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CONCEPTUAL ECOLOGICAL MODEL OF THE SIAN KA'AN BIOSPHERE RESERVE, QUINTANA ROO, MEXICO

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Abstract: Located on the Caribbean Coast in the State of Quintana Roo, the Sian Ka'an Biosphere Reserve (RBSK) is one of Mexico's largest protected areas. The ecosystems of Sian Ka'an and the Greater Everglades are similar in many respects. The natural systems of Quintana Roo, Mexico and Florida's Greater Everglades and adjacent coastal ecosystems support economically important fisheries and tourism industries. Both systems are threatened by growing human populations and associated development, as well as other stressors on the ecosystem, including unsustainable uses, agricultural and urban development, and increased extraction of natural resources. Valuable lessons in ecosystem ecology and management are being learned from the South Florida Ecosystem Restoration Initiative (SFERI) that can and should be applied to the Sian Ka'an Biosphere Reserve. Conceptual ecological models have been used in Greater Everglades ecosystems to communicate major issues in restoration and to identify attributes and biological indicators for evaluating alternative restoration plans and for designing monitoring and assessment programs. The conceptual ecological model for RBSK is a conservation model rather than a restoration model; it does not explain effects that have already occurred but, rather, hypothesizes effects that, based on experience, are likely to occur. Stressors in the Sian Ka'an Conceptual Ecological Model are driven by local and national societal needs and not natural drivers. Attributes identified were similar to those in Greater Everglades systems and included hydrology and water quality, upland, wetland and coastal fauna, and vegetation patterns. Visual aesthetics also were identified as significant. Linkages between stressors and attributes are being used to design and communicate science and management needs for the Reserve.

Key Words: Sian Ka'an, Biosphere Reserve, Mexico, tourism, conceptual model

BACKGROUND

Located on the Caribbean Coast in the State of Quintana Roo (Figure 1), the 6,510 km^2 Sian Ka'an Biosphere Reserve (RBSK) is one of Mexico's largest protected areas (Figure 2). Natural systems of RBSK and the Everglades form sections of large peninsulas, with slight elevational gradients, extending into warm waters. Offshore barrier coral reefs are separated from large interior freshwater wetlands by extensive, highly productive mangrove estuaries and lagoons. Both natural systems support economically important fisheries and tourism industries and are threatened by growing human populations and associated development. The

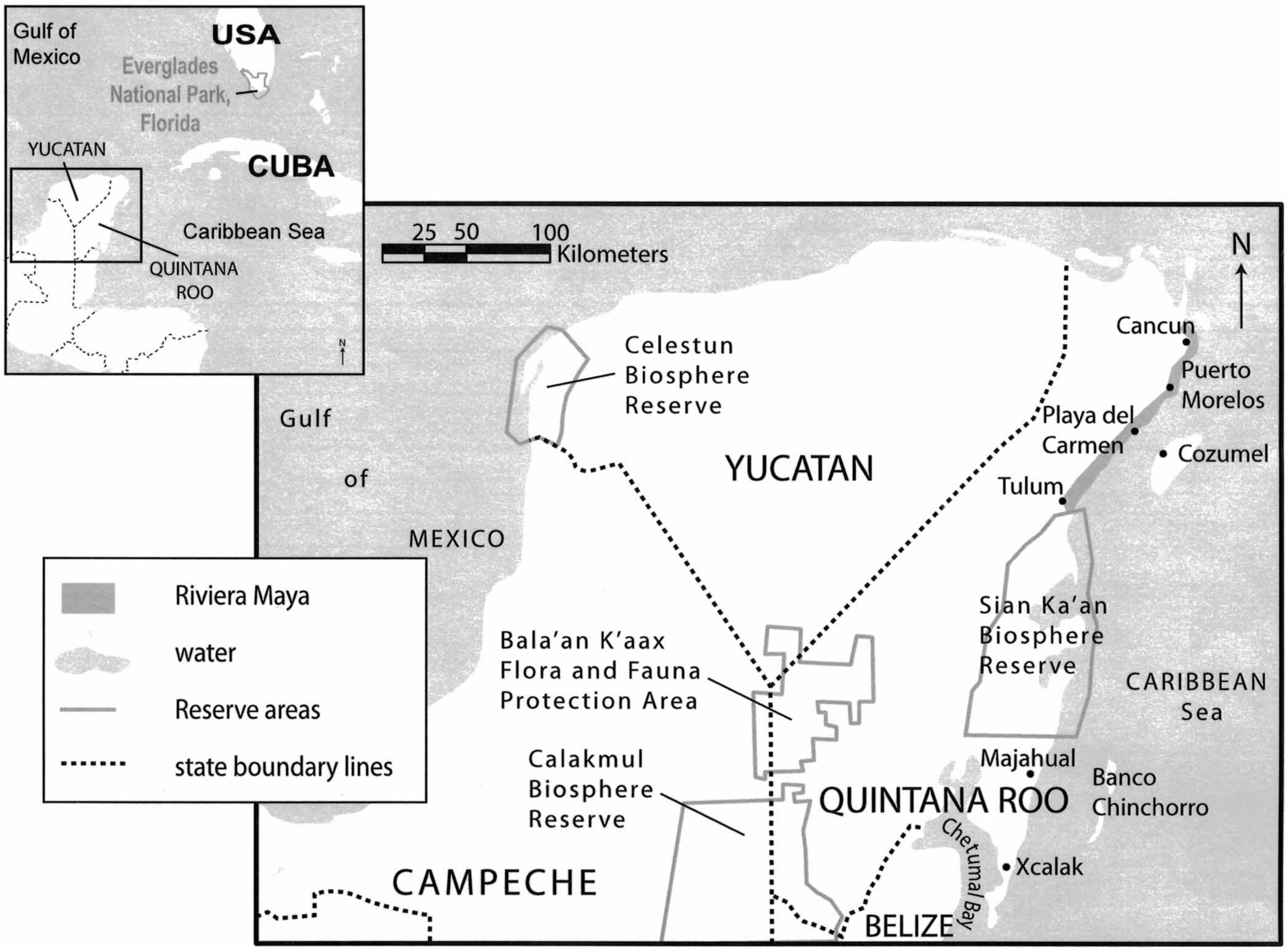

Figure 1. Locations of Sian Ka'an Biosphere Reserve, Quintana Roo, Mexico and Everglades National Park, Florida, USA.

Sian Ka'an Conceptual Ecological Model (Figure 3) and the Greater Everglades Ecosystem Conceptual Ecological Model (Ogden et al. 2005) have similar attributes with different degrees of degradation. The Sian Ka'an Conceptual Ecological Model was created to demonstrate how valuable lessons in ecosystem ecology and management being learned from South Florida's Everglades Ecosystem Restoration Initiative (SFERI) could be applied to similar systems.

Conceptual ecological models have been used as part of SFERI to identify major stressors, attributes, and linkages that best indicate change in ecosystems. Conceptual ecological models have also been used to identify attributes and biological indicators for evaluating alternative restoration plans (Rosen et al. 1995, Gentile 1996, Barnes and Mazzotti 2005) and for designing monitoring and assessment programs (RECOVER 2004). Conceptual ecological models have been instrumental in securing funds for research, monitoring, and assessment studies relevant to the Comprehensive Everglades Restoration Plan (CERP). RBSK has the opportunity to test the use of conceptual ecological models in a system that has not been as extensively or intensively developed or degraded as the Greater Everglades ecosystem and to communicate science and management needs to garner support and funding.

Supported by ecological assessments (CIQRO 1983), the RBSK was established in 1986 by the Mexican Federal Government and is recognized as an International Biosphere Reserve. The goal of the Reserve is to protect flora, fauna, and ecosystems while satisfying needs of the local human population (SEMARNAP 1996). The Reserve is managed by the National Commission for Protected Natural Areas (CONANP). CONANP collaborates with Amigos de Sian Ka'an on management plans for projects within the community, educational campaigns, zoning plans, research, conservation efforts, monitoring, and citizen participation.

The coast of Sian Ka'an is the largest coastal marsh protected in Mexico (Morales 1992). The area is similar to the Everglades, with a small elevational gradient

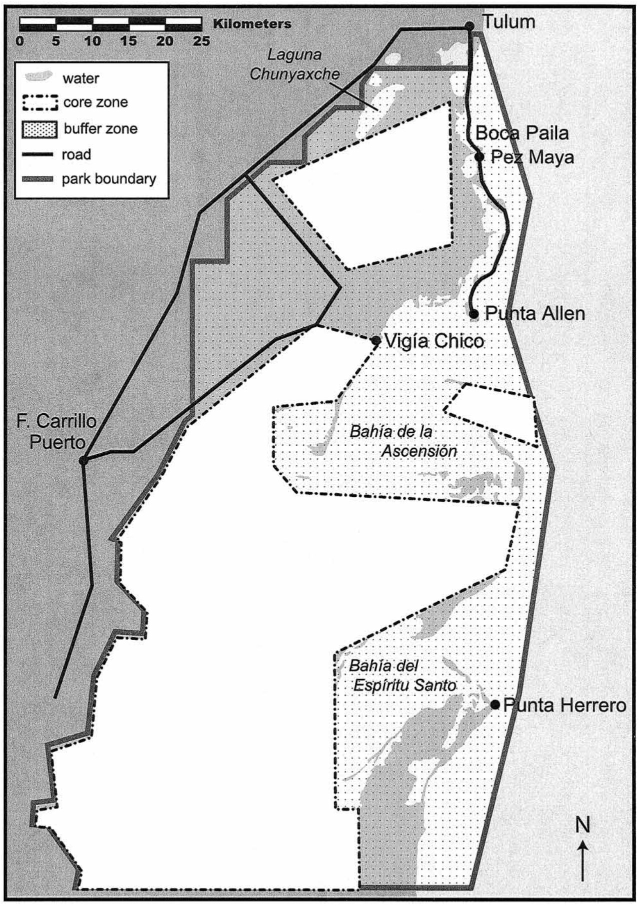

Figure 2. Map of Sian Ka'an Biosphere Reserve depicting the Reserve boundaries, roads, core zones and water bodies.

between forests and coasts leaving some areas dry and some seasonally flooded. Its soils are not conducive to agriculture (CIQRO 1983, López Ornat 1983, Consejo et al. 1987), and while there are no surface rivers, there is an extensive underground river system (SEMARNAP 1996). The RBSK's boundaries are the Caribbean Sea and barrier reef to the east, a mosaic of marshes and semi-evergreen forest in the southeast, and Chetumal Bay and Espiritu Santo Bay Catchment Basin in the south (UNESCO 1996). The northern and western edges are bound by communal properties. Roughly one-third of the area is tropical forest, one-third freshwater and saltwater marshes and mangroves (Olmsted and Duran 1990), and one-third marine and coral reef.

The climate is tropical, with a rainy summer wet season and occasional hurricanes between June and October (CIQRO 1983). In the November to May dry season, 20% of the land remains flooded compared to 75% flooded after rainy seasons (UNESCO 1996). Easterly winds blow almost continuously from May to November, while northerly winds blow during the rest of the year. Annual average rainfall for the area is 1,300 mm; September is the wettest month and March the driest. Rain and subsurface water flow underground to replenish sinkholes, lagoons, and other water sources (SEMARNAP 1996).

As a result of its large size, benign climate, fluctuating hydrology, and heterogeneous habitats, Sian Ka'an is ecologically diverse (Rangel et al. 1993, Pozo de la Tijera and Escobedo Cabrera 1999). The RBSK provides habitat for many threatened and endangered species and many animals with economic value. Vegetation types in the RBSK include medium elevation semi-evergreen forest, medium and low-elevation semi-deciduous forest, low-lying flooded forests, palm savanna, freshwater and saltwater marshes, petenes (tree islands), dwarf mangroves, fringing mangroves, and coastal dunes and keys (Olmsted and Durán 1990).

Biosphere reserves are part of UNESCO's ''Man and the Biosphere'' (MAB) program and are legally protected under Mexican federal laws. The purpose of biosphere reserves is to merge human needs with conservation of natural resources based on sustainable long-term success of inhabitants within and adjacent to biosphere reserves (UNESCO 1974). Key features of biosphere reserves are core zones of complete protection of key resources surrounded by mixed-use buffer zones (Figure 2). Buffer zones are particularly important given the pressures on the RBSK from tourism, and its culturally and archaeologically significant areas (Arreola Muñoz 1989). Historically, indigenous Maya traveled into the reserve area for worship, hunting, food, trade, and medicine (Emory 1989), and the area's small-scale wood harvesting and agriculture has been sustainable for centuries. Since 1983, *ejidos* (communal lands) in Quintana Roo have been cited as one of the few successful community-based, forest-management projects (Argüelles and Armijo 1995, Zabin and Taylor 1997). Traditional practices in RBSK are necessary for both the Reserve and local Mayan communities to thrive.

About 25,000 people live in *ejidos* surrounding the RBSK. Local residents engage in wood, fiber, and chicle extraction, subsistence and illegal hunting, agricultural development, and handicraft production (Amigos de Sian Ka'an 1999). Fishing and tourism are main industries, with forest extraction, cattle, and agriculture supporting the rest of the local community (INE 1993). Around 1000 people live in the Reserve, mainly in two fishing villages: Punta Allen and Punta Herrero (UNESCO 1996). Most of the Reserve is federal land, but 2.66%, primarily along the coast, is privately owned (Bezaury et al. 1996). Fishing (primarily for spiny lobster), involves 70% of the Reserve's residents (Emory 1989).

RBSK can learn from mistakes made in South Florida and can apply the conceptual ecological model to

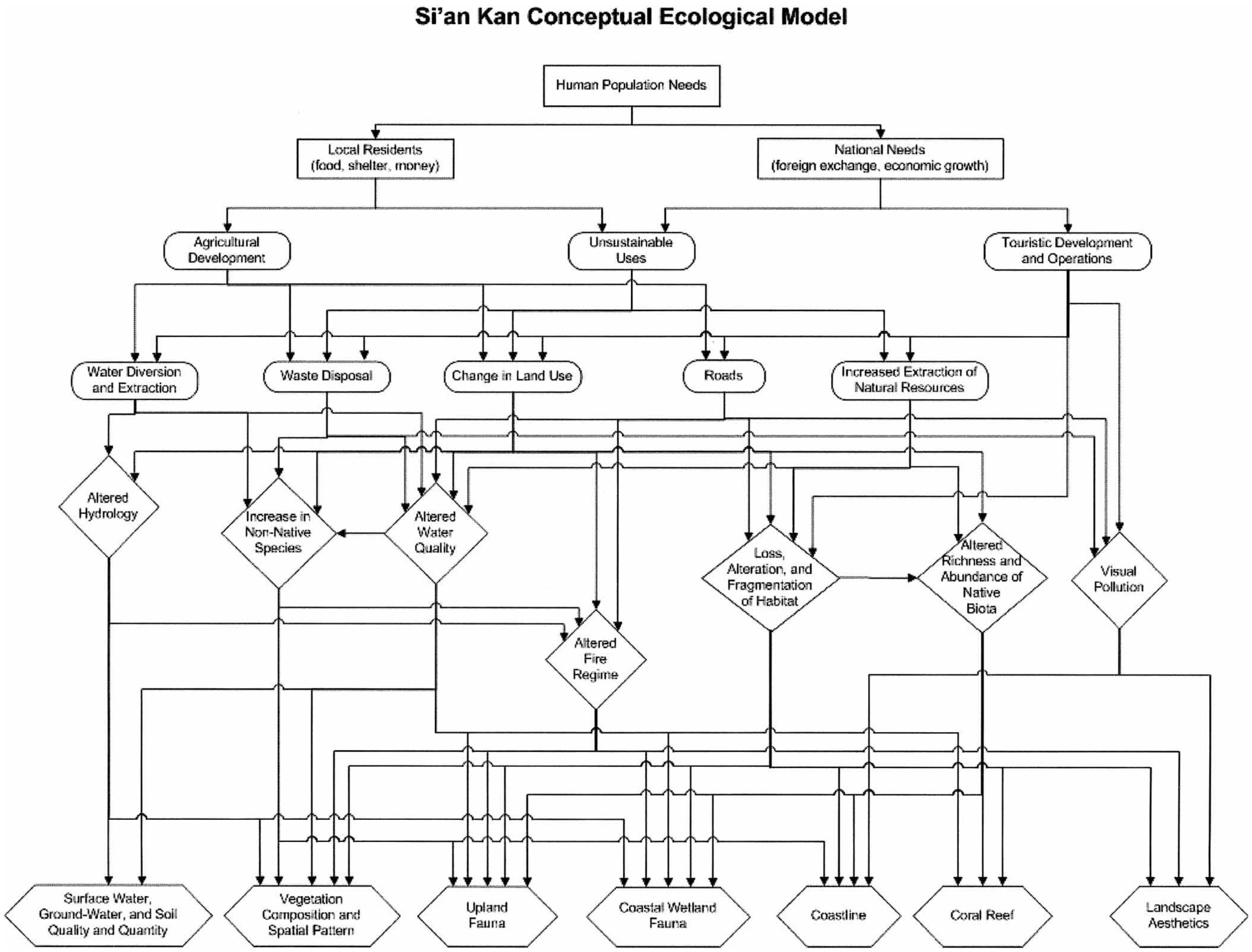

Figure 3. The Sian Ka'an Conceptual Ecological Model.

management, rather than restoration. The Sian Ka'an Conceptual Ecological Model identifies areas for monitoring, research, and management; biological indicators will assess deterioration to minimize damage rather than estimate improvements to guide recovery. The objectives of the Sian Ka'an Conceptual Ecological Model were to 1) collect information on the status of RBSK, 2) develop a consensus on stressors, attributes, and their potential linkages, and to 3) communicate management and science needs.

MODEL CREATION

The process for constructing the conceptual ecological model for the Sian Ka'an Biosphere Reserve (Figure 3) was similar to that of Greater Everglades conceptual ecological models (Ogden et al. 2005). Drivers, stressors, attributes, and effects/linkages were initially identified from workshops with area experts from Amigos de Sian Ka'an (ASK), the National Commission for Protected Natural Areas (CONANP) staff, and other agencies and institutions beginning in November 1999. The model was refined in meetings with individual staff from ASK and CONANP.

DRIVERS

In the Sian Ka'an Conceptual Ecological Model, socio-economic needs result in a local-need driver (food, shelter, money) and a national-need driver (foreign exchange, economic growth). National needs exert pressure through touristic development and operations, and unsustainable resource uses. Local pressures also affect unsustainable uses and agricultural development. Ecological and economic needs must be balanced, and Sian Ka'an must be managed to provide for local people (Price 1996). This balance becomes critical with increasing human population. Local needs are more

Table 1. Tourism Statistics for Riviera Maya.

Year	Tourists	Room Numbers	Room Growth (%)	% of Occupancy
1996	390588	3597	144.7	75.3
1997	434635	4918	36.7	76.2
1998	595050	10095	105.3	77.4
1999	801521	12653	25.3	73.25
2000	1215727	15297	20.9	82.08
2001	1504052	18731	22.4	73.15
2002	1793864	21014	12.2	72.09
2003	2016984	22624	7.7	77
2004	2430371	23512	9.6	86.5
2005	2542000	25906	9	81.6

Source: Fideicomiso para la Promocion Turistica de la Riviera Maya 2004.

easily integrated into environmental protection, and their stress can be alleviated through education and alternative uses. Stressors resulting from national needs (tourist development and foreign exchange) are difficult to manage and alter.

STRESSORS

Stressors were chosen based on early signs of potential negative impacts (tourism) or based on experience from other systems such as the Greater Everglades (water extraction, diversion, and contamination from agricultural and residential development). In the RBSK, internal and external stressors are interrelated and are a function of human population growth and consumption of natural resources. The model lists primary stressors (those caused directly by drivers) and secondary stressors, which are caused by primary stressors. Secondary stressors are discussed with the primary stressor that causes them.

Touristic Development and Operations

Increasing tourism stresses the natural environment and its resources (Hawkins and Roberts 1993, Molina et al. 2001). Guidelines for low-impact tourism in Sian Ka'an (Molina et al. 2001) describe the following negative impacts associated with tourism development: 1) habitat loss, 2) alteration of surface and underground water flow, 3) ground-water pollution, 4) extraction of resources, 5) erosion and sedimentation, 6) decrease in biodiversity, and 7) reduced traditional and recreational use for local communities. Pressure from tourism is evident in Cancun, Tulum, and locations around the RBSK (Table 1). Development requires new infrastructure to host and entertain tourists, more roads leading to more traffic, a reliable water supply, and more land for development. Coastal property in the RBSK is in demand for tourism development; dunes and beaches are valued for their location, recreational opportunities, and real-estate potential. Unplanned development can affect natural functions, biodiversity, and traditional uses of resources (Molina et al. 2001). The Riviera Maya (Cancun, Playa del Carmen, and Tulum) attracts millions of tourists, some of which filter to the RBSK (Table 1). Tourism will increase jobs but will also increase intensity of land use, reduce native vegetation cover, increase sport and commercial fishing, and increase general ecosystem stress (IUCN 2003).

Tourism also increases crime, waste, noise, and traffic (Croall 1995, Costa and Noble 1999). Touristic operations may also degrade the source of income. Wildlife viewers and photographers actively seek and approach wildlife, increasing chances of affecting a species or its habitat. Boats traveling to see flamingos in the Celestun Reserve (Yucatan) disturb flocks by approaching too close (Ceballos Lascurain 1996). Roosts and rookeries of water birds, such as those in Sian Ka'an, are especially vulnerable to disturbance from visitors (Bouton and Frederick 2003). Ecotourism cannot be viewed as a benign, non-consumptive use of land and biological resources, especially in the tropics (Jacobson and Figueroa López 1994).

Agricultural Development

The area around the RBSK is inhabited by Mayans practicing a shifting subsistence ''slash and burn'' type of agriculture (Bosselman 1978, Kiernan 2000). A crop is harvested for a few years before exhausting the soil. A new small tract of forest is then burned and converted to agriculture fields to support the next crop (Bosselman 1978). Mayan farmers cut down small patches for corn fields (*milpas*), typically on secondary forest to grow corn, cabbage, and beans in excess of their needs so wild animals do not deplete the farmers' food. This food increases animal population densities around *milpa* areas. Farmers then have access to animal protein without affecting wild populations (Jorgenson 1993). In a sustainable *milpa* system, each burned site may be used after regrowth, but increasing human populations lead to larger areas burned more frequently (Bartlett 1956, Corner 1960, Brown 1971). Demographic pressure has been diluted by work in tourism areas; however, human population growth may increase land clearing around the RBSK.

Farming and ranching compose 29% of Mexico's land use (SEMARNAT 2001) and may become a significant stressor on the Sian Ka'an Biosphere Reserve with an increase in demand for agricultural production. Similar to the Greater Everglades, hydrology can be altered and habitats lost and fragmented to provide adequate land for agriculture.

Agricultural development and vegetation removal also have allowed non-native species expansion. The coconut palm was introduced for harvest of copra and replaced 60% of the natural fragile vegetation on coastal dunes. However, since the collapse of the copra industry and appearance of lethal-yellowing disease, nearly 65% of the tree population (totaling more than 300,000 trees) has died (Espejel 1983, Arellano Guillermo et al. 2001). The demise of the copra industry left a disturbed coastal area. The coastline was then invaded by Australian pine; however, an Australian pine control program initiated by Amigos de Sian Ka'an and continued over the years by CONANP is allowing the regrowth of coastal dune vegetation.

Unsustainable Uses

Unsustainable uses of natural resources are often associated with fulfilling immediate socio-economic needs within human populations. Poverty increases needs for economic growth, food, fuel, and shelter. Sustainability is often sacrificed to satisfy immediate needs.

The RBSK has experienced stress from unsustainable uses through altered habitats, water and soil contamination, and habitat destruction. Historically, environmental practices, such as fire for agricultural purposes, were conducted on a small scale, making them sustainable. However, settlers in the 1920s who planted dunes and extracted red cedar and mahogany from inland forests were deriving their predominant income from chicle and copra extraction by 1925 (SEMARNAP 1996). In the 1950s, the Mexican government granted a mahogany concession, Industrialized Wood of Quintana Roo (MIQRO), which the government later took over in 1959. This allowed exclusive wood harvesting rights over national and communal lands covering 5,000 km^2. By 1982, 400 km^2 of hardwoods had been harvested (Galletti and Argüelles 1987, Galletti 1989, 1992, 1993, Argüelles and Armijo 1995). The rate and extent of timber extraction around the RBSK continues to be unsustainable (UNESCO 1996).

The species most threatened for overexploitation is the chit palm used to make lobster traps (SEMARNAP 1996). Resource demand has led to its overharvesting in Quintana Roo (Durán 1989, Olmstead and Alvarez Buylla 1995). Many woody species are rapidly being extracted (CIQRO 1983, López Ornat 1983, Consejo et al. 1987). Selected removal has impacted mahogany, red cedar, white cedar, siricote, and several other species of logwood (UNESCO 1996). Only about 15–20% of forests have not been harvested (SEMARNAP 1996). Mahogany continues to be poached from *ejidos* (Kiernan 2000).

Impacts of wildlife extraction have not been quantified but have the potential to degrade natural resources further (Kiernan 2000). Subsistence and market hunting for white-tailed deer, peccary, paca, and other species occur in and around RBSK (Merediz 1995). Extraction of species for pet trade and commercial markets, such as parrots and butterflies, offers an opportunity for sustainable income if managed appropriately (Bodmer 1995, Fa et al. 1995, Cuarón 1997, Gracida 1998).

Inappropriate waste disposal is a major unsustainable use in the RBSK. Human population increases produce greater organic and human waste and other sources of contamination. Sian Ka'an must dispose of wastes without contaminating water supplies or land areas.

ECOLOGICAL ATTRIBUTES

Attributes for the Sian Ka'an Conceptual Ecological Model were chosen for potential linkages with stressors and their economic value or ecological importance or both. Economically important species are either extracted for commercial or subsistence purposes (spiny lobsters and pacas) or are objects of tourism (crocodiles and wading birds). Ecologically important components were chosen on their listed status (endangered crocodiles) or as indicators of ecosystem conditions (wading birds and wetland hydropatterns).

Water Quantity and Quality

Wetlands having surface-water hydroperiods of three to eight months cover a large portion of the RBSK. Similar to the Greater Everglades, Sian Ka'an is an oligotrophic system on a limestone plain sloping toward the coast (Molina et al. 2001). However, different from the Greater Everglades, Sian Ka'an is dominated by marl soils, with no areas of peat formation. Small, inland, freshwater lagoons are supplied with water from rainfall and subterranean aquifers through springs or cenotes. Rainwater in Sian Ka'an drains through a porous, rocky surface into aquifers flowing in a southwest-northeast direction underground. Inland lagoons, marshes, and swamps drain towards the coast through wetlands or small creeks and channels. Near the coast, sea water mixes with inland freshwater and the aquifer in brackish water lagoons, bays, and wetlands. The coastal salinity pattern is very important for healthy populations of lobsters, sport and commercial fishes, manatees, wading birds, and crocodiles.

The sub-surface water supply is critical for ecosystems and humans. Water from the underground aquifer erodes surrounding limestone, eventually causing a cave in, forming sink holes or cenotes. Many cenotes

Table 2. Flora of the Sian Ka'an Biosphere Reserve. Species below are characteristic of the habitats where they are found and are considered ecologically or economically important. Plant communities are from Olmstead and Duran (1990).

Flora	Common Name	Scientific Name	Author
Coastal	red mangrove	*Rhizophora mangle*	Linnaeus
	buttonwood	*Conocarpus erectus*	Linneaus
	white mangrove	*Laguncularia racemosa*	(L.) Gaertn. f.
	black mangrove	*Avicennia germinans*	(L.) Linnaeus
	geiger tree	*Cordia sebestena*	Linnaeus
	sea grape	*Coccoloba uvifera*	(L.) Linnaeus
	chit palm	*Thrinax radiate*	Lodd. Ex J.A. & J.H. Schultes
	bay cedar	*Suriana maritime*	(L.)
	sawgrass	*Cladium jamaicense*	Crantz
	spikerush	*Eleocharis spp.*	
	bayhops	*Ipomoea pes-caprae*	(L.) R. Br.
	cattail	*Typha angustifolia*	Linnaeus
	moon vine	*Ipomoea macrantha*	Roemer & J.A. Schultes
Subperennial forest	breadnut	*Brosimum alicastrum*	Sw.
	sapodilla	*Manilkara zapota*	Linnaeus (van Royen)
	yellow genip	*Talisia olivaeformis*	HBK
	lancewood	*Nectandra coriacea*	(Sw.) Griseb
	drypetes	*Drypetes sp.*	
Semi-evergreen forest	sapodilla	*Manilkara zapota*	(L.) van Royen
	gumbo limbo	*Bursera simaruba*	(L.) Sarg.
	false tamarind	*Lysiloma latisiliquum*	(L.) Benth.
	lancewood	*Nectandra coriacea*	(Sw.) Griseb
	Australian pine	*Casuarina sp.*	
	lignum vitae	*Guaiacum sanctum*	Linnaeus
Semi-deciduous forest	gumbo limbo	*Bursera simaruba*	(L.) Sarg.
	false tamarind	*Lysiloma latisiliquum*	(*L.*) Benth.
	white cedar	*Simarouba glauca*	DC.
	red cedar	*Cedrela odorata*	Linnaeus
	siricote	*Cordia dodecandra*	DC.
	mahogany	*Swietenia macrophylla*	King
	poisonwood	*Metopium browneii*	Jacq.
	sapodilla	*Manilkara zapota*	(L.) van Royen
	black poisonwood	*Metopium brownie*	(L.) Krug & Urb.
	Jamaican dogwood	*Piscidia piscipula*	(L.) Sarg.
	mountain guava	*Psidium sartorianum*	(O. Berg) Nied
Flooded forests	logwood	*Haematoxylum campechianum*	Linnaeus
	black olive	*Bucida spinosa*	Jennings

are connected directly with the aquifer through underground passageways and porous limestone and are the only source of freshwater for some areas (López Ornat 1983). Most of this water is clear (with little algae or plankton) and moves through the limestone aquifer (SEMARNAP 1996). Water salinity varies depending on its distance from the coast and tidal influence (SEMARNAP 1996). Sinkholes are critical refuges for flora, fauna, and aquatic communities, and some have archaeological significance (Molina et al. 2001). Some cenotes have tourist potential as well for swimming, fishing, cave diving, and bird watching (Molina et al. 2001).

Vegetation Composition and Spatial Pattern

Vegetation in Sian Ka'an is diverse, with similarities to South Florida particularly in wetlands and hammocks. Slight variations in topography and hydrologic conditions result in different plant communities. An estimated 1,200 species of vascular plants are found among nine vegetation types, including old and medium growth forests, seasonally inundated lowland forests, grasslands, and mangroves (Olmsted and Durán 1990). The range of aquatic and terrestrial habitats forms a diverse vegetation mosaic (Durán and Olmsted 1990) (Table 2). The RBSK has seasonally flooded forests and completely dry areas with a 15–25 m high, sub-evergreen tropical forest. Red mangroves dominate coastal areas, sawgrass and *Eleocharis* spp. grow in inland marshes, and cattail resides in deeper freshwater pockets.

Fauna

As a result of its large size, diversity of habitats, and unique hydrologic patterns, Sian Ka'an hosts one of the most diverse fauna in all of Mexico (Navarro and Robinson 1990, Navarro and Suárez 1992). About 63% of bird species on the Yucatan Peninsula are found in Sian Ka'an (MacKinnon 2002), 30 species of bats (Juárez and Merediz 1994), and 24% of the 450 terrestrial mammals of Mexico occur in the RBSK (Cervantes et al. 1994). Inventories of vertebrate species can be found in Gaumer (1917), Genoways and Jones (1975), García (1983), Navarro López et al. (1990) and Schmitter Soto (1998). A total of 339 species of birds have been recorded, with many using the Reserve for breeding and/or nesting (Rangel et al. 1993) and are listed in Navarro and Robinson (1990), Navarro and Suárez (1992), and MacKinnon (2002). Faunal attributes are divided into coastal wetland species and upland forest species (Table 3).

Aquatic Fauna. Aquatic fauna in Sian Ka'an are important ecologically and economically. Spiny lobster, conch, tarpon, snook, and bonefish are economically important. Harvesting of spiny lobsters provides the greatest economic income for the RBSK, earning more than one million dollars (US) in exports annually and selling for US $6.99–14.99 per pound in the US market (Tangley 1987, Martín 2003). Both the queen conch and spiny lobster are regulated by closed seasons and capture quotas (Loreto 1999). Protection has increased occurence of manatees, dolphin, and hawksbill, loggerhead, leatherback, and green sea turtles (Hernández 1988). Manatees, sea turtles, water birds, and crocodiles are important species for ecotourism operations.

Upland Fauna. Unlike much of the Greater Everglades ecosystem, Sian Ka'an's upland forest is largely intact, supporting a diverse fauna (SEMARNAP 1996). Five species of cats, many bats, upland forest birds, and three species of parrots live in the Reserve. Parrots became an important and sustainable income source for local communities around Sian Ka'an, as is the case of the *ejido* Tres Reyes (Gracida 1998). Bats and butterflies may be good indicator species for forest health due to their reliance on habitat structure and plant species composition (de la Masa 1989).

Coastline

The coastline of the RBSK is a sensitive and vulnerable ecosystem, ecologically important for its vegetation diversity, critical species habitat, nesting grounds, and structural integrity. Beaches are nesting, feeding, and resting sites for birds, crocodiles, and turtles, and dunes buffer inland developments and habitats against storms and waves. The vegetation mosaic is unique to the coastal area with its combination of plant species from the Caribbean and the Yucatan. It is resilient and adapts to natural catastrophes that frequently occur, like hurricanes (Arellano Guillermo et al. 2001). The coastline also attracts human activities, such as residential and touristic developments, and is often referred to as the ''Turquoise Coast'' (Molina et al. 2001). Salt mining and other activities also affect the ecosystem (Arellano Guillermo et al. 2001).

Coral Reef

The Mesoamerican Barrier Reef System is over 380-km long and is the second largest barrier reef in the world. The reef is a structural attribute that extends from Cancun to the Bay Islands in Honduras (Molina et al. 2001), just 500–1,000 m off shore. It protects the coast by serving as a breakwater to reduce wave action and prevent beach erosion, especially during storms and hurricanes (Loreto 1999, Molina et al. 2001). Reef destruction has led to excessive beach erosion elsewhere (Molina et al. 2001).

The Mesoamerican Barrier Reef System contains more than 50 species of corals, 400 species of fish, and 30 species of sea fans, while 92% of 346 species of reef fish in Mexico are found in the Yucatan (MacKinnon 1994, Coral Cay Conservation Expeditions 2003). Black coral is harvested from the reef for handicrafts and jewelry and has benefitted divers, artisans, and merchants through sales to tourists (Padilla 1999). Harvest sites rotate once the area is exploited, and new colonies take forty years to replenish (Padilla 1999). The lagoon between the reef and the shore greatly adds to the reef's biodiversity. Seagrasses and mangroves growing in the lagoon serve as fish and invertebrate nursery grounds (Molina et al. 2001).

Landscape Aesthetics

Beautiful marine and wetland vistas, spectacular forests, surprising cenotes, stunning wildlife, and peace and tranquility associated with the Sian Ka'an wilderness comprise important aesthetic attributes of the RBSK. The magnificence of the vistas offered by the Reserve is reflected by its name, Sian Ka'an, which in Mayan means ''where the sky is born.'' Aesthetic at-

Table 3. Fauna of the Sian Ka'an Biosphere Reserve. The species below are characteristic of the ecosystems where they are found and are considered ecologically or economically important.

Fauna	Common Name	Scientific Name	Author
Coastal			
Crustacean	spiny lobster	*Panulirus argus*	Latreille
Gastropod	queen conch	*Strombus gigas*	Linnaeus
Fish	tarpon	*Megalops atlanticus*	Valenciennes
	snook	*Centropomus undecimalis*	Bloch
	bonefish	*Albula vulpes*	Linnaeus
	grouper	*Epinephelus* spp.	
		Mycteroperca spp.	
	snapper	*Lutjanus* spp.	
Marine Mammals	manatee	*Trichechus manatus*	Linnaeus
	dolphin	*Tursiops truncatus*	Montagu
Reptiles	hawksbill turtle	*Eretmochelys imbricata*	Linnaeus
	loggerhead turtle	*Caretta caretta*	Linnaeus
	leatherback turtle	*Dermochelys coriacea*	Vandelli
	green sea turtle	*Chelonia mydas*	Linnaeus
	American crocodile	*Crocodylus acutus*	Cuvier
	Morelet's crocodile	*Crocodylus moreleti*	Duméril and Bibron
Water Birds	White ibis	*Eudocimus albus*	Linnaeus
	Roseate spoonbill	*Ajaia ajaja*	Linnaeus
	Jabiru stork	*Jabiru mycteria*	Lichtenstein
	Wood stork	*Mycteria americana*	Linnaeus
	Flamingo	*Phoenicopterus ruber*	Linnaeus
	Reddish egret	*Egretta rufescens*	J. F. Gmelin
	Olivaceous cormorant	*Phalacrocorax olivaceous*	Humboldt
	Great blue heron	*Ardea herodias*	Linnaeus
	Snowy egret	*Egretta thula*	Molina
	White ibis	*Eudocimus albus*	Linnaeus
	Frigatebird	*Fregata magnificens*	Mathews
	Brown pelican	*Pelecanus occidentalis*	Linnaeus
	Osprey	*Pandion haliaetus*	Linnaeus
	Boatbill heron	*Cochlearius cochlearius*	Linnaeus
	Bare-throated tiger heron	*Tigrisoma mexicanum*	Swainson
Upland Fauna			
Mammals	jaguar	*Panthera onca*	Linnaeus
	puma	*Felis concolor*	Linnaeus
	ocelot	*Felis pardalis*	Linnaeus
	margary	*Felis wiedii*	(K) Schinz
	jaguarondi	*Felis yagouaroundi*	Berlandier
	Baird's tapir	*Tapirus bairdii*	Gill
	spider monkey	*Ateles geoffroyti*	Kuhl
	howler monkey	*Alouatta pigra*	Lawrence
	white-tailed deer	*Odocoileus virginianus*	Zimmermann
	paca	*Agouti paca*	Linnaeus
	possum	*Marmos mexicana*	Merriam
	peccary	*Tayassu tajacu*	Linnaeus
	yellow-shouldered bat	*Sturnira lilium*	Anthony
	fruit-eating bat	*Artibeus jamaicensis*	Leach
	yellow bat	*Lasiurus intermedius*	H. Allen
	vampire bat	*Desmodus rotundus*	E. Geoffroy
	tent-making bat	*Uroderma bilobatum*	Peters
	wrinkle-face bat	*Centurio senex*	Gray

Table 3. Continued.

Fauna	Common Name	Scientific Name	Author
Forest Birds	Ocellated turkey	*Meleagris ocellata*	Cuvier
	Great curassow	*Crax rubra*	Linnaeus
	Toucan	*Rapmhastos sulfuratus*	Lesson
	King vulture	*Sarcoramphus papa*	Linnaeus
	White-fronted parrot	*Amazona albifrons*	Sparrman
	Yucatán parrot	*Amazona xantholora*	Gray
	Olive throated parakeet	*Aratinga nana*	Vigors
Butterflies	blue morpho	*Morpho peleides*	Kollar
	kite-swallowtail	*Protesilaus philolaus*	Boisduval
	apricot sulphur	*Phoebis argante*	Frabricius

tributes are a big reason tourists come to Sian Ka'an. Ironically, these same attributes are very vulnerable to increasing tourist activity (Molina et al. 2001).

ECOLOGICAL EFFECTS: CRITICAL LINKAGES BETWEEN STRESSORS AND ATTRIBUTES/ WORKING HYPOTHESES

Effects and linkages are described as hypotheses for connecting stressors to attributes in the conceptual ecological model (Figure 3). Although there is anecdotal evidence that ecosystems in Sian Ka'an are beginning to respond to stress, there are few baseline data against which to measure effects. Responses are not being adequately quantified by inventory, monitoring, and research programs.

Increase in Non-Native Species

Both intended and unintended introductions of non-native species of plants and animals can alter structure and composition of biotic communities and can alter fire regimes (FDEP 1994; Figure 3). Although the RBSK has not reached the same level of damage from non-native species invasion as the Greater Everglades, similar habitat, hydrology, and water-quality alteration increase the vulnerability of the RBSK. Both the RBSK and the Greater Everglades suffer from Australian pine invasion because of its ability to adapt to coastal environments and its lack of natural competition. In 1993, 70% of beaches and mangroves along the RBSK were invaded by Australian pine (Alfredo Arellano Guillermo pers. comm.). Plant-removal techniques of cutting and herbiciding, as used in the Greater Everglades, are ridding the Reserve of Australian pine (Arellano Guillermo pers. comm.). Feral cats and dogs are also problems in the Reserve, eating turtle eggs, spreading diseases, and possibly eating birds (Comunicado SK 2000). Two exotic fish species have been confirmed in Quintana Roo: tilapia Mozambique (*Oreochromis mossambicus*, Peters) and tilapia del Nilo (*Oreochromis niloticus*, L.), but so far, none have been found the the Reserve (Gonzalo Merediz pers. obs.).

Altered Hydrology

Hydropatterns. Changing water levels, periods of inundation, and flow rates can alter a landscape, as evidenced in the Greater Everglades ecosystem (Davis and Ogden 1994). Water management affects water and soil quantity and quality, alters ecosystems locally and regionally, and alters nutrient and material transports (Committee on Selected Biological Problems in the Humid Tropics 1982). This affects species composition and ecosystems processes. Shorter hydroperiods and lower ground-water levels alter fire regime, species composition, and spatial patterns of plant communities (Davis and Ogden 1994, SCT 2003). Sian Ka'an has yet to experience obvious direct effects from altered hydrology on depth and period of inundation (hydropattern) of wetland habitats or on ground-water levels. Continued extraction of water in and around the Reserve, coupled with water diversions for agriculture or by roads, will have increasingly negative impacts. Exploitation of freshwater shifts the equilibrium of fresh and saltwater located near coastal areas and allows saltwater to invade aquifers, contaminating freshwater supplies and altering salinity patterns (Molina et al. 2001).

Water Quality. Vegetation removal for development or agriculture can contaminate water and alter sediment composition (Clarke 1966, Spencer 1966, Walter 1971). Vegetation serves as a buffer for trapping sediments and filtering water (Bennett 1935, Molina et al. 2001). Removing vegetation leads to increased erosion, destroys habitat, and facilitates spread of non-native species (Molina et al. 2001).

Water can be contaminated by runoff from roads, boat operations, agriculture, or human waste, thereby affecting water quality for human consumption, recreation, and fishing. Inappropriate waste disposal contaminates water and soil, reduces landscape aesthetics, and alters species composition. Ground water is the sole source of drinking water in RBSK. The city of Felipe Carrillo Puerto is within the same hydrographic basin as the Reserve, and its wastes (domestic, industrial, and agricultural) filter into the aquifer (UNESCO 1996), affecting water quality for the entire region. Only 2% of Carrillo Puerto's wastewater is treated in some way (Comisión de Agua Potable y Alcantarillado de Quintana Roo 2004).

Sian Ka'an has urgent needs for sewage disposal and urban-growth planning (Thorsell and Sigaty 1998). UNESCO (1996) reports that wastewater is being discharged directly into the ocean along the Caribbean coast of the Yucatan. Artificial wetlands and composting toilets in several villages along the Mexican Caribbean are improving wastewater discharge (Lang et al. 1998); however, oil, petrol, and inorganic or organic wastes dumped or spilled from tourist boats also pollute water (Hunter and Green 1995). Insufficiently treated water can contaminate water bodies with nutrients and bacteria and alter pH levels, leading to eutrophication. Nichupte Lagoon in Cancun is currently addressing inadequately treated wastewater resulting in eutrophication (Molina et al. 2001). Porewater toxicity tests off the Mayan Reef revealed toxic sediments (Nipper 2001). Contaminants affecting drinking water (Molina et al. 2001) can originate from landfills (Pye and Patrick 1983), which are quickly filling with little attention being paid to appropriate design and construction.

Altered Fire Regime

Fire originates from two main sources in RBSK: natural fires from lightning strikes and man-made fires from agricultural or hunting activities. Natural fires burn in the wet season and tend to be less damaging than man-made fires set in the dry season, particularly in exceptionally dry years (Griffith 2000). A road through a natural area not only provides an artificial fire break, but it alters spatial and temporal pattern of inundation, creating wetter and drier areas that are more or less prone to fire than in natural wetland areas. Water extraction can lower ground-water levels, altering inundation period. In systems like RBSK and the Greater Everglades where ground water and surface water are connected, lowered ground-water levels result in shorter surface hydroperiods, increasing vulnerability to natural and man-made fires. Altered fire regime can cause changes in vegetation composition and spatial pattern, affect coastal and upland fauna, and decrease the landscape aesthetics (FDEP 1994).

Loss, Alteration and Fragmentation of Habitat

Tourism Infrastructure Destroys Habitats. Although Sian Ka'an is ''preserved,'' Cancun, Playa del Carmen, and tourist regions north of the Reserve are growing at rates of 20–25% per year, converting kilometers of sandy beaches and square kilometers of mangrove wetland, coastal dune vegetation, and tropical forest habitat (Table 3) (Stewart 1990). Cancun has more than 400,000 people, and its beaches are lined with over 27,522 hotel rooms (INEGI 2000, Secretaría de Turismo 2004). Development of the area gave little attention to environmental impacts as the coastal region, formerly filled with mangrove wetlands and tropical forest, was totally transformed (Bosselmann 1978). In 1972, two areas were designated ''wildlife sanctuaries'' but were quickly developed into hotels (Bosselman 1978). This could occur around the borders of Sian Ka'an and on private land along the coast.

Tourism development around the RBSK has already affected small-scale changes in the ecosystem: water extraction and saltwater intrusion, development of coastal dunes and mangrove swamps, damage to reefs, and dumping of sewage into wetlands (Molina et al. 2001). Explosive coastal tourism growth threatens the coral reef (Lang et al. 1998). Neotropical migrant bird numbers have decreased with deforestation (Robbins et al. 1989). An increase in tourism development and touristic operation leading to loss and alteration of habitat affects every biological attribute.

Most tourism development is planned for the coastline between Cancun and Tulum, south of the RBSK near Majahual, and in private inholdings in the Reserve. Developers clear dune vegetation for land development. This facilitates invasion by non-native plants, results in sand erosion, and exposes developed sites to strong winds and tides during storms (Molina Islas and Sánchez 1996). Beach erosion has been a serious problem in the area (Molina Islas and Sánchez 1996), worrying both land owners and tour operators. In some locations, dunes have been replaced with man-made structures such as seawalls, which may not withstand hurricane conditions (Molina et al. 2001). Increase in tourism and development reduces nesting habitat on the Yucatan coastline for animals like the loggerhead turtle (Tellez and Muñoz 1996) and shore and wading birds (Klein et al. 1995, Bouton and Frederick 2003). Sea turtles are now endangered largely due to overexploitation and habitat alteration of nesting beaches (Hernández 1988). Poaching, animal predation, and lights and activities from beachfront resorts have impacted turtles negatively (Emory 1989).

The Mesoamerican Barrier Reef System also is affected by the tourism industry from nutrient pollution, sedimentation, traffic, boat groundings, and overharvesting of reef resources (Lang et al. 1998, Walker et al. 2004). Stony corals and reef fish stocks have been reduced, and snorkeling and scuba-trip effects are multiplying (Lang et al. 1998). This is not unique, as 25 of 30 Caribbean countries report that tourism factors into reef deterioration, largely from anchoring and uneducated divers (MacKinnon 1994). The tourism industry also conflicts with the local human population because of differing attitudes and uses (MacKinnon 1994).

The reef is vulnerable to changes in water quality (Lang et al. 1998). Reefs near cities, tourist resorts, agricultural fields, or marinas suffer from a high concentration of sediments, nutrients, and pesticide pollutants (Lang et al. 1998). Tourism infrastructure also requires dredging waters and other coastal activities, which can negatively impact reefs (Dollar 1982, Grigg 1994, Muthiga and McClanahan 1997). Reefs north of the Yucatan have low coral cover (17%), and coral disease is common (Walker et al. 2004). Boats also damage reefs either with chemical pollutants or physical groundings (Lang et al. 1998, Walker et al. 2004).

Agricultural Development Alters Habitat. Agricultural development also alters and fragments critical habitats. Poor soils in Quintana Roo require large areas of cleared land combined with pesticides, herbicides, and fertilizers for successful agriculture (CIQRO 1983, López Ornat 1983, Consejo et al. 1987). Residents destroy forest and wetland habitat to provide agricultural plots, increasing erosion, disrupting habitat, fragmenting the landscape, and destroying landscape aesthetics. Fire is the preferred method by which farmers remove the forest, which frequently destroys more habitat than intended (Griffith 2000).

Roads Fragment Habitat. Only one improved road enters the RBSK, running from Felipe Carrillo Puerto to Vigia Chico, with boat access to Punta Allen (SEMARNAP 1996). It was constructed in 1955 to transport chicle to the port of Vigia Chico. Effects of the road are limited due to few trails branching off the road, although about 0.4 km^2 of red mangrove were destroyed by deposition of spoil. An unimproved road connects this road to Chunyaxche, and unimproved roads connect Tulum with Punta Allen and Majahual with Punta Herrero.

Altered Richness and Abundance of Native Biota

Resource exploitation impacts many species within the RBSK. Mexico's 100 varieties of palms have played a critical cultural role in house construction, artisan products, food, and oil, and although the chit palm is an endangered species, it continues to be exploited. The Technical Advisory Committee of Sian Ka'an instituted a ban on harvesting chit palms in the Reserve, and lobster traps are now made of concrete as a result.

Overconsumption is often correlated with fishing practices since many commercial species are vulnerable to overfishing. Overexploitation of high trophic level fish has impacted fish community structures (Russ 1991). Black coral, queen conch, fish, and sea turtles are illegally captured (Lang et al. 1998). Only queen conch and lobsters are regulated (Basurto 1997). The queen conch population was prominant in the 1970s (de la Torre 1984) but has disappeared in some areas (de Jesús Navarrete 2001). The annual lobster catch was consistent in Quintana Roo from 1990 to 2001 (average 570,000 kilograms/year), decreasing from the average of 1,000,000 kilograms/year during 1982–1989 (Aguilar et al. 2003).

Areas without regulations are exposed to constant exploitation (Domínguez Viveros et al. 1992), and illegal extraction continues in spite of regulations (Navarrete et al. 2000). Over the last ten years, conservationists have attempted to alter both location and practices of local fishermen to preserve conch and lobster populations. The National Fisheries Secretariat (SEPESCA) attempted to ban hooks in spiny lobster harvests to protect egg-bearing females and smaller lobsters. Current regulations consist of catch quotas, minimum harvest size (20 cm in length), a November 1–April 30 closed season, and limited entry regimes (Basurto 1997). Although most extraction is done by cooperative fisheries, independent fishermen continue to hunt without permits, frequently using more damaging techniques (Basurto 1997). Black coral is also being harvested at an unsustainable rate, and if methods continue, the supply and livelihood associated with it will be destroyed (Padilla 1999).

Overconsumption also applies to illegal or legal hunting and the pet trade. Subsistence hunting is still important in areas around the RBSK (Robinson and Redford 1991, Fitzgibbon et al. 1995), and wildlife is often exploited for commercial uses (Bodmer 1995, Fa et al. 1995, Cuarón 1997). Illegal animal trade is detrimental to the environment by reducing numbers of animals, thereby impacting genetic diversity, reproductive success, and altering species composition. Female monkeys are hunted to capture young, disrupting the social structure of the group (Navarro 1990). The jaguar population was formerly found throughout southeastern Mexico, but the population has been intensely hunted for furs and cubs sold on the illegal pet market (Ojeda Capella and Gutiérrez 1990). Fortunately, the existence of few roads limits accessibility to the RBSK and inhibits hunting and forest extraction by local people (SEMARNAP 1996).

Visual Pollution

Visual pollution occurs when unwanted objects (e.g., vehicles, structures, other people, boats, litter) clutter the landscape. Although trash is an obvious example, in Sian Ka'an ''Jeep Safaris,'' (caravans of 10 to 20 small convertible sports utility vehicles) travel through the RBSK on ''eco-adventure'' trips. Ecotourism-based boat traffic is also increasing in the Reserve, with three or four boats where few were ever seen only five years ago (Mazzotti personal observation).

MANAGEMENT AND SCIENCE NEEDS

Due to its complexity and magnitude, awareness of Sian Ka'an's ecosystem degradation must be widely appreciated to garner support for science and management (Molina et al. 2001). Because the Sian Ka'an Conceptual Ecological Model is a model for conservation rather than restoration, working hypotheses and linkages reflect what we think may happen instead of causal linkages explaining what happened. Inventories to establish baseline levels and processes must be done before impacts occur and monitoring will be needed to quantify impacts as they become evident. A research program can be designed before impacts become evident to determine cause. Modeling can be used to forecast impacts. A conceptual ecological model can be an important tool to prioritize these needs. Consequently, this model should be considered an *a priori* model to illustrate how the ecosystem may be affected by local and national human population needs. The Sian Ka'an Conceptual Ecological Model can communicate and garner support for planning, management, and science needed to maintain and improve ecological condition of the RBSK.

Comparable to the Greater Everglades Ecoystem Conceptual Ecological Model (Ogden et al. 2005), the conceptual ecological model of the Sian Ka'an Biosphere Reserve covers a large area, with a variety of habitats ranging from interior to coastal. In the Sian Ka'an model, stressors are driven directly by human needs. Natural impacts, such as sea-level rise and climate change, are important but were not considered in the Sian Ka'an model because they are disturbances within the system. This model addresses effects of human activities as they are likely to show a more immediate impact on the ecosystem and are amendable to planning and management. The role of hurricanes, fires, and especially sea-level rise on structuring communities of Sian Ka'an should be evaluated through research and modeling. Sian Ka'an is as vulnerable to sea-level rise as the Greater Everglades. Changes in shoreline, shifting of habitat locations, and alterations of salinity regimes can be anticipated (Wanless et al. 1994, Twilley et al. 2001, Scavia et al. 2002). Modeling temporal and spatial patterns of sea-level rise in Sian Ka'an ecosystems should be a top priority.

In Sian Ka'an, ecosystem management is people management. Community-based, natural-resource management programs engage local Mayan communities to preserve cultural and natural resources and promote sustainable use to provide social and economic benefits for current and future generations. There are two fishing cooperatives within the Reserve (Punta Herrero and Punta Allen) and three cooperatives outside the Reserve that fish along the Reserve's coastline (Basurto Origel and Zárate Becerra 1991). Independent commercial fishermen also fish within the Reserve (Basurto Origel and Zárate Becerra 1991). Sport fishing has increased with the establishment of fishing resorts and camps at Club Boca Paila and Casa Blanca Fishing Lodge (Basurto Origel and Zárate Becerra 1991). Four cooperatives offer sport fishing guide services in Bahia de la Ascension (Amigos de Sian Ka'an 2001).

The Tres Reyes *ejido*, neighboring RBSK, participated in a population study of parrots on their land. Results were presented to federal environmental authorities who subsequently authorized a parrot-harvesting quota for the *ejido*. Tres Reyes sustainably and legally harvests parrots, selling them at a price 50 times higher than before the project started, which preserves the forest where parrots reproduce. Arguably more successful is the development of local ecotourism cooperatives that organized to receive support and training from ASK, CONANP, and others. Today, ecotourism is a real and profitable business for local people. Ecotourism has encouraged local people to learn more about ecosystems and actively participate in its conservation. Five cooperatives offer ecotours in the Reserve (Amigos de Sian Ka'an 2001). Other examples are making furniture and handicrafts from local timber and nature-based embroideries by women.

Continuing and adapting Mayan traditions of sustainable use of natural resources is an easier goal than meeting national needs for economic growth and foreign exchange. A suite of environmental policy tools, such as decrees for establishment of additional protected areas, specific management programs, conservation easements, and zoning, will be needed for conservation and proper use of natural resources. Integrated resource-management programs should be based on science and should implement low-impact practices for tourism and for resource extraction such as fisheries. Recently, the state and federal governments published a unique Ecological Land Use Management Plan for the coast of Sian Ka'an Biosphere Reserve (POQROO 2002), originally designed by

ASK. It regulates land use on private proprieties inside the Reserve. Thanks to this environmental policy tool, Sian Ka'an is the first protected area in Mexico to combine regulatory controls with innovative mechanisms (transfer of development rights and environmental easements) to achieve important conservation objectives balanced with controlled development on public and private lands.

Private land conservation will be an important component of an integrated resource management plan. Sites should be preserved for exceptional biodiversity or strategic location through conservation easements or acquisition of private and communal lands. ASK is now integrating conservation of public and private lands. In November 2004, the federal government established the eighth protected area proposed by ASK: the Bala'an K'aax Flora and Fauna Protection Area. While protecting forested public lands critical for water catchment for the RBSK (150 km away), it also promotes the participation of neighboring *ejidos* in the sustainable use of their natural resources. ASK also purchased a 0.26 km^2 coastal property within the RBSK, Pez Maya, to guarantee long-term conservation of 3 km of beach and dunes, while implementing and promoting the Zoning Plan through developing conservation easements, and negotiating development rights from other properties to freeze them, reducing development densities along the coast of the RBSK. The Environmental Zoning Plan (EZP) banned development on 28% of the Reserve's coastline and limits hotel and vacation-home construction on the remaining 102 km of coastline. Homes are forbidden within 100 m of oceanfront, and the predicted ''balanced development'' is 450 homes (around four homes per km of coastline) and 750 hotel rooms (around nine rooms per km of coastline) (Bezuary Creel 2002).

Good management decisions are based on sound science. A high priority for RBSK should be to set up an inventory and monitoring program, to establish baseline conditions, and to detect changes in the status of resources. In Sian Ka'an, inventory and monitoring programs are much more developed for coastal and wetland resources than they are for either terrestrial systems or hydrology and water quality.

A coral-reef monitoring program was initiated in the RBSK in 1992 (Gutiérrez and Bezaury 1993). Currently, monitoring is linked with more regional efforts based on the Mesoamerican Barrier Reef System program and methods. So far, no significant changes in the reef community structure have been found (Loreto 2002). However, this 12-year baseline data set will be valuable for assessing future impacts to the coral reef from increasing coastal and tourism development. Adding monitoring grouper and snapper populations could aid ability to detect changes in reef ecosystem integrity (Ault et al. 2005).

Long-term surveys of crocodile population have been a major monitoring component of wetland systems in the RBSK since 1989 (Lazcano Barrero 1990). These studies have shown the possibility of combining conservation of crocodiles and their habitat while generating income for local people through ecotourism (Merediz 1999). The information gathered has been important for management of freshwater and brackish-water wetlands. For example, in coastal lagoons, primary habitat for the more endangered American crocodile, data will provide a basis for regulating sport-fishing activities and coastal development. Crocodile monitoring has been successfully linked with scientific tourism; international visitors participate in field work, assist researchers, obtain a lifetime experience, and contribute a fee to fund future monitoring efforts. In addition, monitoring in Sian Ka'an wetlands has involved annual aerial wading bird and manatee surveys and surveys of lobster catches and visitor use.

Some preliminary work has been done on inventorying upland species. ASK has baseline data on bat species composition and abundance with levels of forest disturbance. Lists of butterfly and bird species have been compiled, and preliminary surveys have been conducted for amphibians, parrots, and peccaries. Although no monitoring programs similar to those for coral reefs or crocodiles have been created, a bird-monitoring program has been initiated by ASK and CONANP, as well as vegetation-cover changes, specifically in the coastal areas. These baseline data will be important for species sensitive to changes in structure and composition of forests, such as bats and butterflies, or those that are exploited, such as pacas, peccaries, or parrots. Structure and composition of forests should be monitored directly to detect changes caused by activities such as timber extraction. Vegetation monitoring also should occur at the landscape level, using maps of land use/land cover to detect changes caused by fire, hurricanes, and changes in hydrology. Socio-economic aspects of environmental management should also be monitored in Sian Ka'an, especially activities related to fisheries and ecotourism.

One lesson learned from the Greater Everglades experience is that, in a system such as Sian Ka'an, changes in hydrology and water quality can have dramatic effects on ecosystem structure and function (Davis and Ogden 1994). A network of hydrologic and water-quality sampling stations synoptic with other components of a monitoring program is imperative. This will facilitate development of causal hypotheses linking changes that may be detected in biological and hydrologic components of the ecosystem. Preliminary water-monitoring efforts are taking place in Sian

Ka'an and its surroundings. Water issues are becoming a critical priority for Quintana Roo and Sian Ka'an in particular.

Monitoring reveals what is happening, but it does not explain why. A research component is needed to determine causes of ecosystem changes. Information on effects of hydrologic changes on wading birds or water quality on coral reefs can be applied to management decisions to eliminate or reduce adverse impacts. The earlier changes are detected and causal relationships determined, the easier and cheaper the remedy.

Models can be developed with research and monitoring data to understand, forecast, and communicate impacts of human activities on valued ecosystems better. Conceptual ecological models, as used here, are effective in helping to understand and communicate important ecosystem components and linkages. With additional research and monitoring, forecasting models can be developed to understand and communicate better the potential impacts from increased development pressure within and around the RBSK and the potential for interaction of natural and human-induced changes to Reserve. Modeling results can also be applied to management decisions to limit adverse impacts. An important lesson to be learned is that successful science application can manage ecosystems instead of restoring them.

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