Coastal Research Library 25

Christopher Makowski · Charles W. Finkl *Editors*

Threats to Mangrove Forests

Hazards, Vulnerability, and Management

Springer

The Success of Hydrological Rehabilitation in Mangrove Wetlands Using Box Culverts Across Coastal Roads in Northern Yucatán (SE, México)

28

Claudia Teutli-Hernández and Jorge A. Herrera-Silveira

Abstract

The construction of roads, shelter ports and artificial mouths has altered the balance between freshwater and saltwater intakes, flow, tidal levels and water quality. This is reflected in the deterioration and death of the mangrove. Restoration, rehabilitation and reforestation methods have been carried out, but their success has not been determined, and sometimes perhaps do not meet the proposed objectives. For example, the opening of sewers as a method of restoration did not meet the objectives proposed in all localities, with Chuburnà, Progreso site east, Vía Antigua, Chicxulub, and Chabihau, being the most impacted. While San Benito, Dzemul, La Línea, and Telchac, had better results with mangroves being preserved. Chabihau, for maintaining a permanent connection with the sea, represents a real salinization. In the north, the concentration of inorganic nutrients in the water column is mainly phosphorus, by the removal of sediments during rain events, which facilitates the flow of nutrients between the sediment and the water column. The high concentrations of sediments suggest that these are basins of accumulation, and therefore, more susceptible to impacts. Among these impacts, organic pollution can be highlighted, resulting in the deterioration of flora and fauna. This condition implies that management measures, such as using box culverts across roads, should be carried out according to the characteristics of each locality.

C. Teutli-Hernández (✉)
CINVESTAV-IPN, Unidad Merida, Merida, Mexico

University of Barcelona, Barcelona, Spain

J. A. Herrera-Silveira
CINVESTAV-IPN, Unidad Merida, Merida, Mexico
e-mail: jorge.herrera@cinvestav.mx

Keywords

Mangrove restoration · Forest structure · Hydrology · Roads impacts

28.1 Introduction

Human activities in the coastal zone of tropical and subtropical regions are increasingly expanding through the construction of roads, tourism infrastructure, urban developments, ports and marine construction, ponds for aquaculture practices, and artificial hydraulic infrastructure for navigation that directly connect freshwater and brackish wetlands to coastal waters (Rivera-Monroy et al. 2006; Twilley and Rivera-Monroy 2005; Twilley et al. 1999). All of these activities are altering salinity and hydrological gradients and the water quality in estuaries and coastal wetlands. In addition, as result of hydroperiod changes, hypersalinity condition are more frequent in coastal regions where evaporation exceeds precipitation as result of salt accumulation (Rivera-Monroy et al. 2006; Castaneda-Moya et al. 2006). These perturbations are reflected on the degradation and increasing mortality of coastal wetlands in tropical regions where mangroves are the dominant vegetation (Giri et al. 2011).

In addition to high ecosystem productivity, mangrove forests are critical habitats for a variety of species, act as buffers against flooding, improve water quality, and dissipate storm energy reducing potential damage to coastal zones (Alongi 2011). Moreover, mangrove forests are identified as critical habitats due to their capacity to provide goods and services to the local and regional human populations (Costanza et al. 1997; Polidoro et al. 2010). Continued coastal development along the tropical and subtropical coastal regions requires the construction of roads, which in many cases have been built over extensive wetland areas, modifying the spatial and temporal hydrological patterns. Indeed, road construction has been identified as one of the

C. Makowski, C. W. Finkl (eds.), *Threats to Mangrove Forests*, Coastal Research Library 25,
https://doi.org/10.1007/978-3-319-73016-5_28

principal causes of mangrove mortality (Batllori-Sampedro and Febles-Patrón 1999; Valiela et al. 2001; Alongi 2008), and a threat to the ecological integrity of subtropical and tropical coastal-marine ecosystems.

Multiple efforts have been implemented to avoid, remedy, mitigate or reverse the impacts of hydrological modifications in mangrove forests throughout restoration or rehabilitation programs (Field 1996; Bosire et al. 2003). However, despite ambitious and expensive efforts, few reports are available describing actual outcomes (i.e., success, partial or total failure). An understanding of the appropriate environmental conditions of the area selected for rehabilitation and a clear definition of rehabilitation goals/objectives, are key components to increase the success of these programs, particularly since mangrove rehabilitation trajectories depend on: (a) the magnitude and type of disturbance; (b) the environmental setting; and (c) the geophysical and ecological processes regulating ecosystem structural and productive attributes (Twilley and Rivera-Monroy 2005). Successful mangrove rehabilitation programs require systematic monitoring of indicator variables such as pore-water salinity, changes in vegetation coverage, productivity and biological diversity, among other variables (Boesch and Paul 2001; Hyman and Leibowits 2001; Twilley and Rivera-Monroy 2005; Lewis 2009). Monitoring of these variables certainly help to define the success of rehabilitation actions, particularly if a set of structural and functional variables are analysed under an adaptive management scheme and a transdisciplinary approach (e.g., hydrology, ecology, engineering, sociology, economy) over a wide variety of spatial and temporal scales (Twilley 1998; Lewis III 2005).

Despite the multiple descriptions concerning the impact caused by modification of the levels, frequency and time of flooding of wetlands (particularly in mangrove ecosystems) (Cahoon et al. 1995; Long and Nestler 1996; Valentine-Rose and Layman 2011; Powell et al. 2011), in Mexico there is still a lack of basic ecological knowledge which permits propose and implement rehabilitation programs and specific actions in order to revert the impacts in different environmental settings in coastal wetlands.

The mangroves of the north coast of the Yucatan Peninsula (SE, México) have been impacted by changes in land use since 1948 and are related to the land use changes, coastal highways construction and railway lines. For example, the construction of seven harbours between the 1970s and 1980s (POETCY 2007), triggering widespread urbanization, promoting land use changes, and changes on the hydrological pattern in the mangroves of these locations. Changes in pore-water salinity and sediments lead to a process of sediment salinization causing a gradual loss of mangrove forest up to 60% of the original coverage (Euan-Avila 1998; Batllori-Sampedro and Febles-Patrón 1999; Zhao et al. 2016). Other land use changes affecting mangrove forest coverage in Yucatán are land reclamation for human settlements, suburban dumps (e.g. rubber), construction of large scale aquaculture infrastructure (semi-intensive shrimp ponds), mangrove tree cutting for fishing arts, and large scale climatic events such as storms and hurricanes (Euán-Avila and Witter 2002).

Land use change assessments in the Yucatan coastal landscape region between 1950 and 1990 indicated that roads and highway construction around urban centres (e.g., Mérida, Motul) facilitating access to beaches and ports was one of the major causes in the gradual increase in human population densities along the coast (Batllori-Sampedro and Febles-Patrón 1999; Euán-Avila and Witter 2002). For example, when these roads were constructed over wetlands the water surface flow was restricted and impacted the hydraulic connectivity between east and west sites of each road and creating two artificial micro-basins (one of each site of the road) and favouring extensive mangrove mortality (Fig. 28.1).

Due to the extension of the mangrove area impacted by the roads (>5000 ha), a rehabilitation program was implemented with the major goal of improving hydrological conditions. The main actions in this program included: (1) construction of box culverts to reconnect the surface water flow between both sides of the roads; and (2) the removal of sediments accumulated in water springs to increase fresh water discharge to reduce excess salt accumulation in affected mangrove areas (Perry and Berkeley 2009; Vyas and Sengupta 2012; Rovai et al. 2013).

However, this program did not consider that all actions of ecological restoration should be accompanied by a program that includes a diagnostic and verification of the degree of success of the actions undertaken (SER 2004). In other words, there is no control or possibility of integrating such actions through adaptive management in order to reach the objective of recovering the functions of the degraded ecosystem.

The objective of this chapter was to evaluate if constructed box culverts improved soil physicochemical properties in areas undergoing mangrove mortality along the Yucatan coastal region. Selected soil properties were considered as performance measures (*sensu* Twilley and Rivera-Monroy 2005) and measured 1 year after project implementation to assess potential changes in forest structural variables (e.g. natural regeneration) and representing rehabilitation trajectories based on "in situ" measurement of non-impacted mangrove forest adjacent to the study area. By selecting areas impacted by roads and undergoing potential hydrological changes as well as evaluating performance of project rehabilitation tasks we wanted to initiate a monitoring baseline to determine long term project success. We also aimed to establish an adaptative monitoring program that could be applied to other disturbed mangrove areas in the unique karstic geomorphic setting of the Yucatan Peninsula.

Fig. 28.1 Road that crosses the mangrove and the impact caused by the interruption of water flows

In the restoration program of the mangroves of Yucatan implemented by the local government the aim was to improve the hydrological conditions and thereby favour the natural regeneration of the mangroves (POETCY 2007). Therefore, in this study physical and chemical variable of the sediment were evaluated as signs of short term recovery (1 year) and structural characteristics of the mangroves were evaluated as a baseline for ecological conditions, identifying whether or not differences exist between both sides (east and west) of the roads along the north coast of Yucatan. The results of this are intended to contribute to the establishment of an ecological baseline for the rehabilitation of mangrove ecosystems in semiarid and karstic areas, as well as to initiate a monitoring program to determine whether or not the rehabilitation actions undertaken were successful in at least reducing the differences in the environmental variables of the water, sediments and structure of the mangroves between both sides of the roads of the mangrove flood zone in the north of Yucatán.

28.2 Materials and Methods

28.2.1 Study Area

The study area is located in the northern region of the state of Yucatán (SE, México). Average annual precipitation and temperature is <500 mm year^{-1} and the average temperature is 25.5 °C (García 1988). Climate warm and dry with the greatest rainfall occurring between July and September and scarce the rest of the year. Evaporation exceeds precipitation particularly March to June with an average value of 1460 mm year^{-1} (Dasilva SMD94 1999). The area target for rehabilitation is the Chuburnà-Chabihau basin which runs parallel to the coastline and is limited to the west by the Chuburnà-Sierra Papacal road and to the east by the Chabihau-Yobain road, approximately 170 km^2. The rehabilitation project was performed by NGO's, state and federal agencies (SECOL, SEMARNAT, SCT) and international institutions (NORTH AMERICAN WETLANDS COUNCIL). The Chuburnà-Chabihau basin is subdivided into micro-basins (Table 28.1) delimited by perpendicular roads to the coastline. Box culvert construction was performed in 1998–1999, with estimated water exchange volume of 10,000 m^3/day.

Due to the soil karstic origins, rainwater infiltrates quickly and freely to the subterranean aquifer, hence there is no surface water flow and the fresh water inputs to the coastal wetlands into the temporal swamp called locally "ciénagas" (swamps), are through point (spring) and non-point underground water discharges. Freshwater from these sources reduces salinity and primarily supplies inorganic dissolved nutrients mainly silicates and nitrates to coastal ecosystems (Herrera-Silveira and Ramírez-Ramírez 1997; Gonneea et al. 2014). A hydrological connection between wetlands and coastal waters in Chuburna, Yucalpeten, Telchac and Chabihau study sites is via man made harbours; whereas in

Table 28.1 Micro-basins on the Chuburna-Chabihau

Sampling sites	Latitude	Longitude
Chuburna- (CHB–W)	21° 14′ 16.8″	89° 49′ 42.0″
Chiburna-E (CHB–E)	21° 14′ 16.8″	89° 49′ 40.4″
Progreso–W (PRG–W)	21° 16′ 31.8″	89° 39′ 39.3″
Progreso-E (PRG–E)	21° 16′ 31.8″	89° 39′ 38.03″
Vía Antigua–W (VAT–W)	21° 16′ 57.3″	89° 38′ 10.5″
Vía Antigua– E(VAT–E)	21° 16′ 57.3″	89° 38′ 8.7″
Chixchulub–W (CHX–W)	21° 17′ 05.7″	89° 36′ 02.1″
Chicxulub–E (CHX–E)	21° 17′ 05.7″	89° 36′ 01.1″
San Benito–W (SBN–W)	21° 19′ 09.0″	89° 25′ 34.2″
San Benito-E (SBN–E)	21° 19′ 09.0″	89° 25′ 32.2″
Dzemul-W (DZE–W)	21° 19′ 34.0″	89° 20′ 56.1″
Dzemul-E (DZE–E)	21° 19′ 34.0″	89° 20′ 55.0″
La Línea–W (LLN–W)	21° 20′ 06.9″	89° 16′ 58.8″
La Línea–E (LLN–E)	21° 20′ 06.9″	89° 16′ 56.3″
Telchac– W (TLH–W)	21° 20′ 17.1″	89° 15′ 44.1″
Telchac– E (TLH–E)	21° 20′ 17.1″	89° 15′ 41.9″
Chabihau– W (CHH–W)	21° 21′ 15.7″	89° 13′ 33.7″
Chabihau– E (CHH–E)	21° 21′ 15.7″	89° 13′ 31.2″

the Carbonera zone area connectivity it is via a natural channel. As result of marine water inputs, microtidal regime tide (<0.7 m) and restricted water circulation in mangrove wetlands due to roads construction, there is a significant salt intrusion into the swamps. Salt accumulation as results of seawater exchange and high evaporation is reflected on high salinity vanes in pore-water and swamps water column (Herrera-Silveira 1996; Zaldivar 1999).

According to Euan-Avila and Witter (2002) and the Zoning Coastal Program of Yucatan (POETCY 2007), the roads and the artificial harbours to connect the sea and wetlands are the origin of the hydrological changes, and the consequences was the loss of 12,807 ha of mangroves (Valderrama-Landeros et al. 2017). Therefore, after the aerial photographs analysis and field trips, nine sampling sites (Table 28.1) were stablished on both sides (west-east) of the coastal roads which go from Chuburna to Chabihau (Fig. 28.2).

Monthly sampling trips were conducted between November 2000 and June 2001 at both sides of each road. Interstitial and water surface salinity were measured "in situ", as well as temperature (°C) and dissolved oxygen (mg l^{-1}) with a YSI-85 multiparametric probe. Surface water samples were collected and analyzed by dissolved inorganic nutrients as dissolved inorganic nitrogen (DIN), soluble reactive phosphorus (SRP) and silicates (Si) measured using standard spectrophotometric techniques described by Strickland and Parsons (1972).

In order to identify the effect of the roads on the mangrove community of north Yucatan, two vegetation sample sites were established in each location (east and west of each road). The vegetation structure of the mangrove forest was determined in two 100 m^2 plots in each road side, using the methods described by Lugo and Snedaker 1974. The structural attributes selected for this study were: diameter at breast (DAP); basal area (m^2 ha^{-1}); density (No. stems ha^{-1}); and height (m) (Shaefeer-Novelli and Cintrón 1990). The complexity index (dimensionless), which is the sum of the forest structural characteristics such as number of species, total density, total basal area and height, was calculated as a quantitative proxy descriptor of the tropical vegetation's structural complexity (Holdridge et al. 1971).

28.2.2 Data Analysis

Physical and chemical variables of the sediment taken from the study sites were analysed through a three-way nested ANOVA, taking into account location, site and the location*season interaction as a source of variation. In the cases where significant differences were observed, an "*a posteriori*" LSD (least significant difference) ($P < 0.05$) analysis was conducted. These analyses were performed using the statistics program JMP® 4.02 (SAS Institute 2000).

In order to determinate significant differences of water quality variables (temperature, dissolved oxygen, salinity and nutrients) between sites (west and east) of each sampling location, a non-parametric ANOVA was conducted using the Kruskal-Wallis significance test and represented with "box-whisker" plots using the STATGRAPHICS 1995 program.

Multidimensional non-metric scaling (MDS) was used to evaluate whether or not the rehabilitation actions had been successful. The ANOSIM test was applied to determine whether or not there were significant differences among sampling sites (Warwick and Clarke 1993), according to their vegetation structural characteristics. This test evaluates the significant differences between groups of replicates of the vegetation structural variables of the plots against a series of random simulations, resulting in a statistic (R). If this R statistic is close to 0 there are no significant differences between groups and increases to a maximum of 1 when the data of both matrices are totally different (Warwick and Clarke 1993).

28.3 Results and Discussion

28.3.1 Physicochemical Variables (Water and Sediments)

The results of the three-way nested ANOVA (Table 28.2) indicate that there are significant differences between both sides of the roads (east and west) of each sampling site with regards to the physical and chemical variables of the water. These suggest that rehabilitation actions 2 years after completing them had not achieved the hydrological rehabilitation.

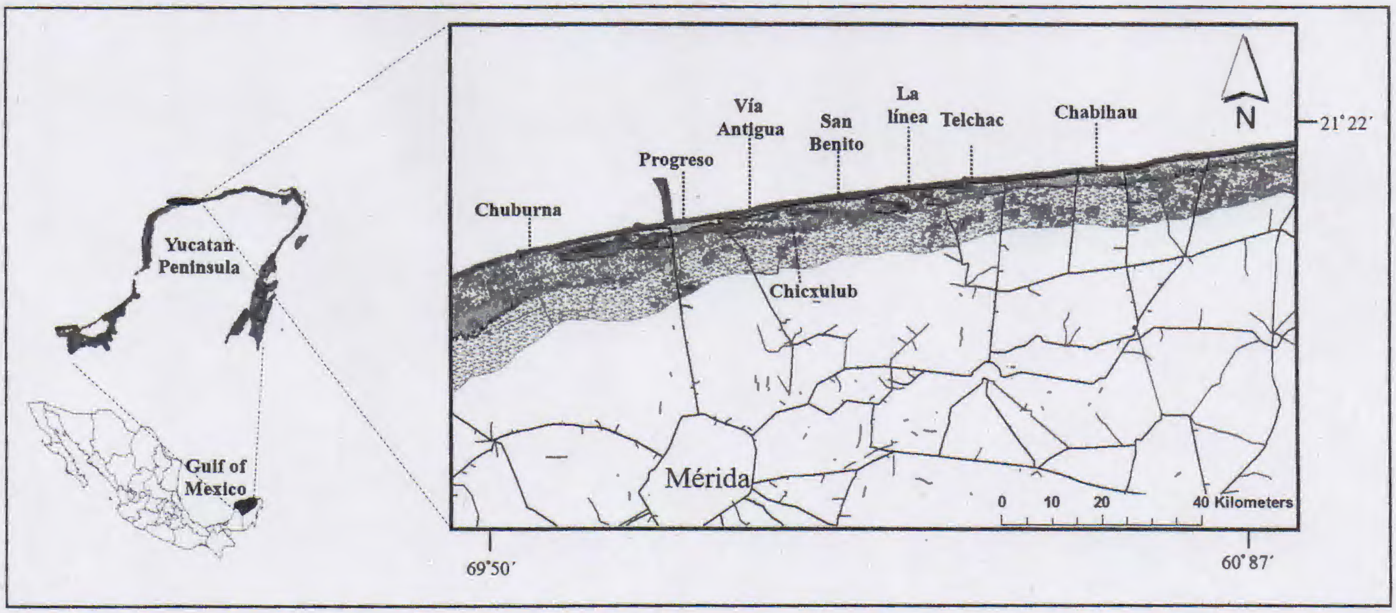

Fig. 28.2 Location of the nine sampling sites

Table 28.2 Chemical characteristics of water among micro-basins

Variables	Oxygen mg l^{-1}	Temperature °C	Salinity psu	DIN µmol l^{-1}	PO_4 µmol l^{-1}	SiO_4 µmol l^{-1}
Station (locations)	.8354	.9969	.4750	.2492	.7719	.9623
Locations	1.72	*.0001	*.0001	*.0018	*.0257	*.0175
Season	.1259	.0604	*.0001	.9700	*.0001	*.0001
Season *locations	.1035	*.0001	*.0001	.5845	.2234	.0278

Similarly, were observed significant differences between locations ($P < 0.05$), indicating variability of the physical and chemical characteristics of water among micro-basins, suggesting that rehabilitation actions should be site-specific (Bashan et al. 2013).

The surface temperature of the water showed variations with an average of 20 °C (Telchac-W) and 30.4 °C (Chuburna-W) (Fig. 28.3a). Higher temperatures (26.9–30.4 °C) were observed toward the west of the study area (Chicxulub W and E and Chuburná-W Chuburna-Chicxulub), while lower temperatures (20 °C in Telchac-W and 24.75 °C in Dzemul-W) were registered between San Benito and Chabihau. The lower temperatures could be associated with a greater influence of groundwater discharges since these freshwater sources have been characterized by low temperatures as well as high concentrations of nitrates and silicates (Herrera-Silveira 1994). In contrast, the zone with higher temperatures probably receives lower groundwater supplies and the residence time of the water is greater, favouring the warming and evaporation of the water column in the swamp. High temperatures have negative effects on the metabolic reactions of the seedlings, limiting the recruitment of new individuals and the growth of the trees (Harry and Nyle 1982). The dissolved oxygen concentrations varied from 0.4 mg l^{-1} (San Benito) to 7.15 mg l^{-1} (Vía Antigua) (Fig. 28.3b). In San Benito and Telchac low values were consistently registered through sampling period. Even though the dissolved oxygen concentrations did not present significant differences ($P < 0.05$) between sites of the roads (west, east) at each location, the differences were observed among locations. Water oxygen balance is mainly related with production and decomposition process in wetlands and the last one is dominant (Reddy and Delaune 2008), so that, in places with high production and decomposition of the leaf litter could stimulate the oxygen consumption in the water column.

In mangroves ecosystems has been demonstrated a direct relationship between the vegetation structure and the productivity, this last measured as litterfall (Wang'Ondu et al. 2014). In San Benito and Telchac structural variables as basal areas and heights show high values (Table 28.3) suggesting that the organic matter in the sediments are high, then this could explain the low dissolved oxygen registered in these sampling sites (Fig. 28.3b).

Surface water salinity showed spatial variations with lowest concentrations in Telchac (1.45 g/kg) and highest in Chabihau (50.6 g/kg). While there were no significant differences in surface water salinity between both sites of the roads, greater seasonal variations were observed among

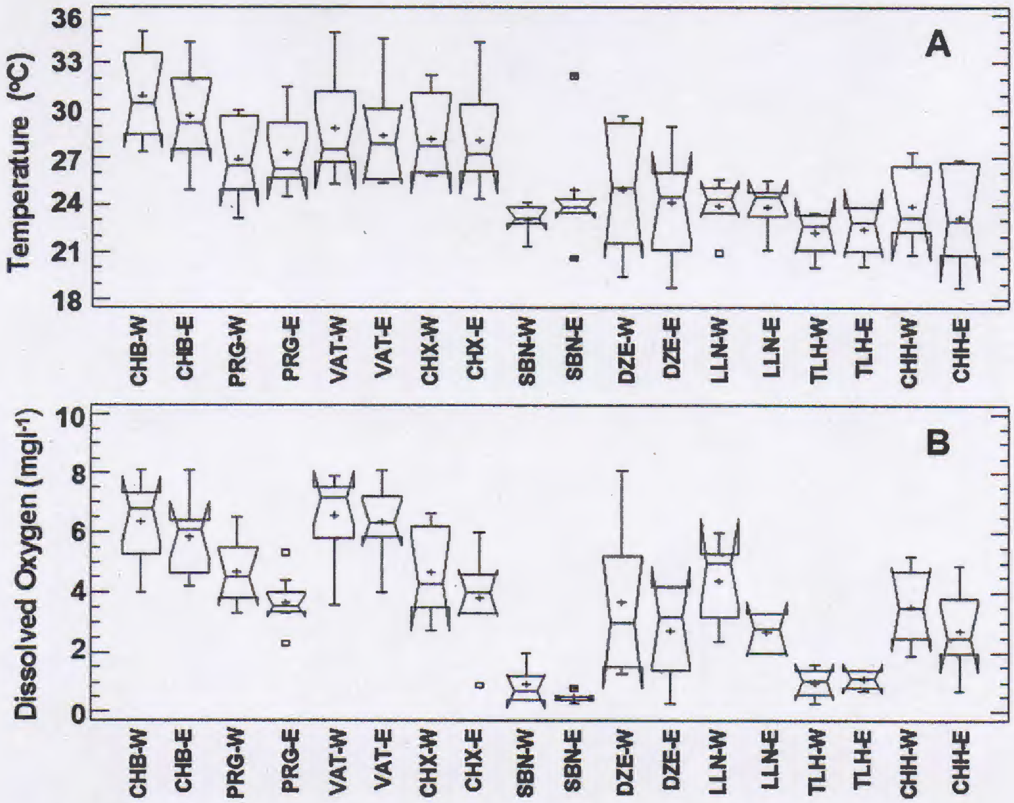

Fig. 28.3 Temperature and dissolved oxygen

locations (Fig. 28.4a), with the greatest variation in Chicxulub (<5 a>80 g/kg) in contrast with Telchac (5–10 g/kg). The hyperhaline conditions in the micro-basins of Chicxulub and Chabihau can be explained by the effect of roads which limit the ebb and flow of surface water, favouring a greater water residence time, evaporation and salt concentration. On the other hand, micro-basins as the Chuburná-Progreso has direct connection (natural or artificial) with the sea, and together with the arid climate favour soil salinization, whereas the sites that show lower surface and pore-water salinity such as San Benito and Telchac (FIG) could be influenced by fresh groundwater inputs and surface water floods.

Spatial differences in the water characteristics between the sub-basins of Chuburna-Chicxulub and San Benito-Telchac, probably are related with another important feature of the karstic system found in Yucatan, known as the "ring of cenotes". This is characterized by large discharges of freshwater on land and at sea, mainly in areas where the "ring of cenotes" meets the coastal zone (Pacheco Martinez and Alonzo Salomon 2003), that in the case of the study area is in the sub-basin San Benito-Telchac, explaining the water characteristics of these. Progreso (west site), San Benito, Dzemul, La Línea and Telchac showed mangrove trees of greater basal areas and heights values (Table 28.3). The hydrochemical characteristics in San Benito, Dzemul, La Línea and Telchac suggest that these locations are influenced by freshwater discharges supplying nutrients and regulating their interstitial salinity (<13 g/kg) (Fig. 28.4b).

The dissolved inorganic nitrogen (DIN $= NO_3 + NO_2 + NH_4$) showed average concentrations less than 10 µmol l^{-1} and no significant differences were registered between sites of roads in each location (Fig. 28.5). Nevertheless, high average concentrations (>20 µmol l^{-1}) were registered in Progreso-W, Via Antigua-E, and in both sites of the road in Chabihau. In the case of Progreso and Vía Antigua, high DIN concentrations might be related with the influence of the leachates from the municipal rubbish dump located in the swamp and influenced by flood during high tides and rainy season. However, the DIN concentrations registered in Chabihau could be explained through decomposition and remineralization processes associated to greater water residence time, favouring the increasing concentrations of reduced forms of nitrogen (Teutli 2003).

The average phosphate concentration was generally low (0.60 µmol l^{-1} and 1.22 µmol l^{-1}) (Fig. 28.6a), and because it is present in calcareous substrates soil fertility is low (Koch and Snedaker 1997). As a result of the karstic characteristics and high water alkalinity of the groundwater in Yucatan region, the supplies of phosphorus via groundwater discharges are low, since the calcium carbonate act as a phosphorus sink through geochemical processes of adsorption by carbonates to form apatite (Carpenter et al. 1998). Nevertheless, high concentrations can be seen in

Table 28.3 Structural characteristics of the mangrove

Locality	Basal area (m^2 ha^{-1})	Density (Ind. ha^{-1})	Height (m)	No. Sps	Species	Complexity index	Type of mangrove
CHB-W	0.75	187	2.83	1	*A. germinans*	0.0039	Basin
CHB-E	225	620	1.90	3	*A. germinans, C. erectus, L. racemosa*	0.0796	Basin
PRG-W	18.89	8182	3.35	3	*R. mangl, A. germinans, L. racemosa*	15.517	Fringe
PRG-E	0.09	100	1.00	1	*R. mangle*	0.0001	Fringe
VAT -W	4.17	3286	2.42	3	*A. germinans, R. mangle, L. racemosa*	0.996	Basin
VAT -E	0.12	102	1.73	3	*A. germinans, R. mangle, L. racemosa*	0.0006	Basin
CHX -W	0.14	77	1.28	2	*A. germinans, L. racemosa*	0.0003	Basin
CHX -E	0.12	74	1.14	1	*A. germinans*	0.0001	Basin
SBN-W	2.46	2222	3.28	2	*R. mangle, A. germinans*	0.3591	Basin
SBN-E	23.00	3333	3.83	1	*R. mangle*	2.9377	Basin
DZE-W	22.75	8663	4.20	1	*R. mangle*	8.275	Basin
DZE-E	24.10	5500	5.39	3	*R. mangle, L. racemosa, A. germinans*	21.427	Basin
LLN -W	25.23	3100	6.14	2	*R. mangle, L. racemosa*	9.517	Basin
LLN -E	20.84	4300	4.47	2	*R. mangle, A. germinans*	8.014	Basin
TLH -W	12.76	9600	4.36	2	*L. racemosa, A. germinans*	10.670	Fringe
TLH -E	11.19	4067	4.85	1	*A. germinans*	2.2065	Fringe
CHH -W	0.40	360	1.89	4	*R. mangle, L. racemosa, A. germinans, C. erectus*	0.0082	Basin
CB - E CHH -E	3.83	2400	3.16	4	*R. mangle, L. racemosa, A. germinans, C. erectus*	0.5806	Basin
*	17 ± 3.7	1760 ± 350	41.3 ± 8.8	3 ± 4		36.4 ± 10.3	Riverine
	9.0 ± 0.7	3580 ± 394	18.5 ± 1.6	2.3 ± 0.2		15.4 ± 3.2	Cuenca
	8.2 ± 1.1	5930 ± 3005	17.9 ± 2.7	2.0 ± 0.3		145.6 ± 4.7	Fringe
	1.0	25,030	0.6	1		1.5	Dwarf

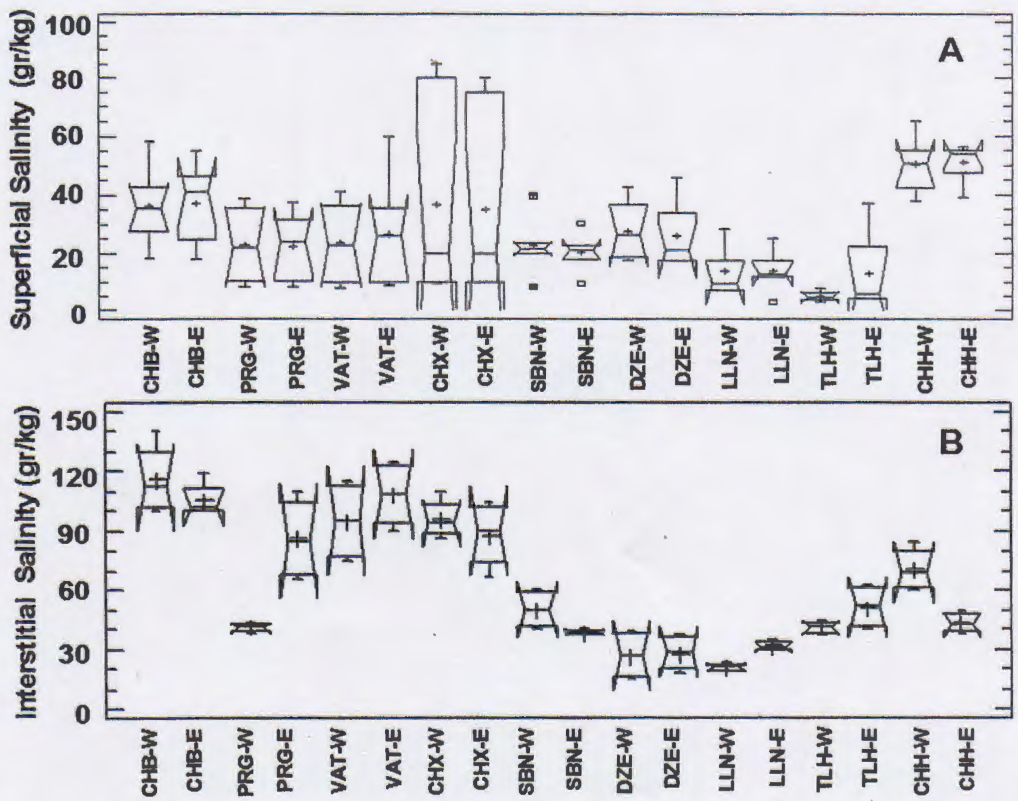

Fig. 28.4 Superficial and interstitial salinity

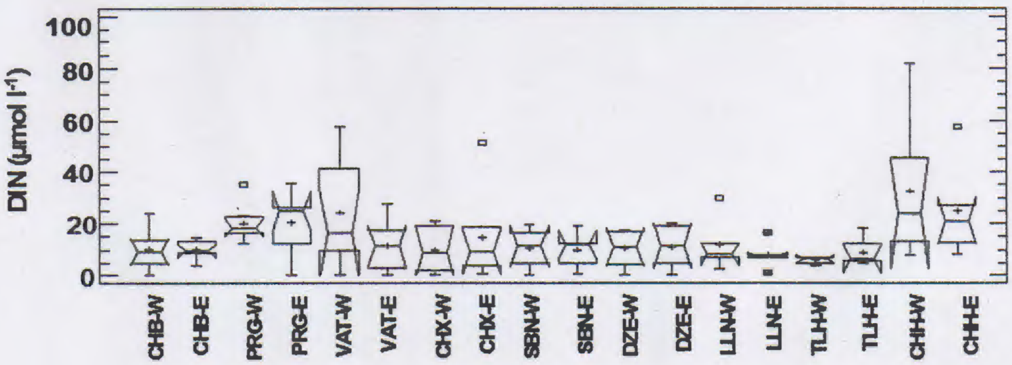

Fig. 28.5 Dissolved inorganic nitrogen

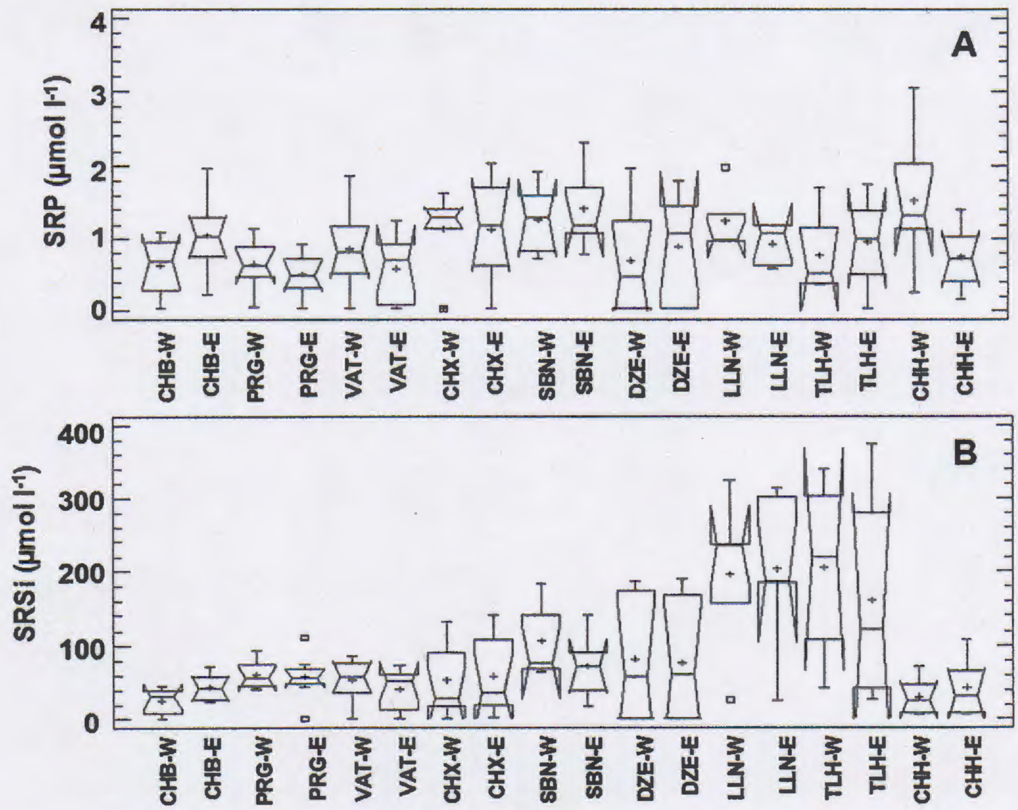

Fig. 28.6 Soluble reactive Phosphorous (SRP) and soluble reactive silicates (SRSi)

Chuburná-E, Vía Antigua-W, San Benito-E and Chabihau-W (Fig. 28.6), which might be associated in the case of Vía Antigua to the leachates of the municipal rubbish dump of the Puerto Progreso. The differences in the phosphorus concentrations between locations are probably, on the one hand, associated with the presence of abundant birdlife, with higher concentrations where they are present, since this zone represents an extensive wetland used at least seasonally by migratory birds (SECOL 2004). The fertilization role of birds to mangrove has been registered in a close area of the study sites (Adame et al. 2015). On the other hand, they are probably associated with inputs from the sea in the locations, which have an artificial connection. Nutrient inputs via bioturbation and faeces from aquatic birds are considered to be autochthonous and haloctonous respectively, contributing to increasing the aquatic productivity of the aquatic ecosystem (Comín and Herrera-Silveira 2000). However, it has also been registered that the haloctonous inputs of phosphorus from sea connections to mangroves zones can proceed from the coastal waters, as occurs in the west zone of Florida (Chen and Twilley 1998).

Silicate concentrations showed significant differences ($p < 0.05$) between locations, with average concentrations varying between 20.8 $\mu mol\ l^{-1}$ in Telchac-W and 105 $\mu mol\ l^{-1}$ in La Línea-E (Fig. 28.6b). Spatially, a zone of low concentrations and lower variability is observed between

Chuburná and Chicxulub, while between San Benito and Telchac greater value concentrations and greater variability were observed. This indicates that the latter locations are influenced by groundwater inputs via springs, since it has been determined that this nutrient shows high concentrations in groundwater discharges (Herrera-Silveira 1994).

According to the results of the water and sediment variables, the aims of favouring the recovery of the impacted zones of mangroves were not achieved in 2 years. High spatial variability of the hydrology in the study area is maintained and no significant changes in surface and pore-water salinity are observed 2 years after the opening of drains in the coastal roads of Yucatán.

28.4 Mangrove Forest Characteristics

The results of the structural characteristics of the mangroves in the study area reflect high variability (Table 28.3), indicating differences in the environmental variables among locations, since it is recognized that the development of mangrove vegetation is a reflection of the magnitude of local hydrological stressors and resources available in the sediments (Twilley 1995; Twilley and Rivera-Monroy 2005).

Basal area is an indicator of the development achieved by the mangrove community with regards to forest biomass; this characteristic varied between 0.09 m^{-2} ha^{-1} in Progreso-E and 25.23 m^{-2} ha^{-1} in La Línea-W. On the other hand, the density of trees in a mangrove forest is a reflection of its state of development; therefore, it acts as an indicator of vulnerability and response capacity in face of anthropogenic and natural impacts (Shaeffer-Novelli and Cintrón 1990). The density of mangroves in the area of study varied between 74 and 9600 trees ha^{-1}, indicating that there are locations with a low level of impact (Dzemul-E), and others with a high impact level (Progreso-E, Chicxulub-E). The average height of trees varied between 1 m (Progreso- E) and >6 m (La Línea-W). It is recognized that the variability in the tree height responds to hydrological characteristics such as salinity; therefore, at lower salinities values of structural characteristics such as height are high due to the freshwater has been related with nutrient inputs (Twilley 1995). On the other hand, the frequency of natural events such as hurricanes have an impact on the average height of the mangrove community, since these have a "pruning" effect, and the magnitude of the impact is related to the degree of exposure that the vegetation has to the path of the maximum winds (Lugo et al. 1976; Cintron et al. 1978; Twilley 1998). Given that the study area is exposed to hurricanes trajectories, this could limit its average height (<5 m). The differences in height between locations may be associated with the high interstitial salinities as in Chuburná-E, Progreso-E, Via Antigua-E and Chicxulub in both sides (Fig. 28.3b) that showed the lowest average heights values (Table 28.3).

The four species of mangrove present in the region of the Gulf of Mexico were registered in the study area: *Rhizophora mangle, Avicennia germinans, Laguncularia racemosa, Conocarpus erectus*. With regards their distribution, there were locations with the four species (Chabihau), and those of monospecific forests (Chuburna-W, Chicxulub-E) (Table 28.3). The abundance and dominance of a mangrove species has been used as an indicator of the specificity of hydrological and sediment variables as salnity, flood, an nutrients among other, acknowledging that *Avicennia germinans* dominates in sites of high salinities, less waterlogged and highly reduced soils (López-Portillo and Ezcurra 1989; Mckee 1995); while *Laguncularia racemosa* is associated with zones of low salinities and relatively greater concentrations of nutrients (Mckee 1995), and *Rhizophora mangle* establishes mainly in sites directly exposed to the flood and tide, where the sediment is less consolidated, salinities are variable (5–60 g/kg) and concentrations of nutrients are low (Jiménez and Lugo 2000). This coincides response of *R. mangle* with what Twilley and Chen (1998) described, in that the distribution of the species of mangrove is related to the interaction of hydrological and sediment variables, which in the case of the north coast of Yucatán are highly heterogeneous (Table 28.3).

In accordance with the complexity index (IC) of Holdridge et al. (1971), which is an integrative measure of structural development of the mangrove forest, high heterogeneity was observed in the study area (Table 28.3). The IC values of the locations between San Benito and Telchac may represent the structure of the typical mangroves for Yucatán, since their characteristics are similar to other sites of the Yucatán Península that have been defined as being in a good state of conservation (Zaldivar et al. 2004). The structural characteristics of the mangroves of Chuburná, Progreso-E, Vía Antigua, Chicxulub and Chabihau are below the values reported in the literature typifying mangrove forests (Table 28.3). These suggest that these sites reflect severe impacts where the hydrological modifications by roads have put them in poor conditions with a lower capacity of resilience in face of natural events such as hurricanes.

The surface and pore water results suggest that these locations are impacted by a process of sediments salinization induced by the seawater inputs to the wetland through the ports and artificial openings that connect both systems (Euan-Avila and Witter 2002). High pore-water salinities (>50 g/kg) in mangrove ecosystems is an stressor for the forest structure of these vegetation being reflected in a low complexity index (Cintrón et al. 1978; Twilley 1995).

The locations that showed high complexity index values, which may be associated with a good conservation status as Progreso (west site), Dzemul, La Línea and Telchac, these could be used as mangrove reference sites (Twilley and Rivera-Monroy 2005). These locations were characterized by a flooding pattern similar to tides with a delay time and subterranean water inputs via springs, which additionally represent a nutrient input (Herrera-Silveira 1996). In particular, the locations of San Benito and Telchac may characterize typical mangroves structure of the central-northern area of Yucatan, since the karstic conditions, dry climate and hurricanes frequency are environmental condition at which these mangroves has been growing. They show a maximum height of 5 m (Telchac-E) and a minimum basal area of 2.46 m^2 ha^{-1} (San Benito-W). These locations exhibit structural characteristics similar to the mangrove forests of Quintana Roo, in which an average height of 3.5 m was observed and densities were between 1520 and 25,000 trees ha^{-1}, indicating that the structure of this community is strongly controlled by the geohydrology and climate patterns including tropical storms (Lara-Dominguez et al. 2005).

As can be seen, the location of Progreso is quite unique, since the characteristics of the mangroves on both sides of the road differ significantly, making the impact by obstruction of water flows to evident (Table 28.3). The Progreso-E site showed very poor condition, where the interruption of water flow has favoured the accumulation and stagnation of sediments (Batllori-Sampedro and Febles-patrón 1999), thereby preventing mangrove seeds from establishing and developing. In contrast, the west site is in a good state of conservation (Table 28.3 and Fig. 28.6b) as a result of the free ebb-flow of the water by the action of the tide.

The differences in the characteristics of the mangrove vegetation between sites of each location suggest that in some cases the roads have affected the hydrological characteristics and have impacted the mangrove sites (Progreso, Vía antigua, San Benito and Chabihau). However, the locations of Chicxulub, Dzemul, La Línea and Telchac did not present differences in the structural characteristics of the mangrove vegetation on both sides of the respective roads, suggesting that local conditions mainly related with groundwater discharges and water flow form the swam to mangroves (Adame et al. 2013) could favour the type of vegetation observed.

According to the results of mangrove structure, the aims of rehabilitation program to favour the recovery of these areas impacted by hydrological changes were not achieved after 2 years. High variability was observed in mangrove structural characteristics between both sides of the roads. These suggest that the restoration activities should be specific according to the environmental characteristics of each mangrove zone. In locations such as Chuburná, Progreso-W, Vía Antigua and Chicxulub which are badly damaged the actions of hydrological rehabilitation should be applied, while in the sites such as Dzemul, La Línea and Telchac which showed signs of being in good condition, no specific rehabilitation action are recommended conservation actions should be the priority.

The results of the nonparametric multidimensional scaling analysis (MDS) using the physical and chemical variables of the water and sediments in addition to the structural characteristics of the mangrove forests, and separating "a priori" the sites that present characteristics of better structural development of the mangrove vegetation (Fig. 28.7 and Table 28.3), indicate that both sets of variables effectively represent different environmental and ecological conditions. Figure 28.7a and the ANOSIM test showed that even though according to the physical and chemical characteristics of the water there are sites in favourable conditions for the mangroves (San Benito-W), their structure vegetation characteristics are poor (Table 28.3). The water characteristics favour the ordination of sites less significant (global $R = 0.577$; $P < 0.01$) than the mangroves forest variables (global $R = 0.839$; $P < 0.001$). These differences suggest that in addition to the physical and chemical variables of the water, other components of the ecosystem such as the level and frequency of flooding, and the fertility of the sediments could play an important role in mangrove condition (Rivera-Monroy et al. 2006). This suggests that the restoration actions should not be directed solely at re-establishing the quality of the surface water and the surface flow of water, but should also take into account characteristics such as the variables of the sediment, hydroperiod, and seasonal changes in the flooding levels among others ecosystem variables. Reforestation should be considered as the last option if after all the other actions the natural regeneration has not been favoured (Lewis III 2005).

Documenting the success or failure of the rehabilitation actions in areas of mangroves through monitoring different types of actions, contributes to generating scientific bases and a conceptual framework on the ecology of restoration of these ecosystems. On the other hand, it helps to define improved rehabilitation actions at a regional scale, the specific plan of action according to the causes of deterioration of each site in particular, and the ecological characteristics of each location, understanding that the process of ecological rehabilitation is complex and dynamic, therefore monitoring is a tool for the definition of actions under the context of adaptive management.

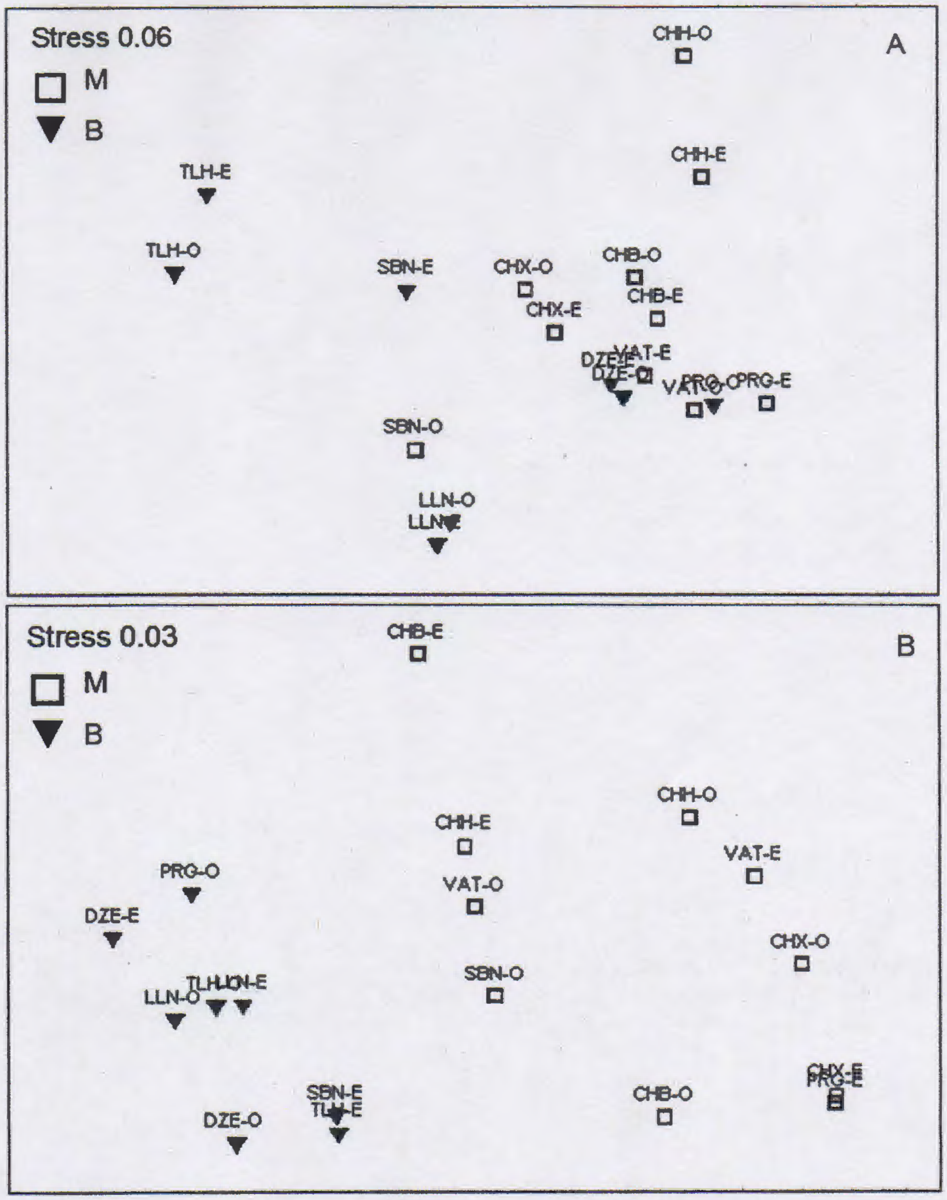

Fig. 28.7 Multivariate analysis

References

Adame MF, Zaldivar-Jimenez A, Teutli C, Caamal JP, Andueza MT, López-Adame A, Cano R, Hernández-Arana H, Torres-Lara R, Herrera-Silveira JA (2013) Drivers of mangrove litterfall within a karstic region affected by frequent hurricanes. Biotropica 45(2):147–154

Adame MF, Hermoso V, Perhans K, Lovelock CE, Herrera-Silveira JA (2015) Selecting cost-effective areas for restoration of ecosystem services. Conserv Biol 29(2):493–502

Alongi DM (2008) Mangrove forests: resilience, protection from tsunamis, and responses to global climate change. Estuar Coast Shelf Sci 76(1):1–13

Alongi DM (2011) Carbon payments for mangrove conservation: ecosystem constraints and uncertainties of sequestration potential. Environ Sci Policy 14(4):462–470

Bashan Y, Moreno M, Salazar B, Alvarez L (2013) Restoration and recovery of hurricane-damaged mangroves using the knickpoint retreat effect and tides as dredging tools. J Environ Manage 116 (15):196–203

Batllori-Sampedro E, Febles-Patrón JL (1999) Landscape change in Yucatan's Norwest Coastal Wetland (1948-1991). Hum Ecol 16(1):8–20

Boesch DF, Paul JF (2001) An overview of coastal environmental health indicators. Hum Ecol Risk Assess Int J 7(5):1409–1417

Bosire JO, Dahdouh-Guebas F, Kairo JG, Koedam (2003) Colonization of non-planted mangrove species into restored mangrove stands in GAzi Bay, Kenya. Aquat Bot 76(4):267–279

Cahoon DR, Reed DJ, Day JW (1995) Estimating shallow subsidence in microtidal salt marshes of the southeastern Unites States: Kaye and Barghoorn revisited. Mar Geol 128:1–9

Carpenter SR, Cole JJ, Essington TE, Hodgson JR, Houser JN, Kitchell JF, Pace ML (1998) Evaluating alternative explanations in ecosystem experiments. Ecosystems 1(4):335–344

Castañeda-Moya E, Rivera-Monroy VH, Twilley RR (2006) Mangrove zonation in the dry life zone of the Gulf of Fonseca, Honduras. Estuar Coasts 29(5):751–764

Chen R, Twilley RR (1998) A gap dynamic model of mangrove forest development along gradients of soil salinity and nutrients resource. J Ecol 86:37–51

Cintrón G, Lugo AE, Pool DJ, Moris G (1978) Mangrove of arid evironments in Puerto Rico and adyacent islands. Biotropica 10 (2):110–121

Comín FA, Herrera-Silveira JA (2000) The role of birds on the trophic structure and nutrient cycles of aquatic ecosystems: a review. In: Comin FA, Herrera-Silveira JA, Ramírez J (eds) Proceedings Limnology and Waterfowl, Monitoring, Modeling and Management, Workshop, Aquatic Birds Working Group. Societas Internationalis Limnologiae, Universidad Autónoma de Yucatán, pp 205–218

Costanza R, Darge R, de Groot R, Farber S, Grasso M, Hannon B, Limburg K, Naeem S, Oneill RV, Paruelo J, Raskin RG, Sutton P, van den Belt M (1997) The value of the world's ecosystem services and natural capital. Nature 387:253–260

DASILVA SMD 94 (1999) IRI/LDEO climate Data Library Magellan star Site. Lamont – Doherty Earth Observatory of Columbia University

Euán-Ávila JI (1998) Análisis de Detección de Cambio del Paisaje: Una Herramienta para el Manejo de las Costa Euan-Avila JI, Witter SG (2002) Promoting integrated coastal management in the Yucatan Peninsula. Mex J Policy Stud 12:1–15

Euan-Avila JI, Witter SG (2002) Promoting integrated coastal management in the Yucatan Peninsula. Mex J Policy Stud 12:1–15

Field C (1996) Restoration of mangrove ecosystems. Internacional tropical Timber Organization and Internacional Society for Mangrove Ecosystems, Okinawa

García E (1988) Modificaciones al sistema de clasificación de Koppen 4ª edición. México, D.F

Giri C, Ochieng E, Tieszen LL, Zhu Z, Singh A, Loveland T, Masek J, Duke N (2011) Status and distribution of mangrove forests of the world using earth observation satellite data. Glob Ecol Biogeogr 20:154–159

Gonneea ME, Charette MA, Liu Q, Herrera-Silveira JA, Morales-Ojeda SM (2014) Trace element geochemistry of groundwater in a karst subterranean estuary (Yucatan Peninsula, Mexico). Geochim Cosmochim Acta 132:31–49

Harry OB, Nyles CB (1982) Naturaleza y propiedades de los suelos. Editorial UTEHA, México, 388p

Herrera-Silveira JA (1994) Spatial heterogeneity and seasonal patterns in a tropical coastal lagoon. J Coast Res 10(3):738–746

Herrera-Silveira JA, Ramírez-Ramirez J (1997) Salinity and nutrients in the coastal lagoons of Yucatan. Mex Verh Internat Verein Limnol 23:1348–1351

Herrera-Silverira JA (1996) Salinity and nutrients in a tropical coastal lagoon influenced by groundwater discharges. Hydrobiologia 321:165–176

Holdridge LR, Grenke WC, Hathaway WH, Liang T, Tosi J (1971) Forest environments in tropical life zones, a pilot study. Pergamon Press, New York

Hyman JB, Leibowitz SG (2001) JSEM: a framework for identifying and evaluating indicators. Environ Monit Assess 66(3):207–232

Jiménez JA, Lugo AE (2000) Rhizophora mangle L. Red mangrove. SO-ITF-SM-2. New Orleans, LA, US, Department of Agriculture, Forest SErvice, Southern Forest Experiment Station, 450–455

Koch MS, Snedaker SC (1997) Factors influencing Rhizophora mangle L. seedling development in everglades carbonate soils. Aquat Bot 59:87–98

Lara-Dominguez A, Day J, Villalobos G, Twilley RR, Alvarez G, Yañez-Arancibia (2005) Structure of unique inland mangrove forest assemblage in fósil lagoons on the Caribbean Coast of Mexico. Wetl Ecol Manag 13:111–122

Lewis RR (2005) Ecological engineering for successful management and restoration of mangrove forests. Ecol Eng 24(4):403–418

Lewis RR III (2009) Methods and criteria for successful mangrove forest restoration. Coastal Wetlands: an integrated ecosystem approach. Elsevier, Amsterdam, pp 787–800

Long KS, Nestler JM (1996) Hydroperiod changes as clues to impacts on cache river riparian wetlands. Wetlands 16:379–396

López-Portillo J, Ezcurra E (1989) Litter fall of Avicenncia germinans L. in a one-year cycle in a mudflat at the lagun Mecoacan,Tabasco, Mexico. Biotropica 17(3):186–190

Lugo AE, Sell MA, Snedaker SC (1976) Mangrove ecosystem analysis. In: Systems analysis and simulation in ecology, vol 4. Academic, New York, pp 114–145

Mckee KL (1995) Seedling recruitment pattern in a Belizean mangrove forest: effects of establishment ability and physico-chemical factors. Oecologia 101:448–460

Pacheco Martinez JL, Alonzo Salomon LA (2003) Characterization of karst material of Carrillo Puerto formation in Yucatan Autonomous University of Yucatan, Mérida, México. Acad Mag Eng 7:7–19

Perry C, Berkely A (2009) Intertidal substrate modifications as a result of mangrove planting: impacts of introduced mangrove species on sediment microfacies characteristics. Estuar Coast Shelf Scence 81:225–237

Polidoro BA, Carpenter KE, Collins L, Duke NC, Ellison AM, Ellison JC, Livingstone SR (2010) The loss of species: mangrove extinction risk and geographic areas of global concern. PloS One 5(4)

Powell N, Osbeck M, Tan SB, Toan VC (2011) Mangrove restoration and rehabilitation for climate change adaptation in Vietnam. World Resources Report Case Study. World Resources Report, Washington, DC. URL: http://www.worldresourcesreport.org

Programa de ordenamiento ecológico del Territorio Costero del Estado de Yucatán (POETCY) (2007) Informe Final. Portal de la Secretaría de Ecología del Estado de Yucatán

Reddy KR, DeLaune RD (2008) Biogeochemistry of wetlands: science and applications. CRC Press, Boca Raton

Rivera-Monroy VH, Twilley RR, Mancera E, Alcantara-Eguren A, Castañeda-Moya E, Casas O, Reyes P, Restrepo J, Perdomo L, Campos E, Cotes G, Viloria E (2006) Aventuras y Desventuras en Macondo: Rehabilitación de la Ciénaga Grande de Santa Marta, Colombia. Ecotropicos 19:72–93

Rovai AS, Barufi JB, Pagliosa PR, Scherner F, Torres MA, Horta PA, Soriano-Sierra EJ (2013) Photosynthetic performance of restored and natural mangroves under different environmental constraints. Environ Pollut 181:233–241

SAS Institute I (2000) Statistical Discovery Software,JMP V4.02. SAS Institute Cary, North Carolina

Schaeffer-Novelli Y, Cintron G (1990) Métodos para la descripción y estudio de áreas de manglar. Ingeniería marítima, ciencias del mar. Escuela superior politécnica del litoral. Puerto Rico

SECOL (2004) Gobierno del Estado de Yucatán. Reporte técnico de aprovechamiento y monitoreo de aves acuáticas de interés cinegético del estado de Yucatán, 68p

SER (Society for Ecological Restoration International Science & Policy Working Group) (2004) The SER International Primer on Ecological Restoration. Society for Ecological Restoration International, Tucson, Arizona. Available from www.ser.org. Accessed Apr 2005

Strickland JD, Parsons TR (1972) A practical handbook of sea water analysis. Fish Res Board Can Bull 122:311

Teutli-Hernández C (2003) Estimación del éxito de la restauración hidrologica de zonas de manglar en el norte de Yucatán, México. Tesis de licenciatura. Licenciatura en Biología. Benemérita Universidad Autónoma de Puebla, 51pp

Twilley RR (1995) Properties of mangrove ecosystems relate to the energy signature of coastal environments. In: Hall C (ed) Maximun Power: the ideas and applications of H.T. University of Colorado, Colorado, pp 43–22

Twilley RR (1998) Mangrove wetlands. In: Messina MG, Conner WH (eds) Southern forested wetland, ecology and management. Lewis Publishers, Boca Raton, pp 445–473

Twilley RR, Chen R (1998) A wáter Budget and hydrology modelo f a basin mangrove forest in Rookery Bay florida. Mar Fresw Res 49(4):309–323

Twilley RR, Rivera-Monroy VH (2005) Developing performance measures of mangrove wetlands using simulation models of hydrology,nutrient biogeochemistry, and community dynamics. J Coast Res 40:79–93

Twilley RR, Rivera-Monroy VH, Chen R, Botero L (1999) Adapting an ecological mangrove model to simulate trajectories in restoration ecology. Mar Pollut Bull 37(8):404–419

Valderrama-Landeros LH, Rodríguez-Zúñiga MT, Troche-Souza C, Velázquez-Salazar S, Villeda-Chávez E, Alcántara-Maya JA, Vázquez-Balderas B, Cruz-López MI, Ressl R (2017) Manglares de México: actualización y exploración de los datos del sistema de monitoreo 1970/1980–2015. Comisión Nacional para el Conocimiento y Uso de la Biodiversidad. Ciudad de México, 128pp

Valentine-Rose L, Layman CA (2011) Response of fish assemblage structure and function following restoration of two samll bahamian todal creeks. Restor Ecol 19(2):205–215

Valiela I, Bowen JL, York JK (2001) Mangrove Forests: one of the world's threatened major tropical environments: at least 35% of the area of mangrove forests has been lost in the past two decades, losses that exceed those for tropical rain forests and coral reefs, two other well-known threatened environments. Bioscience 51(10):807–815

Vyas P, Sengupta K (2012) Mangrove conservation and restoration in the Indian Sundarbans. Sharing Lessons on Mangrove Restoration, 93pp

Wang'ondu V, Bosire J, Kairo J, Kinyamario J, Mwaura F, Dahdouh F, Koedam N (2014) Litter fall dynamics of restored Mangroves (Rhizophora mucronata Lamk. and Sonneratia alba Sm.) in Kenya. Restor Ecol:824

Warwick RM, Clarke KR (1993) Increased variability as a symptom of stress in marine communities. J Exp Mar Biol Ecol 172(1–2):215–226

Zaldivar JA (1999) Estructura de la comunidad del manglar y su relación con las características físicas y químicas del sedimento en laciénaga Sisal – Chuburnà, Yucatán, México. Tesis de licenciatura. Licenciatura en Biología. Universidad Autónoma de Yucatán, 61pp

Zaldivar-Jiménez AZ, Silveira JH, Molina CC, Parra DA (2004) Estructura y productividad de los manglares en la reserva de biosfera Ría Celestún, Yucatán, México. Madera Bosques 10(1):25–35

Zhao Q, Bai J, Huang L, Gu B, Lu Q, Gao Z (2016) A review of methodologies and success indicators for coastal wetland restoration. Ecol Indic 60:442–452