


CONSERVATION SCIENCE IN MEXICO'S NORTHWEST

ECOSYSTEM STATUS AND TRENDS IN THE GULF OF CALIFORNIA




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DIAGNOSIS OF DEGRADED AREAS AND PROPOSALS FOR ECOLOGICAL RESTORATION IN BAJA CALIFORNIA SUR

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Areas that show ecological degradation processes in Baja California Sur, Mexico, were identified by means of land-cover analysis through spatial analysis of information in a geographical information system (GIS) and the application of a vegetation index (VI). Seven areas are recognized as critical in the north, central and south portions of the state. All seven present soil degradation to some extent from 1990 to 2000. Corrective measures are recommended in order to revert or minimize this process.

1. INTRODUCTION

The studies of land-cover and land-use change are at present at the center of attention of environmental research. The importance of knowing the state of the environment resides in the need to have real and quantifiable elements to be used in the decision making processes regarding the use and management of natural resources. In Mexico, the study of the magnitude, dynamics and causality of land-cover and land-use change is a priority. Data obtained by Masera *et al.* (1997) indicate that Mexico ranks among the nations with higher deforestation rate in the world.

The state of Baja California Sur, in the extreme north-west of Mexico, is no exception. The great biological richness of its arid zones is each year seriously affected by land-use changes. These changes impact the physical and biological environment, eroding the soil and modifying the habitat, the biological interactions of their wild populations, the animal behavior, and the ecosystem processes. Additionally, they accelerate the introduction of invasive species and increase the fragmentation of wild areas near roads and rural and urban developments (Trombulak and Frissell 2000, Nellemann 2001, Arriaga *et al.* 2004, Arriaga 2009).

Understanding the impact of land-use and land-cover changes implies the study of coupled environmental and socio-economic factors (Bocco *et al.* 2001). Current land-use has important implications in the future climate of the earth and consequently great feed-back implications for future land-use (Agarwal *et al.* 2002), a powerful reason to understand the interactions between human activities and natural resources. Land-use change is an extensive, accelerated, and momentous process caused by human action and changing the face of the earth, and in many cases it also causes changes that negatively impact human populations and their ability to derive sustenance from their environment (Rosete-Vergés *et al.* 2008).

Most changes in terrestrial ecosystems are due to one or more of these factors: (a) land-cover conversion, (b) land degradation, and (c) land-use intensification. These processes, usually grouped in what is known as *deforestation* or *forest degradation*, are associated with important ecological impacts at virtually all scales: locally they induce the loss and degradation of soil, cause changes in the microclimate and promote the loss of species diversity; regionally they affect the dynamics of entire basins, ecosystems and human settlements; and at a global level they contribute to greenhouse-gas emissions which drive global climate change (Bocco *et al.* 2001).

Land-use changes are commonly separated from land-cover changes despite the similarities in methods and approaches (Weng 2002). According to Brown *et al.* (2000) in border regions with economies based mainly in extractive economies (*i.e.*, mostly in developing countries), land-use and land-cover are almost always semantically equivalent. For example, the activity of land-use associated to logging leads to a land-cover with reduced tree cover or no trees (Lambin 1997). However, in a post-modern economy that is led by information and information access, as most of modern Europe and the United States, land-use and land-cover seem to be less equivalent (Brown *et al.* 2000).

A form of assessing the dynamics of land-use change is by measuring changes in vegetation cover and non-vegetated land uses. Traditionally the measurement of land-cover and land-use change is done through remote sensing (usually aerial photographs and satellite imagery) or thematic mapping. Pragmatically, the concept of the term "land-cover" describes the objects distributed over a specific territory, while "land-use" refers to the result of the socio-economic activities that are (or were) taking place in a particular land-cover type. These activities are related to the appropriation of natural resources used to generate goods or services (Bocco *et al.* 2001).

The investigation presented in this chapter was carried out in order to determine which ecologically degraded zones in the state of Baja California Sur, Mexico require urgent attention. In this context, our results establish seven critical zones, determine the extension of their degradation, the basins to which they belong, the types of vegetation affected and the recommended corrective measures to stop this accelerated process.

2. METHODS

Our approach was based on the analysis of changes of vegetation cover from satellite imagery, using NOAA-AVHRR[1], LANDSAT TM[2], and LANDSAT ETM[3] images. A vegetation index (VI) was applied to quantify the changes in vegetation cover and locate the areas with most degradation or susceptibility to it. Results were tested against independent information on land-use and vegetation for the state of Baja California Sur (B.C.S.) obtained from CONABIO (1998).

The vegetation indices commonly used to understand the characteristics and dynamics of natural and induced vegetation are the product of algorithms applied to low-cost sensors such as NOAA-AVHRR (Rouse 1974, Holben 1986, Santiago León 2003) and medium-cost such as the Landsat series (Santiago León 2003).

The information provided by satellite imagery provides many elements that are potentially apt to be applied in the evaluation of natural resources in time series. As a result of this work a database with information of the degraded areas or areas in process of environmental degradation in B.C.S. was generated, and preliminary recommendations were proposed for the ecological restoration of the critical areas.

2.1. Procedure 1: analysis of NOAA-AVHRR images

The AVHRR system was conceived as a scanning radiometer for meteorological purposes and was first launched on a polar-orbiting satellite in 1978. But the data it provides have allowed to develop applications in the field of Earth observation, and since then it has come to be one of the most valuable sources of data for non-meteorological purposes in a whole variety of environmental, scientific, and management contexts (Goodrum 1999, Cracknell 2001, Suárez-Seoane 2005).

From the total bands of the NOAA-AVHRR satellite, two provide relevant information to calculate the VI, considering the response of the vegetation to the red and near-infrared spectral ranges:

[1] NOAA–AVHRR: National Oceanic and Atmospheric Administration-Advanced Very High Resolution Radiometer.
[2] TM: Thematic Mapper from NASA Landsat Program.
[3] ETM: Enhanced Thematic Mapper from NASA Landsat Program.

- Band 1 (0.580-0.680 μm): chlorophyll absorption range
- Band 2 (0.725-1.100 μm): vegetation reflectance

The Normalized Difference Vegetation Index, or NDVI, is then calculated applying the following formula:

$$NDVI = \frac{NIR-RED}{NIR+RED} = \frac{band2-band1}{band2+band1}$$

Ten NOAA-AVHRR GAC[4] hemispheric images of 8 km pixel size were used (Maselli *et al.* 2002). Their analysis provided a panoramic view of the vegetation index (VI) ranges in the zone of study and a preliminary reference to delimitate the analysis to the period from August to October, the rainy season when the vegetation index for this normally arid region shows larger contrasts and is more stable. The general areas that present notorious changes in their VI were identified with this procedure and a more detailed analysis was centered on these areas.

The VI change analysis was made in a ten-year time series from 1990 to 2000, using 20 and 15 NOAA-AVHRR LAC[5] images respectively. Each of these 35 satellite images has a spatial resolution of 1 km. The totality of the state of Baja California Sur was included in this coverage. Areas that present a significant VI change were delimited from this analysis.

Before any analysis is conducted all satellite images must be geometrically and radiometrically corrected. To ensure the quality of the results adjustments were made on: (1) signal degradation, (2) cloudiness, (3) atmospheric conditions (aerosols, water vapor, etc.), (4) observation point, and (5) ground effects (geology).

For the representation of the vegetation index a color palette (false color) was applied on the images. Additionally, compounds of images of daily indices were used, from which the Maximum Value Composite (MVC) was obtained (Holben 1986). This allowed us to minimize the problems caused by the atmospheric effects and observation angles, which often complicate the use and interpretation of images (Cocero *et al.* 2000).

2.2. Procedure 2: analysis of LANDSAT TM and ETM images

Once the pre-selection of the sites was concluded, we proceeded to derive the VI with more detail from the 30 m resolution images of Landsat TM and ETM

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[4] GAC, Global Area Coverage denominated for global or hemispheric coverages obtained from NOAA-AVHRR with resolution of 8 and 16 km.
[5] LAC, Local Area Coverage denominated for the type of image obtained from the NOAA-AVHRR satellite series with 1 and 4 km resolution options.

TABLE 1. Characteristics of the Landsat TM and ETM images. Bands 3 and 4 are used to derive the vegetation indices (http://landsat7.usgs.gov/project_facts/history/)

Band	Spectral range	Resolution in meters	Satellite
1	Visible (0.45 – 0.52µm)	30	TM, ETM
2	Visible (0.52 – 0.60µm)	30	TM, ETM
3	**Visible (0.63 – 0.69µm)**	**30**	**TM, ETM**
4	**NIR[i] (0.76 – 0.90µm)**	**30**	**TM, ETM**
5	NIR (1.55 – 1.75µm)	30	TM, ETM
6	Thermal (10.40 – 12.50µm)	120	TM
6*	Thermal (10.40 – 12.50µm)	60	ETM
	Low Gain / High Gain		
7	Mid IR (2.08 – 2.35µm)	30	TM, ETM
8	Panchromatic (PAN) (0.52 – 0.90µm)	15	ETM

satellites. As in the previous procedure, VI change analysis was calculated on a time series from 1990 to 2000. To have a full coverage of the state we used a total of 16 images, 8 for each year (information was obtained from the server at the University of Maryland).

The analysis of Landsat TM and ETM images to calculate the VI was also based on the principles of vegetation response to the spectral ranges of red and near-infrared. Like in the previous procedure the NDVI was applied, substituting the corresponding band for these satellites as shown in Table 1.

$$NDVI = \frac{NIR\text{-}RED}{NIR+RED} = \frac{band4\text{-}band3}{band4+band3}$$

As before, each image was geometrically and radiometrically corrected prior to their analysis. It is important to mention that the analysis performed was affected by the characteristics of vegetation and geology of Baja California Sur, due to high reflectance of the study area, resulting in the loss of high quality signal from vegetation indices; however, the above methodology seeks to minimize these problems.

The range of values obtained using the NDVI goes from -1 to +1. Only positive values correspond to areas with vegetation, negatives indicate bare soil (Suárez-Seoane 2005). For purposes of the analysis only positive values (greater than zero) were used in order to simplify the processes and to focus the analysis.

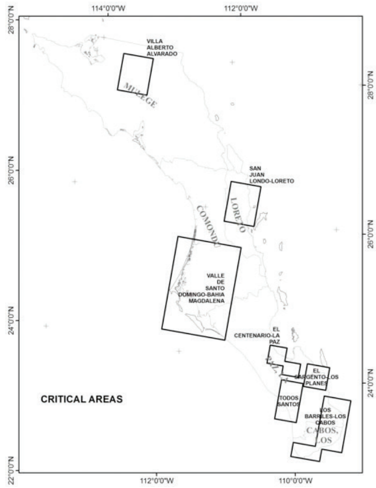


FIGURE 1. Location of areas with important changes in VI from 1990 to 2000 in the state of Baja California Sur, México. Results derived from NOAA-AVHRR 8km and 1km the image analysis. Ortega Rubio and Santiago Leon 2005.

2.3. Procedure 3: Contrasting results with existing information

In order to refer the results to known geographic elements in the study area, we used a series of regional thematic maps, including (a) Surface Hydrology and Basins (CONABIO 1998), (b) Land-Use and Vegetation (Inventario Forestal 2000), (c) Roads and Towns, and (d) municipal and state boundaries (obtained from INEGI). Layering of maps was performed using a Geographic Information ArcGIS. Finally, after contrasting the VI obtained and contrasting its consistency against other thematic maps, we proceeded to select priority sites. For practical purposes, each site was assigned the name of the main locality within it.

3. RESULTS

Comparing the vegetation indices (VI) derived from the NOAA-AVHRR images at 8 km resolution from the years 1990 and 2000; significant changes were observed in the northern, central and southern parts of the State of Baja California Sur. Subsequently, and as a result of the analysis of NOAA-AVHRR 1 km images, seven areas were identified in which a significant change in VI was detected and thus important changes in land-use were inferred to have taken place. When referencing our results with the existing information it was found that the critical areas correspond to urban centers, agriculture areas, and extensive ranching sites (see Figure 1).

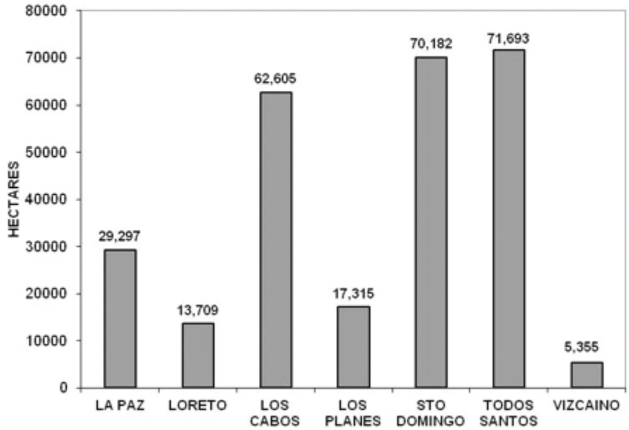


FIGURE 2. Degraded area for each critical site, measured in hectares.

The value of VI is proportional to amount of natural cover and is an indicator of vulnerability to soil degradation. A low VI corresponds to deforested areas that are more susceptible to soil degradation. In agreement to this criterion the areas selected from NOAA-AVHRR image analysis are listed below; listed on a top-down VI hierarchy:

- Los Cabos (Los Barriles-Cabo San Lucas)
- Santo Domingo (Santo Domingo–Bahía Magdalena)
- La Paz (El Centenario–La Paz)
- Todos Santos
- Los Planes (El Sargento–Los Planes)
- Loreto (San Juan Londó–Loreto)
- Vizcaíno (Villa Alvarado)

3.1. Synthesis of results: Areas under some type of soil degradation stress

Within each critical area, the total degraded area was estimated in hectares and the vegetation type most affected by land-use change was identified. A synthesis of these results is presented below. Purple markings on the image represent sites with high VI change between 1990 and 2000.

The sites with greater affected area were Todos Santos and Santo Domingo, both with over 70,000 ha showing signs of degradation through land-use change (see Figure 2). Los Cabos ranked slightly below this figure, with some 62,000 hectares

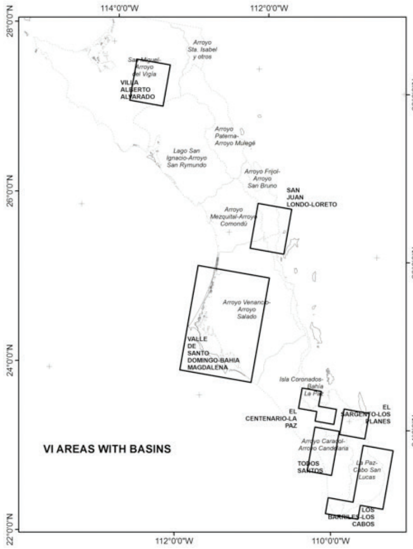


FIGURE 3. Overlapping of high VI change areas with basins of the B.C.S. state.

affected by land-use change, but showed a rate of decline in the overall VI values much higher than that of any of the other sites. The total area showing significant loss or degradation of native vegetation cover between 1990 and 2000 is 270,157 hectares, corresponding to 4% of the land surface of the State of Baja California Sur[6].

There is a spatial association between our critical areas, as defined by rapidly declining VI values, and the main water basins in the State (see Figure 3). The overlap between the areas of rapid land-use change and their sustaining basins provides an important element to analyze the potential impact of vegetation loss and soil degradation on water supply and aquifer recharge. Eight of the ten main basins of the state are to some extent contained within the polygons of our selected critical sites (see Table 2).

4. DISCUSSION AND CONCLUSIONS

The use of 8 km pixel size images from NOAA-AVHRR provided an overview of the range of vegetation indices (VI) in the State. The preliminary analysis provided

[6] The percentage corresponds to area of study. The total area of Baja California Sur state calculated by GIS according to INEGI data is 7,060,736 ha; this number does not include islands.

TABLE 2. Critical selected sites, basins to which they belong and main land-use activities realized in each site.

Critical site	Basins	Degraded surface (ha)	Main land-use activities
La Paz	Arroyo Caracol-Arroyo Candelaria Isla Coronados-Bahía La Paz La Paz-Cabo San Lucas	29,297	Urban and tourism Development Extensive cattle Raising Grazing land Forestry Deforestation
Loreto	Arroyo Frijol-Arroyo San Bruno Arroyo Mezquital-Arroyo Comondú Arroyo Venancio-Arroyo Salado Isla Coronados-Bahía La Paz	13,709	Urban and tourism Development Extensive cattle Raising Irrigation Agriculture Grazing land Deforestation
Los Cabos	Arroyo Caracol-Arroyo Candelaria La Paz-Cabo San Lucas	62,605	Urban and tourism Development Deforestation Extensive cattle Raising
Los Planes	Arroyo Caracol-Arroyo Candelaria La Paz-Cabo San Lucas	17,315	Urban and tourism Development Extensive cattle Raising Irrigation Agriculture Forestry
Santo Domingo	Arroyo Venancio-Arroyo Salado	70,182.30	Forestry Extensive cattle Raising Irrigation Agriculture
Todos Santos	Arroyo Caracol-Arroyo Candelaria La Paz-Cabo San Lucas	71,693	Urban and tourism Development Irrigation Agriculture Grazing land Extensive cattle Raising Forestry
Vizcaíno	Lago San Ignacio-Arroyo San Raymundo San Miguel-Arroyo del Vigía	5,355	Irrigation Agriculture Extensive cattle Raising Deforestation
	Total	270,157	

a methodological framework that allowed to identify the months of August to October as the dates on which the vegetation index for this arid region shows more contrasts. This allowed us to detect major changes in land-use change and identify areas subject to soil degradation through the loss of vegetation cover at a large scale. The analysis of the NOAA-AVHRR 1 km images allowed us to delineate areas with significant VI changes in greater detail.

We recognize seven critical areas with significant changes in their VI between 1990 and 2000 (see Table 3):

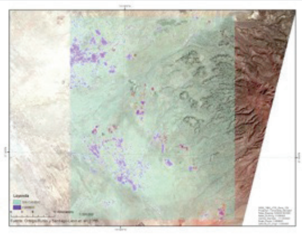
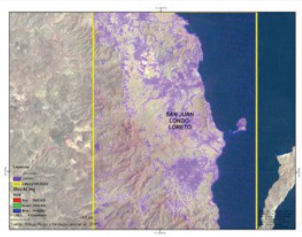
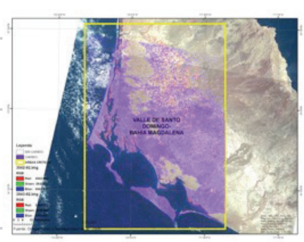
Los Cabos has the highest degree of variation in VI and thus presents the fastest degradation. Its rapidly-growing population, the growing demands for land from both, tourism and real estate, as well as other associated activities such as livestock ranching, agriculture, and forestry, are the main elements of degradation of the existing vegetation. The most affected vegetation types are the sarcocaulescent shrubland and the tropical deciduous forests of the lowland slopes.

Santo Domingo is a prime example of the areas that have been affected by loss of natural vegetation driven by the opening new areas to agriculture. Currently clearing of new areas has been largely reduced and in parts halted by the exhaustion of the aquifer and the lack of good quality water for agriculture. The area, however, still harbors extensive grazing of the desert ranges and cutting of desert trees such as mesquite to make charcoal for the urban markets. These activities affect the lowland areas, valleys, and arroyos, where species such as mesquites (*Prosopis* spp.) are cut for their wood.

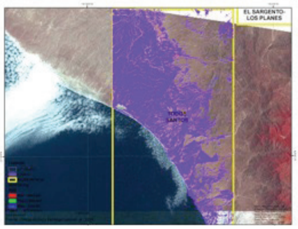
La Paz. In this region ranching and urban development (driven largely by tourism and the real estate market) are the main drivers of land-use change, coupled with deforestation driven by irrigation agriculture, and wood cutting for urban supply of materials and fuels. These activities focus mainly on the sarcocaulescent shrublands and on formations of giant columnar cacti. Other elements that affect this area are the roads and power lines that increase the fragmentation of wild lands in areas close to roads or to urban developments (Trombulak and Frissell 2000, Nellemann 2001, Arriaga *et al.* 2004, Arriaga 2009).

Todos Santos is the region with the largest proportion of the area with some form of soil degradation. The rapid increase in tourism and the ensuing demand for urban real estate in recent years have been intense drivers of land-use change, coupled with historic activities of agriculture and cattle ranching that have continued over generations.

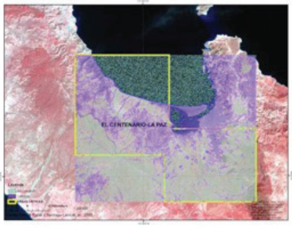
TABLE 3. Synthesis of sites and main activities and vegetation affected.

Site	Vizcaíno (Villa Alberto Alvarado)	
Total degraded area	5,355 ha	
Geographic reference coordinates	27°30'N, 113°30'W	
Main activities / land use	Agriculture Extensive cattle ranching Forestry	
Affected native vegetation and previous land-use	Microphyllous desert shrubland Halophytic vegetation Irrigation agriculture	
Site	**Loreto (San Juan Londó-Loreto)**	
Total degraded area	13,709 ha	
Geographic reference coordinates	26°00'N, 111°30'W	
Main activities / land use	Irrigation Agriculture Extensive cattle raising Grazing land	
Affected native vegetation and previous land-use	Sarcocaulescent shrubland	
	Mesquite forest	
	Grazing land	
	Irrigation agriculture	
Site	**Santo Domingo (Valle de Santo Domingo-Bahía Magdalena)**	
Total degraded area	70,182 ha	
Geographic reference coordinates	25°00'N, 112°00'W	
Main activities / previous land use	Agriculture Extensive cattle raising Forestry	
Affected native vegetation and previous land-use	Mangrove forest Sarcocaulescent shrubland Crassicaulescent shrubland Irrigation agriculture	

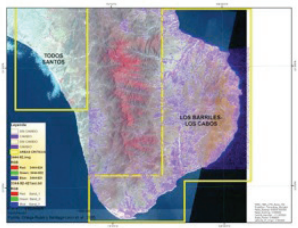
Site	Todos Santos
Total degrated area	71,693 ha
Geographic reference coordinates	23°30'N, 110°15'W
Main activities / land use	Agriculture Extensive cattle raising Forestry
Affected native vegetation and previous land-use	Sarcocaulescent shrubland Crassicaulescent shrubland Grazing land Irrigation agriculture



Site	La Paz (El Centenario-La Paz)
Total degrated area	29,297 ha
Geographic reference coordinates	24°00'N, 110°30'W
Main activities / land use	Agriculture Extensive cattle raising Forestry Urban development
Affected native vegetation and previous land-use	Sarcocaulescent shrubland Crassicaulescent shrubland Irrigation agriculture Urban development



Site	Los Cabos (Los Barriles-Los Cabos)
Total degrated area	62,605 ha
Geographic reference coordinates	24°00'N, 110°30'W
Main activities / land use	Agriculture Extensive cattle raising Forestry Urban development
Affected native vegetation and previous land-use	Sarcocaulescent shrubland Tropical deciduous forest Irrigation agriculture Grazing land



In recent years, Los Planes has established itself as a prime tourist destination for fishermen and people that practice water sports, and, as a result, deforestation has increased to give rise to real estate developments in the area. At the same time, historic ranching and irrigation agriculture have continued and even grown, largely to supply the booming local markets.

Loreto includes several types of land-use pressures: There is deforestation of the coastal Gulf shrubland, the presence of cattle ranching in the western portion of the town of Loreto and the basin of San Juan Londó, and different places that have been cleared for agriculture and then abandoned because of the decline of the aquifers and the enforcement of regulations for water extraction.

The large coastal plains of El Vizcaíno stand out as an area greatly affected by land-use change. During the last decades this area has been subject to growing demands from both desert agriculture and ranching, with the clearing of large tracts of land for irrigation from the rapidly-dwindling aquifer. Communication channels such as roads and power lines are also important factors of fragmentation of plant communities, mostly affecting the halophytic vegetation of the coastal plains and the inland desert scrub.

The considerations to select the analyzed areas as critical took into account as first element the variations in vegetation indices NDVI. The limits proposed in this paper are based on a regular polygon area, and represent a first approximation to the location of the areas of greatest VI change, according to the methodology employed. The quality of information provided by the analysis was derived from sensors of low and medium resolution (NOAA-AVHRR 1000m and Landsat ETM 30m respectively). Future projects following-up on these results should consider an analysis of greater detail in scale and spatial resolution of degraded areas.

In conclusion, although Baja California Sur is the most isolated and least populated State of Mexico, the level of degradation that occurs in these seven priority areas is alarming, having reached over 270.000 ha in only 10 years. This underscores the growing needs for management plans and environmentally friendly practices, and emphasizes the urgency of creating a sustainable culture that ensures the preservation of natural resources for future generations.

5. RECOMMENDATIONS

Although the Baja California Sur is the State with the most land area under environmental protection in Mexico, there are widespread conditions that promote the loss of vegetation cover and the rapid deterioration of the soil, seriously affecting ecosystem health in the region. Among the recommended actions to implement to stop this degradation process are:

1. Halt deforestation. This is a main priority, it is urgent to stop new permits aimed at:

a) New urban development's outside of the urban area

b) New agriculture areas

c) New forestry permits

2. Develop Land Planning (*Ordenamiento Ecológico*) studies for each basin in order to establish the types, locations and intensities of new productive activities allowed in each area as well as sites required for the conservation of natural resources.

3. It is urgent to minimize and restrict the impact ranching, opting for alternatives that allow a more sustainable consumption of natural resources and constrain grazing to animal densities in accord to the limited carrying capacity of the desert ranges.

4. Develop reforestation programs using native species to reverse the damage caused by natural and anthropogenic erosion. Such species should be produced in nurseries, including in their production modern technologies such as tissue culture techniques and bio-fertilization with symbiotic microorganisms.

5. Last but not least, the development of training and awareness programs that ensure community practices that are respectful with the natural resources are of critical importance in this still unique part of Mexico.

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Exploring Mexico's northwest, the Baja California Peninsula, its surrounding oceans, its islands, its rugged mountains, and rich seamounds, one feels diminished by the vastness and the greatness of the landscape while consumed by a sense of curiosity and awe. In a great natural paradox, we see the region's harsh arid nature molded by water through deep time, and we feel that its unique lifeforms have been linked to this desert and sea for thousands of years, as they are now.

These landscapes of fantasy and adventure, this territory of surprising, often bizarre growth-forms and of immense natural beauty, has inspired a wide array of research for over two centuries and continues to inspire the search for a deeper knowledge on the functioning, trends, and conservation status of these ecosystems in both land and ocean.

This book offers a compilation of research efforts aimed at understanding this extraordinary region and preserving its complex richness. It is a synthesis of work done by some exceptional researchers, mostly from Mexico, who indefatigably explore, record, and analyze these deserts and these seas to understand their ecological processes and the role of humans in their ever-changing dynamics.

Elisabet V. Wehncke

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