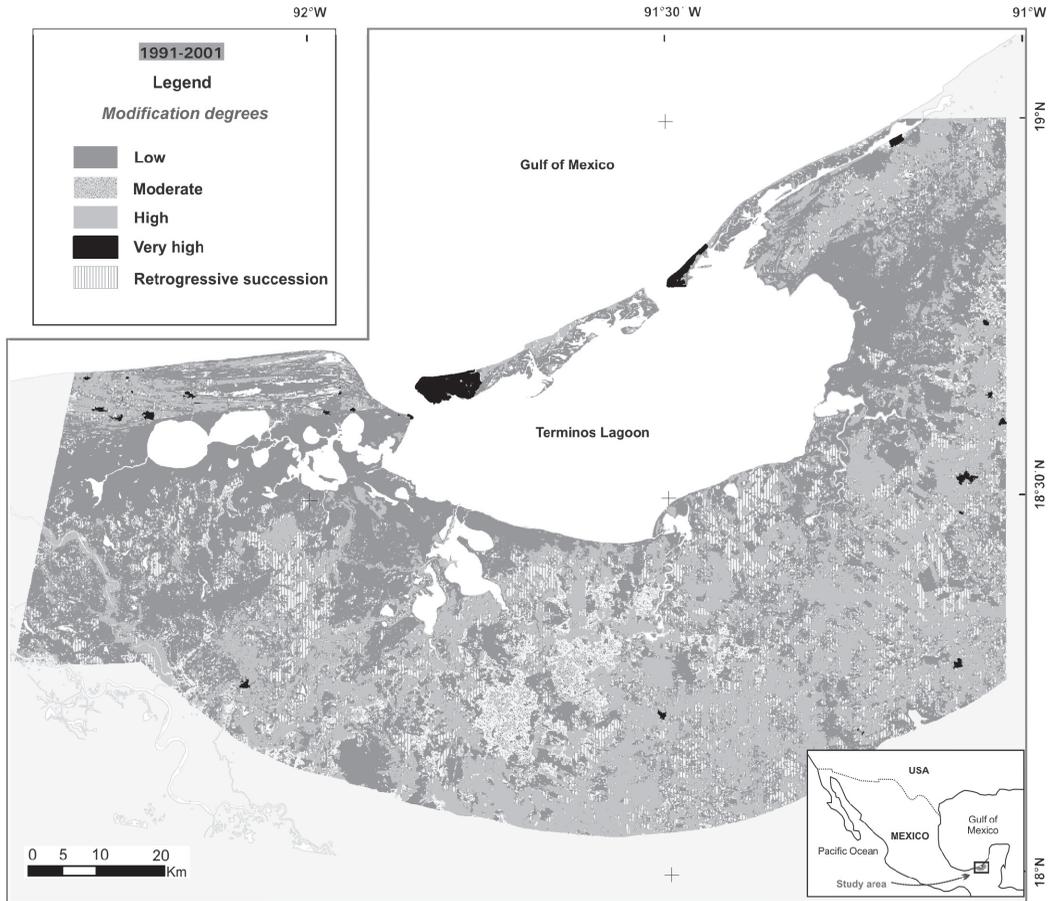


Fig. 6. Land cover modification index between 1991-2001.

The third highest percentage corresponds to incipient secondary succession, with 8.7% between 1974 and 1991, and 20.7% between 1991 and 2001 (Fig. 5 and Fig. 6). This indicates an ample range of successional stages of low and medium tropical subdeciduous forests

and abandoned agricultural land in which the newer ecounits evolve into successional phases of several ages.

The low percentages of very high modification, between 0.4 and 0.7%, are associated with urban and suburban settlements and their

peripheral rural areas. The areas with moderate modification correspond to isolated or dispersed landscape units containing vegetation in the recovery process and relict elements of the original vegetation cover. This involves natural innovation processes on non-persistent, recent or old (relative to the studied time period) deforested areas.

The deforestation, agricultural and cattle raising exploitation rhythms have been modulated by regional and national economic policies. In Southeastern Mexico, colonization and land grants to *ejidos* (a form of communal land property) produced a significant effect on forestry and agriculture (Galletti, 2002). Soon after, during a second period until 1997, agricultural policies were given a boost in Southwestern Campeche, making it the third largest rice producing state with 67.753 tons per year, only surpassed by the states of Veracruz and Sinaloa (Apoyos y Servicios a la Comercialización Agropecuaria [ASERCA], 1997).

For both historical periods considered, middle and low degrees of modification were registered in the functional range of each landscape unit (Table 4); due to the intrinsic limitations of coastal wetlands for primary

productive activities. Geofacies were high only in the barrier island littoral, with modifications present as a result of the urban and suburban expansion of Ciudad del Carmen, Sabancuy and Isla Aguada. Certain units display no changes, such as the intertidal palustrine in ordinary flooding regime geofacies (0.04); during recent decades the red (*R. mangle*) and black mangrove (*A. germinans*) areas have gained local coastal areas.

The behavioral analysis of the land cover modification indices by landscape unit for both time periods considered shows the same modification tendencies during both analyzed decades (Fig. 7 and Fig. 8). This means that at least during those periods, the anthropic pressures and the political-administrative regulation on the territory were kept constant. The oscillation of the rhythms of perturbation is maintained in all landscape units, with the exception of the 1991-2001 decade, when the relation between the increases in areas with higher perturbation shows an increase.

The physiognomic expression of landscapes using the environmental status of vegetation cover is a reliable and practical indicator of the functional health of the system.

TABLE 4
Modification geoinicator by landscape units and historical period in the Terminos Lagoon area

Geosystems	Geofacies	1974-1991	Grades	1991-2001	Grades
1. Littoral (LG)	a. Beach ridges (BrLg)	0.14	Low	0.20	Low
	b. Barrier island (BiLg)	0.51	High	0.26	Moderate
2. Palustrine (PG)	a. Intertidal in ordinary flooding regime (IPof)	0.04	Low	0.04	Low
	b. Intertidal in extraordinary flooding regime (IPef)	0.16	Low	0.12	Low
	c. Supratidal (SPg)	0.26	Moderate	0.19	Low
	d. Emergent (EPg)	0.11	Low	0.11	Low
3. Karstic-palustrine (KPG)		0.16	Low	0.12	Low
4. Fluvio-palustrine	a. Captive (FPCg)	0.17	Low	0.10	Low
	b. Semicaptive (FPSg)	0.28	Moderate	0.21	Moderate
	c. Active AFPg	0.30	Moderate	0.19	Low
5. Fluvio-lacustrine-estuarine (AFPg)		0.15	Low	0.13	Low
6. Fluvial (FG)		0.21	Moderate	0.21	Moderate
7. Diluvial-alluvial depositional (DADG)		0.22	Moderate	0.20	Low
8. Automorphic (AG)		0.29	Moderate	0.21	Moderate

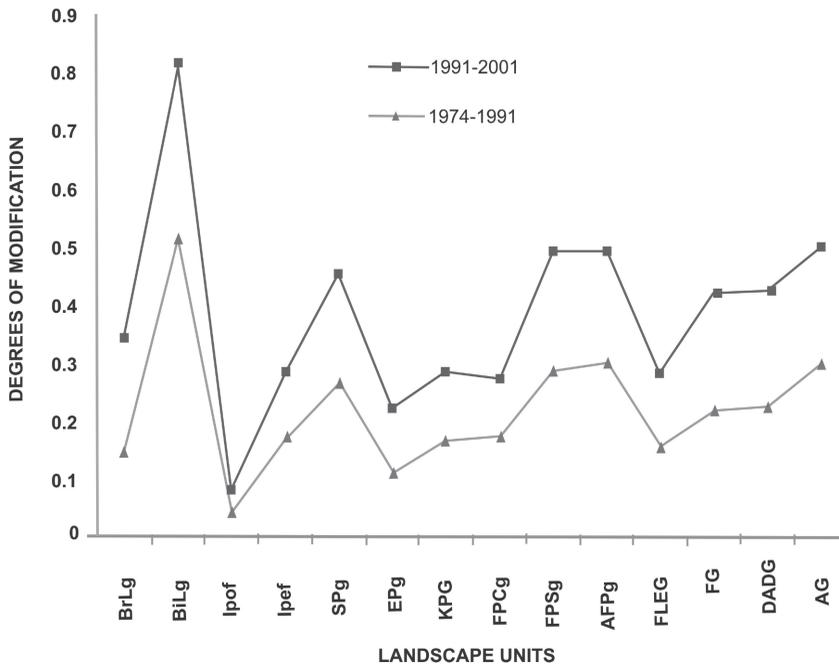


Fig. 7. Temporal behavior of modification index by landscape unit.

Vegetation cover shows a clear correlation between natural or induced perturbations and their expression in the territory, and provides clues as to its prospective management. From these emergent properties it is possible to make inferences about the functional condition of the natural system.

It should be noted that since the areas are weighted according to their areal coverage and modification levels, some values are repeated in different landscape land units. This generalization is related to the spatial resolution associated with the territorial scale of the geosystems and geofacies.

The historical policies of territorial appropriation in the study region have allowed the geosystems to be maintained within permissible environmental resilience and recovery limits, a situation that is not found elsewhere in Southeastern Mexico.

DISCUSSION

Geoindicators are theoretical, methodological and practical tools for environmental

diagnosis that allow the interpretation of complex and diffuse information about the environment status and transform it into useful information for decision making. Its application to functionally homogeneous units makes the identification of environmental problems with a territorial expression more efficient, and allows priorities to be established that will address them.

With the perspective proposed by Machado (2004) and Oldeman (1990), which explains the territory as a continuum supporting different types of naturalness, this study characterizes the modification levels within homogeneous territorial units as land units or landscape units.

The ecological condition of the landscape is consequence of its temporal evolution, including natural and anthropogenic disturbances. If no reference exists to indicate changes over time, policy makers risk erroneous assessment regarding the source of the modifications and the historical transformation to the present. Thus, having a landscape condition reference of its original, or at least prior condition, becomes indispensable.

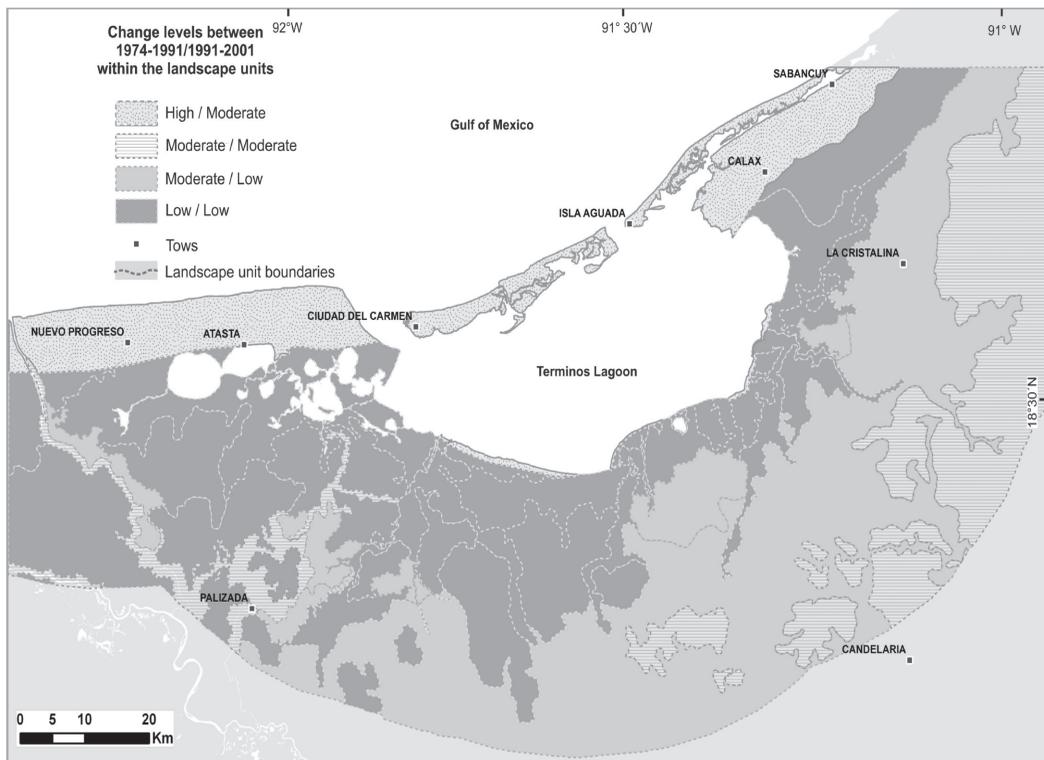


Fig. 8. Territorial expression of modification index by land units in both dates.

The weighted numerical interpretation of qualitative data is not only useful for comparing the proportions of coverage in areas with different degrees of modification, but to also in understanding how disturbed areas have evolved over time.

Unlike current software, in which algorithms propose universal scenarios that are applicable to any reality, this paper affirmed that natural and anthropogenic modifications are unique and depend on the particular intensity and persistence by land unit for a specific historic period.

The characterization of territorial units for environmental diagnosis requires reaching the chorological level of geotope, i.e., the minimal undividable terrain unit in which environmental characteristics cannot be subdivided into smaller sectors. This is because although the high and very high modification degrees have restricted territorial cover, they have a fundamental relevance in environmental

terms. Furthermore, zones that are permanently disturbed at high levels of alteration over long time periods never recover their original natural condition or some intermediate degree of modification. Likewise, adopting the geotope as the unit of analysis allows us to focus on environmental degradation, its patterns of territorial expansion and its relation to local environmental history.

Because the degrees of modification contemplated general criteria for ecological and anthropic measures, they could be applied to any territory, whenever considered according to the criteria of artificialness and especially the degree of functional weakening, based on the classification of changing transitions.

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RESUMEN

Geoindicador de modificación de la cobertura aplicado a un ambiente costero tropical. Los cambios ambientales debidos tanto a procesos naturales como a las modificaciones antrópicas, se pueden caracterizar a través de la modificación de la cobertura y sus implicaciones ambientales en el tiempo. El objetivo del presente estudio es proponer y aplicar un geoindicador de modificación de la cobertura para evaluar la condición ambiental del territorio dentro del ámbito funcional de las unidades de paisaje. La evaluación del geoindicador se basa en el análisis multitemporal de imágenes de satélite Landsat de resolución espacial media y su clasificación no supervisada de acuerdo a la dirección tipificada de transiciones en el uso de la tierra. Incluye la detección de cambios entre pares de imágenes entre 1973, 1991 y 2001 para identificar áreas sin cambio y áreas en las que se observan cambios ambientales positivos o negativos con base en la cobertura. La metodología propuesta se aplicó en la zona costero-palustre de Campeche, México, y los valores encontrados durante los períodos 1974-1991 y 1991-2001 fueron: bajos, de 46.5% y 40.9%, respectivamente, debido a las limitaciones intrínsecas de los humedales costeros para las actividades primarias. Grados altos para las zonas de transición urbana y suburbana con 39.5% y 32.1% para el primero y segundo período, respectivamente. El grado de modificación moderado, oscila entre el 4.9% para el primer período y 5.7% para el segundo período, y se observó en unidades del paisaje en etapas sucesionales retrogresivas. El geoindicador propuesto muestra: evidencias fisonómicas directas y funcionales indirectas de la afectación a la cobertura original por las actividades humanas, los patrones dispersos de regeneración, la introducción de elementos alóctonos antrópicos y la artificialización del paisaje original.

Palabras clave: geoindicador ambiental, unidades del paisaje, detección de cambio, percepción remota.

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