ATOLL RESEARCH BULLETIN

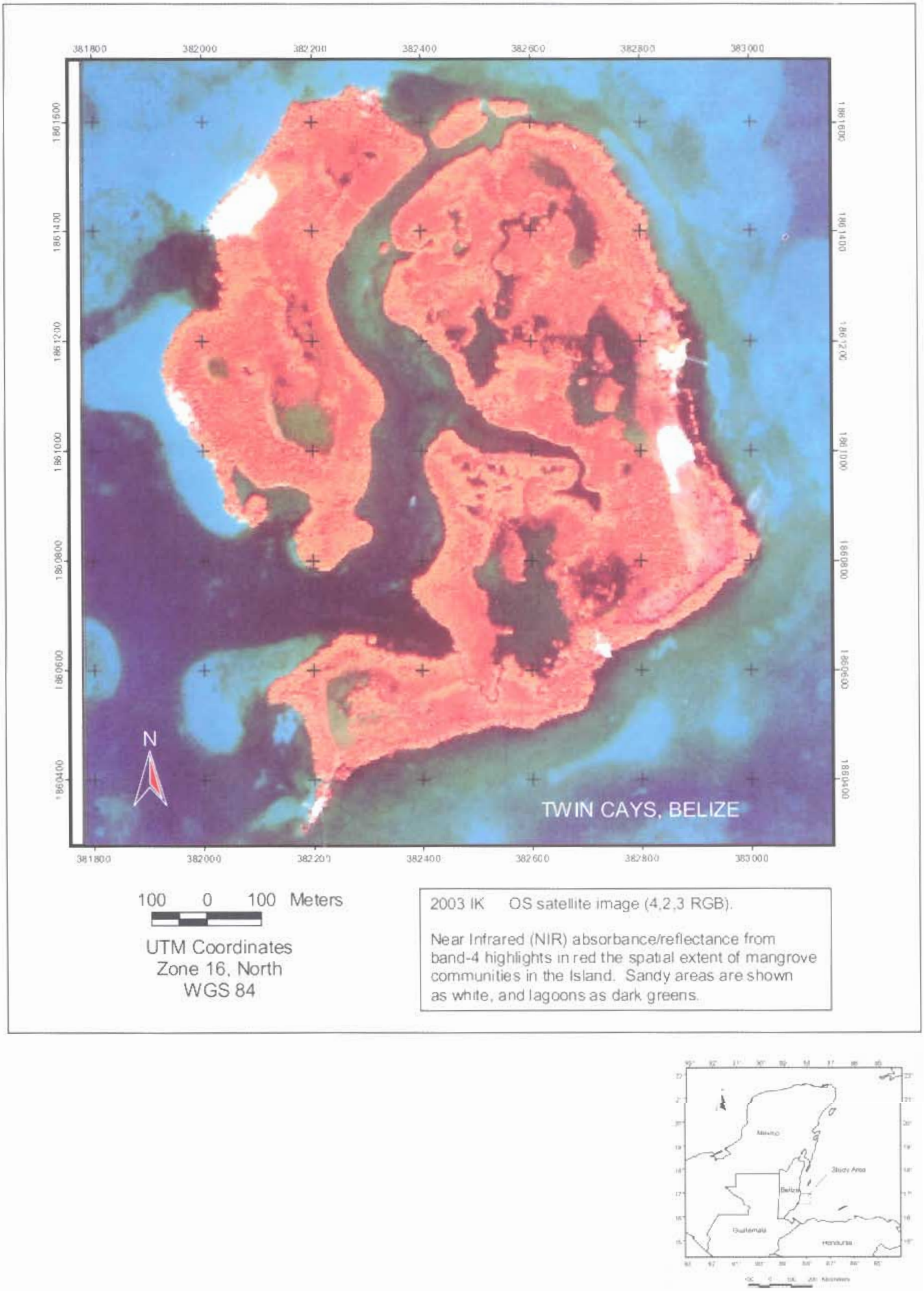
NO. 513

MANGROVE LANDSCAPE CHARACTERIZATION AND CHANGE IN TWIN CAYS, BELIZE USING AERIAL PHOTOGRAPHY AND IKONOS SATELLITE DATA

BY

WILFRED RODRIGUEZ AND ILKA C. FELLER

ISSUED BY
NATIONAL MUSEUM OF NATURAL HISTORY
SMITHSONIAN INSTITUTION
WASHINGTON, D.C., U.S.A.
SEPTEMBER 2004



2003 IKONOS satellite image (4,2,3 RGB).

Near Infrared (NIR) absorbance/reflectance from band-4 highlights in red the spatial extent of mangrove communities in the Island. Sandy areas are shown as white, and lagoons as dark greens.

Figure 1. Twin Cays archipelago as imaged from IKONOS-2 December 16, 2003.

MANGROVE LANDSCAPE CHARACTERIZATION AND CHANGE IN TWIN CAYS, BELIZE USING AERIAL PHOTOGRAPHY AND IKONOS SATELLITE DATA

BY

WILFRID RODRIGUEZ[1] AND ILKA C. FELLER[1]

ABSTRACT

We used aerial black-and-white and color photography, in conjunction with multispectral IKONOS satellite imagery, to classify mangrove vegetation and to characterize the spatial distribution of deforestation from 1986 to 2003 at Twin Cays, an intertidal mangrove archipelago located in the Mesoamerican Barrier Reef ecosystem in Belize, Central America. The classification map consists of seven classes and 29 subclasses that reflect the present (up to 2003) condition of mangrove forests (e.g., species, growth status, and deforestation) in the island. Land cover change analysis during this 15-year period showed a 52% increase in deforestation of mangrove communities across the archipelago, the creation of numerous survey lines, and the disappearance of parts of the fringe zone. The vegetation map presented in this study will help us develop spatial relationships at the plot and landscape scales between mangrove growth patterns and biogeochemical, nutrient cycling processes, and hydrological data in follow up studies. Our results could also be used by natural resource managers as a decision-making tool for sustainable management of mangrove tropical ecosystems in the Caribbean and other regions.

INTRODUCTION

The ecological importance of mangrove forests in tropical areas has long been recognized (Chapman, 1969; Blasco, 1988 a,b). Mangrove forests are a characteristic feature of coastal shorelines and reef ecosystems of the tropics and subtropics; their root systems (prop roots and pneumatophores) stabilize the sediment, dampen wave energy, provide habitat and shelter for numerous organisms, and form the base of the nearshore marine foodweb (Vicente et al., 1993).

A partial regional inventory (Snedaker, 1993) estimated that the five species (*Avicennia germinans* L. Stearn, *Cornocarpus erectus* L., *Laguncularia racemosa* L., *Gaertn.* F., *Pelliciera rhizophorae* Triana and Planchon, and *Rhizophora mangle* L.) that form the mangrove flora of the Intra-Americas Sea occupy an area of approximately 3.2 million hectares or ~15% of an estimated total world area of mangroves of 22 million hectares. Snedaker (1993) also showed that in Belize, island and land area of mangrove forests has been estimated as 75,000 ha (Fisheries Unit Laboratory, Belize City), 100,000

---

[1] Smithsonian Environmental Research Center, PO Box 28, Edgewater, MD 21037

ha (Klaus Rützler, Smithsonian Institution, Washington), and 244,000 ha (Oscar Rosado, Ministry of Natural Resources, Belmopan).

In Central America and the Caribbean, deforestation practices for farming and development purposes have been the direct cause of destruction of mangrove communities (Ibrahim and Hashim, 1990; Ramirez-Garcia et al., 1998; Chauvaud et al., 2001; Sanchez-Azofeifa et al., 2003). Clearing of mangrove forests continues up to the present throughout the tropics, and it is especially worrisome when it happens in peat-based islands like Twin Cays (Macintyre et al., 1995) along the Belizean reef system. With that type of geomorphology human pressures to develop the landscape would only bring rapid ecological degradation.

In the Mesoamerican Barrier Reef ecosystem along the Belize coast, research carried out over approximately two decades has focused on the biodiversity, nutrient cycling, biogeochemistry, and sensitivity of mangrove forests existing in tidal islands like Twin Cays (e.g., Feller, 1995; Rützler and Feller, 1996; McKee et al., 2002; Feller et al., 2003 a,b,c). Woodroffe (1995) conducted a vegetation classification of Twin Cays based on seven categories of land cover (e.g., unvegetated flat, *Rhizophora* scrub, *Rhizophora* thicket, *Rhizophora* woodland, *Avicennia* woodland, *Avicennia* open woodland with *Rhizophora* scrub, and dead *Rhizophora*). His classification was an important first step but it was not detailed enough to discriminate mangrove status in relation to hydrology, nutrient availability, and disturbance. Characterization and quantification of the spatial heterogeneity of these processes are needed to understand the history of mangrove growth and to predict the impact of future landscape changes to these sensitive ecosystems.

As our understanding of a number of ecological processes (i.e., nutrient cycling, hydrology) in island mangrove forests in the Caribbean evolves, there is a need for an accurate and detailed characterization and monitoring of land use/cover status, and land-cover change. Land use refers to human influences and productive aspects of the landscape, while land cover describes the biophysical attributes of the surface. Land cover is a fundamental parameter that provides a descriptive definition of the biomes present at a location. It is regarded as the most important aspect of global change affecting ecological systems (Vitousek, 1994). Land cover also has significant effects on basic ecological processes, including biogeochemical cycling, global warming (Skole and Tucker, 1993; Penner, 1994) and soil erosion, which affects land use sustainability (Douglas, 1999). Land cover is also estimated to be the most important variable affecting biodiversity (Chapin et al., 2000; August et al., 2002). Human induced land-cover changes are significant and are more relevant to change detection than natural causes (Running et al., 1999).

Use of remotely sensed data has been fundamental in the quantification of land-cover at different scales. The recent deployment of satellite sensors such as IKONOS (Space Imagining Corp., Thornton, CO, USA) launched in 1999 provides the finest spatial resolution publicly available from space – 1-m panchromatic and 4-m multispectral (blue, green, red, and near-infrared (Table 1)) – with high radiometric fidelity and geometric accuracy (Dial et al., 2003; Zanoni and Goward, 2003). The ease of its integration with other geographical digital data (i.e., aerial photography) within a Geographic Information System (GIS) presents an ideal platform to advance study of the biocomplexity of mangrove communities in the Caribbean. Classification of tropical ecosystems using high-resolution, remotely-sensed images is a cost-effective method to update and quantify land-cover distributional patterns and spatio-temporal changes in island ecosystems due to natural or anthropogenic pressures including deforestation, the dynamics of clearing, abandonment, regrowth and re-clearing.

Our main objectives in this study were to: 1) characterize the spatial distribution of mangrove species as it relates to growth, tidal influence, and human disturbance using high spatial resolution (1-m) aerial photography and IKONOS satellite data; and 2) quantify land-cover changes resulting from deforestation over a 15-year period from 1986 to 2003. An important goal of this study was to determine the current state (until December 2003) of mangrove forests in Twin Cays. That information is critical in the spatial integration of hydrological and biogeochemical data and their relationship to mangrove growth. The new functional classification presented in this manuscript will also serve as the principal reference data for a subsequent image classification of IKONOS satellite imagery based on computerized spectral pattern recognition.

Table 1. IKONOS instruments characteristics.

Band	Electromagnetic Spectrum	Wavelength (μm)	Ground Resolution (m)
1	BLUE	0.45 - 0.52	4
2	GREEN	0.52 - 0.60	4
3	RED	0.63 - 0.69	4
4	Near IR	0.76 - 0.90	4
Panchromatic		0.45 - 0.90	1

METHODS

Study Area

This study was conducted in Twin Cays, a peat-based archipelago of off-shore mangrove islands just inside the crest of the barrier reef of central Belize, approximately 12 km from the mainland. Most of the 75 ha of land mass at Twin Cays is in two islands, East Island and West Island. The geology of the island consists of a carbonate substrate made up of a dense limestone formed by finger corals and mollusk fragments overlaid by 8 to 12 m of peat that has accumulated over the past 8000 years (Macintyre et al., 1995). Twin Cays receives no terrigenous inputs of freshwater or sediments. The shoreline gradient is intertidal but physiognomically varied and interrupted by tidal creeks that bring water into the interior area of the island flats and shallow ponds. The vegetation is dominated by *Rhizophora mangle* L. (red mangrove), *Avicennia germinans* (black mangrove), and *Laguncularia racemosa* (white mangrove). Forests here are characterized by a pronounced tree-height gradient, which parallels other gradients such as productivity and tidal flushing. The tree-height gradient can be subdivided into three zones. From the sea to landward, the seaward-most zone is a narrow fringe of uniformly tall red mangrove trees (5-6 m). Next is a transition zone (2-4 m tall), where all three mangrove species are present, followed by a zone of uniformly stunted, dwarf red mangrove trees (~1.5 m), which form vast stands in the interior of the islands. The Smithsonian Institution's Marine Field Station on nearby Carrie Bow Cay, approximately 5 km from the study site, provided laboratory, living accommodations, and logistical support during the fieldwork (Rützler and Feller, 1996). Staging of equipment and boat support were also provided at the Smithsonian's research station.

Data and Image Processing

Characteristics of the digital data used in this study are presented in Table 2. The 1986 black-and-white photo (photographed by Royal Air Force) and 2003 color photo (photographed by Ilka C. Feller) were scanned, saved in tagged image file format (tiff) and registered to the satellite images. Satellite data included 1-m multispectral IKONOS images for the years 2001 and 2003.

Image preprocessing of satellite imagery consisted of radiometric and geometric corrections, and spectral enhancement prior to classification and change detection analysis. For geometric correction of both aerial and satellite data, we used the image-to-image registration method with the IKONOS 2001 image as reference. All images were georeferenced to the Universal Transverse Mercator (UTM) coordinate system, and spatial resolution was maintained at 1 m. The root-mean-square error between scene coregistrations was maintained at ± 0.5 pixels to avoid misregistration problems. Because of image warping and other inconsistencies found in the aerial photography data that prevented their perfect overlay on the new satellite data, we used a rubber-sheet model with approximately 320 Ground Control Points (GCPs) in their coregistration process. Spectral enhancement was done on both IKONOS images to help us in the creation of boundary polygons and vegetation classification; they included: Principal Component Analysis (PCA), Normalized Difference Vegetation Index (NDVI), natural color, and transformation of red, green, and blue (RGB) values to intensity, hue, and saturation (IHS) values (ERDAS 2003). Image processing was done with ERDAS Imagine 8.6 software (ERDAS Atlanta, GA, USA). All data were integrated into a GIS for storage, update and subsequent geographic analysis.

Land-Cover Classification

To inventory and map mangrove forests and other land cover types, it is necessary to classify remotely-sensed images into land cover categories or types. This is called thematic mapping of land-cover "themes". A number of classification schemes have been developed that can incorporate land-use and/or land-cover data obtained by interpreting remotely-sensed data. The U.S. Geological Survey Land Use/Land Cover Classification System (Anderson et al., 1976; USGS, 1992) is a resource-oriented (land-cover) scheme with eight main categories. This system contrasts with various human activity (land-use) oriented systems, such as the Standard Land Use Coding Manual (Jensen et al., 1983) or the U.S. Fish and Wildlife Service (Cowardin et al., 1979) system, which is widely used to characterize wetland systems based on hydrological, soil, and vegetation characteristics.

Classification of land-cover types in Twin Cays began with on-screen visual-interpretation and digitization of mangrove and landscape features from aerial photography taken in March 2003 and was finalized with new thematic information extracted from satellite data from December 2003 in which the latest deforestation on East Island was clearly visible (Fig.1) . The 2003 classification map was used as baseline data to classify the 1986 black-and-white image into general land cover classes (i.e., forest, ponds, etc.). Reference or ancillary data consisted of ground-truthing done for two weeks in August 2003, oblique aerial photos taken in March 2003, satellite data from 2001, and expert knowledge. Classification was accomplished using ArcInfo 8.3 (ESRI, Redlands, USA) and ERDAS Imagine 8.6 software. Classification of satellite images based on computer data categorization (spectral analysis) will be presented in a second manuscript.

Table 2. Characteristics of the satellite imagery and aerial photography used in the study.

Image	Latitude*	Longitude*	Acquisition date	Multi-spectral Files
IKONOS	16.9294	-88.1555	13 December 2003	R,G,B,NIR bands
IKONOS	16.9295	-88.1548	13 September 2001	R,G,B bands
Aerial Photo	Without coordinates		15 March 2003	Color (R,G,B)
Aerial Photo	Without coordinates		Year 1986	Black and White

Notes: * Lower left corner of the image scene, negative longitude for west. R, G, B, NIR refers to red, green, blue, and near infrared spectral bands. Spatial resolution was 1-meter. Coordinate system for all images: Universal Transverse Mercator (UTM), North hemisphere, Zone number 16, Datum WGS84.

Change Detection Analysis

Two methods of change analyses were performed in this study. The first involved a simple comparison of selected land cover classes to quantify their overall percent change from 1986 to 2003. The second method of change detection is called post-classification comparison (Singh, 1986; Jensen, 1996). The advantages of this technique are that it provides 'from-to' information for each pixel and does not require data normalization (e.g., reduction of interscene variability resulting from differing atmospheric conditions, radiation incidence angle, and detector disparity) because the two dates are classified separately (Singh, 1989). However, this method does propagate error from the initial land cover maps- the accuracy of the resulting change map is dependent on the accuracy of the land cover maps used to create it (Jensen, 1996).

With five vegetation/land cover categories (U, D, B, S, F) a matrix of dimension 5 x 5 is formed, producing a total of 25 possible combinations of 'from-to' change classes (Table 3). Since we were specifically interested in quantifying changes in forest cover only five combinations were included in the analysis: undisturbed-forest to deforested (UD), undisturbed-forest to beach erosion (UB), undisturbed-forest to survey lines (US), deforested to undisturbed-forest (DU), and deforested to beach erosion (DB). Because creation of survey lines on the landscape entails some deforestation, we decided to merge deforested and survey lines classes for change analysis.

Table 3. Matrix of all possible "from-to" change themes that could be formed with five land cover categories used in the classification of aerial photography from 1986 and IKONOS satellite imagery from 2003. Each row and column combination represents one type of land cover change from 1986 to 2003. For example, class UD is the change from an undisturbed mangrove forest in 1986 to a deforested area in 2003.

From (row): 1986 To (column): 2003	Undisturbed forest	Deforested	Beach erosion	Survey line	Lost fringe
Undisturbed forest	UU	UD	UB	US	UF
Deforested	DU	DD	DB	DS	DF
Beach erosion	BU	BD	BB	BS	BF
Survey line	SU	SD	SB	SS	SF
Lost fringe	FU	FD	FB	FS	FF

Note: since beach erosion and survey lines were not in evidence in the 1986 data, only undisturbed and deforested classes were considered in the "from-to" change analysis. In this study the change classes of interest included: UU, UD, UB, US, DU, DD, and DS. Shaded classes were not considered for analysis.

RESULTS

Land-Cover Classification

Using satellite and aerial photography data we were able to characterize with a high level of detail the status of mangrove forest communities in Twin Cays. The resource-oriented classification scheme developed in our study was primarily based on forest structure characteristics (e.g., height, density, and growth) and tidal-flow influences on mangrove vegetation. Classification consisted of seven general classes (Level I) and 29 subclasses (Level II) (Table 4 and Fig. 2).

A breakdown of level II classes showed 78% of the total landscape in Twin Cays, during the year 2003, characterized by six land cover types which included: (1) *R. mangle* dwarf with 25%; (2) mixed woodland with 15%; (3) fringe with 13%; (4) open pond dwarf with 10%; (5) clearcut areas with 8%; and (6) *R. mangle* floc zones (e.g. areas of decaying algal material) with approximately 7% (Table 5). Although deforested land did not make up a large percentage of the total area of Twin Cays, a recent land clearing event where 21,335 m^2 (see zone LC-2 in Fig. 2) of mangrove were cut between March and December in 2003 suggests that deforestation events will likely continue into the future.

Other thematic classes with an important ecological spatial-temporal component include algal mats, diebacks, hydrology-zone trees and relic fringe. Feller et al. (2003 a, c) have related these zones to nutrient cycling and biogeochemical processes influencing mangrove growth in Twin Cays.

Land-Cover Change

The spatial distribution of anthropogenic disturbance at Twin Cays during 1986 and 2003 are shown in Figures 3 and 4. An overall comparison of five land cover classes during this 15-year period showed a 52% increase in deforestation of mangrove communities across the archipelago, a 6% decrease in undisturbed mangrove forests, as well the creation of survey lines and the disappearance of parts of the fringe zone (Table 6).

Results from the overall comparison do not quantify land-cover changes occurring from one particular class to another, information that is necessary because change could be natural and/or anthropogenic. Post-classification change detection analysis quantifies those 'from-to' land cover categories changes. A selected number of these more detailed changes are presented in Table 7, and their spatial distribution is shown in Figure 5. Results for the undisturbed-forest category showed that on a percentage basis, change from undisturbed forest to other categories was relatively small, i.e., 90% of forest in 1986 remained undisturbed in 2003. Change to deforested areas reached 8%, beach erosion 0.3 %, and losses in mangrove forests in the fringe zone (rim of the island) about 1 %. Results for the deforested category showed and interesting result for the change from deforested to undisturbed-forest (DU) (i.e., forest regeneration). This change represented a 46% regeneration of deforested mangrove areas computed from the 1986 data.

Changes in the total area of Twin Cays showed increases of mangrove forest in the fringe zone totaling12,850 m^2, most of if found on the southwest section of West Island (Fig. 5). Nevertheless, this gain in mangrove vegetation was somewhat offset by fringe losses in East Island that ranged from 4,762 m^2 to 7,968 m^2. The higher value was the result of including beach erosion in the fringe-loss category.

Table 4. Classification scheme, based on forest structure and tidal flow influences, used to categorize mangrove vegetation in Twin Cays, Belize.

Level I	Level II	Criteria
1. *Avicennia germinans* forest	1.1 *A. germinans* basin	Tall, straight-trunked *A. germinans*, dense *Batis maritima* understory, 4-7 m tall, not permanently flooded, flushing varies seasonally.
	1.2 *A. germinans* dwarf	Dominated by *A. germinans*, with few *R. mangle* intermixed, 1.4 < 1.5 m tall.
	1.3 *A. germinans* orchard	Widely spaced trees, little understory, spreading canopies, 3-4 m tall, not permanently flooded, flushing varies seasonally.
	1.4 *A. germinans* scrub	Sparse and slow growth, lots of dead wood, along moribund zones, not permanently flooded, flushing varies seasonally.
	1.5 *A. germinans* woodland	Dense stands of *A. mangle* in the interior of the island, 2-3 m tall
	1.6 Regenerating *A. germinans*	New growth, dense, small trees, intermixed *R. mangle* and *L. racemosa*, 2-3 m tall.
	1.7 Lone *A. germinans* tree	Large trees (5-6 m tall) standing alone.
2. *Rhizophora mangle* forest	2.1 *R. mangle* dwarf	*R. mangle* stand in shallow ponded areas in the interior, ≤1.5 m tall.
	2.2 *R. mangle* floc zone	Pure *R. mangle* stand adjacent to floc accumulating areas along ponds in the interior of the island, vigorous, fast growing, flooding varies.
	2.3 *R. mangle* woodland	Dense stands of *R. mangle* in the interior of the island, 2-3 m tall
	2.5 Lone *R. mangle* tree	Large trees (5-6 m tall) standing alone.
	2.6 Fringe	Pure *R. mangle* stand along water's edge around the periphery of the islands, 4-7 m tall, not permanently flooded but flushed daily.
	2.7 Relic fringe	Remnants of old area *R. mangle* fringes where water flow once existed.
	2.8 Moribund	Typically adjacent to floc zone tree, lots of dead branches and trees, dominated by *R. mangle*, 2-3 m tall, not permanently flooded, flushing varies seasonally.

Level I	Level II	Criteria
3. Mixed forest	3.1 *R. mangle*/*A. germinans* dwarf	Mixed dwarf stand, but usually dominated by *R. mangle*, typically dense, often with *Distichlis spicata* understory, ≤1.5 m tall.
	3.2 Mixed woodland	*R. mangle* dominated, *A. germinans* & *L. racemosa* mixed, 2-4 m tall, not permanently flooded, flushing varies seasonally.
4. Agriculture	4.1 Planted coconut trees	Deforested areas, filled and used for planting schemes.
5. Water	5.1 Ponds	Unvegetated, relatively deep, soft bottom.
	5.2 Open pond dwarf	Sparse vegetation, shallow, firm bottom, *Batophora oerstedi* subtidally on roots and peat.
	5.3 Algal mats	Alongside ponds, thick crust on surface of deep floc layer.
6. Barren	6.1 Beach	Sandy areas along the shoreline.
	6.2 Clear-cuts	Deforested areas without mangrove trees, herbaceous vegetation only.
	6.3 Eroded shoreline	Areas where deforestation of fringe accelerated the effect of wave erosion.
	6.4 Dieback	Patches of dead mangrove trees, usually adjacent to floc accumulation areas,
7. Other	7.1 Experimental trees	Phosphorus fertilized dwarf trees, vigorous growth, 2-5 m tall.
	7.2 Hydrology zone trees	Trees alongside tidal channels, increased flushing, vigorous growth.
	7.3 Saplings	Young trees alongside floc accumulation area, vigorous growth.

Table 5. Thematic classes identified on the 2003 classification map of Twin Cays, Belize. Their corresponding areas, relative importance (% of total area) and perimeters were quantified with a geographic information system (GIS).

Land Cover Classification (Level II)	Area (m^2)	Percent of Total (%)	Perimeter (m)
Algal Mats	3,214.8	0.43	1,295.4
A. germinans Basin	5,842.0	0.78	656.0
A. germinans Dwarf	1,495.0	0.20	216.0
A. germinans Orchard	12,033.0	1.61	1,686.0
A. germinans Scrub	22,805.0	3.05	4,074.0
A. germinans Woodland	180.0	0.02	68.0
Beach	484.0	0.06	168.0
Clearcut	59,146.4	7.90	4,472.8
Coastal Scrub	2,101.0	0.28	484.0
Dieback	3,006.0	0.40	984.0
Eroded Shoreline	2,819.0	0.38	548.0
Experimental Trees	2,363.0	0.32	1,214.0
Fringe	99,667.3	13.31	21,808.6
Hydrology Zone Trees	4,034.0	0.54	880.0
Lone *A. germinans*	1,713.0	0.23	496.0
Lone *Laguncularia*	117.0	0.02	58.0
Lone *R. mangle*	2,667.0	0.36	1,132.0
Mixed Woodland	115,102.3	15.38	15,092.2
Moribund *R. mangle*	3,124.2	0.42	705.9
Open Pond Dwarf	73,305.2	9.79	9,107.4
Planted Coconuts	8,949.0	1.20	758.0
Pond	28,588.0	3.82	2,800.0
Regenerated *A. germinans* Forest	8,174.0	1.09	676.0
Relic Fringe	4,426.9	0.59	803.2
R. mangle Dwarf	189,006.2	25.25	21,638.6
R. mangle Floc Zone	49,882.0	6.66	12,570.0
R. mangle Woodland	24,222.0	3.24	6,072.0
R. mangle / *A. germinans* Dwarf	19,166.0	2.56	2,500.0
Saplings	995.0	0.13	464.0
Total	748,628.4		113,428.2

Table 6. Comparison of areas under different land cover during two periods, 1986 and 2003.

Land Cover Class	1986 Area (m^2)	Percent of Total Area (%)	2003 Area (m^2)	Percent of Total Area (%)	Percent Change in Land Cover 1986 - 2003
Undisturbed forest	615,493	82	578,205	77	-6
Deforested	30,349	4	63,547	8	+52
Beach erosion	0	0	3,339	0.4	+100
Survey lines	0	0	2,119	0.3	+100
Lost fringe	0	0	4,791	1	+100

Note: Percent change = $((A_{2003} - A_{1986}) / A_{2003}) \times 100$

Table 7. Post-classification change detection analysis using deforested and survey line classes as cover. "From-to" change analysis determined change from two land-cover classes in 1986 (e.g. undisturbed and deforested) to undisturbed, deforested, beach erosion, and lost fringe categories in 2003.

	Year 2003			
Year 1986	Undisturbed forest	Deforested	Beach erosion	Lost fringe
Undisturbed forest (m^2)	551,376	51,322	2,034	3,704
Percent (%)	90	8	0.3	1
Deforested (m^2)	14,103	14,058	1,305	720
Percent (%)	46	46	4	2

Note: Areas are given in m^2. Percent values are based on 1986 total areas (Table 6).

	Year 2003			
Year 1986	Undisturbed (U)	Deforested (D)	Beach erosion (B)	Lost fringe (F)
Undisturbed (U)	653,269	51,322	2,034	3,704
Percent	91.06	7.15	0.28	0.52
Deforested (D)	14,103	14,058	1,305	720
Percent	46.47	46.32	4.30	2.37

Note: Areas are given in square meters. Percent values are based on 1986 areas.

DISCUSSION

"Habitat fragmentation is the most serious threat to biological diversity and is the primary cause of the present extinction crisis" (Wilcox and Murphy, 1985). Habitat fragmentation causes the fracture of ecosystem processes, it hinders dispersal and movement of species, and it also increases invasion from generalists into the interior of isolated habitats. Spatio-temporal processes in mangrove forest communities have not been studied extensively. Spatial patterns play an important part in plant community dynamics. These patterns reflect a complex series of interactions of past-and-present events and form the basis for future states of growth and condition (Herben et al., 2000).

Land Cover Classification

We have used multitemporal and multispectral data to classify and characterize the landscape in Twin Cays archipelago. The high number of vegetation themes (e.g., 29 land-cover classes) used in the classification presented in this study were the result of an effort-intensive methodology based on visual-interpretation, on-screen digitization, ground-truthing, and expert knowledge. The next step in our analysis will be to classify satellite data based on computerized spectral-pattern recognition using the present classification results as training polygons, reducing processing time and providing accurate characterization of other areas along the Mesoamerican Barrier Reef and the coast of Belize.

The land-cover classification developed in this study is part of the basic digital database needed in the development of a comprehensive spatially-explicit biogeochemical model of mangrove forests at the field and landscape scales (i.e., distribution of Net Primary Productivity (NPP) of mangrove forests). Such quantitiative information can be important in sustainable resource management and climate change studies.

Land Cover Change

In change detection analysis, each natural and anthropogenic change in the landscape has a characteristic cause and effect. It is important to inventory all of the forms of change. The natural changes often dictate human action, and form the basis for much environmental research. The human change is important to inventory to determine the long term effects to undisturbed mangrove forests. This, in turn, will help interested parties to define the kind of policy that encourages intelligent use of mangrove forest resources and protects their valuable contribution to the overall health of the Belizean Reef ecosystem.

Land-cover change in Twin Cays has been dramatic during a 15-year period and it is clear that it can occur within very short periods of time as it was found from imagery taken within a 9-mo interval in 2003. The impact of this type of deforestation on mangrove net primary productivity and other biogeochemical- and nutrient-cycling processes in Twin Cays is still unknown. The series of aerial photographs and satellite images from 1986, 2001, and 2003 revealed that the changes in the Twin Cays' landscape were mainly attributable to anthropogenic activity. Additional oblique photographs of the islands taken in 1991 are our first records of survey lines in the island's interior which were cut to mark the boundary lines of at least seven leases to land at Twin Cays. These lines remain clearly visible in the subsequent aerial photographs and satellite images and have been quantified in the study presented here (Fig.5). In some instances, the areas delineated by the survey lines were later deforested. In addition, two of the clear-cut areas were filled with bottom materials dredged from adjacent waters. Change detection analysis showed that 6% of the landmass at Twin Cays had gone from undisturbed to disturbed. However, observations while ground-truthing these data suggest that hydrological changes caused by the cutting of mangroves have magnified the impact of the disturbance. For example, newly formed tidal channels have developed along the survey lines and have altered the water-flow patterns into the interior of the island. Thus, they provide a more rapid and frequent renewal of ocean water to interior ponds. Wright et al. (1991) showed that prior to these survey tracks, tidal exchange in these areas was extremely restricted. We observed that the growth pattern of dwarf forest along these survey lines had changed in response to the altered hydrological regimes. As a result, we created a vegetation class, hydrology-zone trees, to describe the distinctive stands of vigorously growing trees found along these newly formed tidal creeks. Studies are continuing to investigate the relationship of the hydrologic changes, tidal flushing, nutrients, and mangrove growth characteristics. Experimental studies at Twin Cays have recently documented a spatial N- to P-limitation gradient across the tree-height gradient, with fringe trees N-limited and dwarf trees P-limited (Feller et al., 2003a). Fertilization with N or P also altered nutrient concentrations of the mangrove tissue. Within 5 yrs, P-fertilized dwarfs were transformed into tall, vigorous trees, similar in growth, nutrient content, and architecture to similar fringe trees located in the hydrology zone.

CONCLUSIONS

Integration of aerial photography and multitemporal, multispectral high spatial resolution satellite imagery within a GIS was used to classify and characterize the status of mangrove forests in Twin Cays. We have developed a number of functional classification themes of mangrove forests based on species, growth status, and deforestation. Results from this new classification will be the basis for future geospatial modeling of the spatial connectivity between nutrient accumulation zones (i.e., algal mats), water-flow changes, and mangrove growth in the island. We have also quantified the changes in mangrove forest cover during the 1986 to 2003 period. Deforestation of mangrove forests has been concentrated mostly on East Island, and seem to continue unabated as recent visits to the island confirm it.

To test and develop new hypotheses of forest change and fragmentation resulting from anthropogenic pressures, the integration of high-spatial multitemporal and multispectral remote sensing/GIS techniques should be applied to the rest of the Mesoamerican Barrier Reef Ecosystem and mainland coastal mangrove ecosystems. From the point of view of mangrove forest conservation and sustainable resource development in the barrier-reef ecosystem, it is clear that new approaches and mechanisms, such landscape and regional monitoring, as well as the creation of buffer zones around protected areas, could be important goals of government and park managers.

ACKNOWLEDGMENTS

We thank the Government of Belize for permission to use study sites at Twin Cays and Klaus Rützler for support and permission to work at the Smithsonian Institution Marine Field Station at Carrie Bow Cay. We thank Matt Baker and anonymous reviewers for their comments and suggestions that greatly improved this manuscript. Financial support was provided by the Smithsonian Environmental Research Center and the National Science Foundation DEB-9981535. CCRE Contribution Number 703.

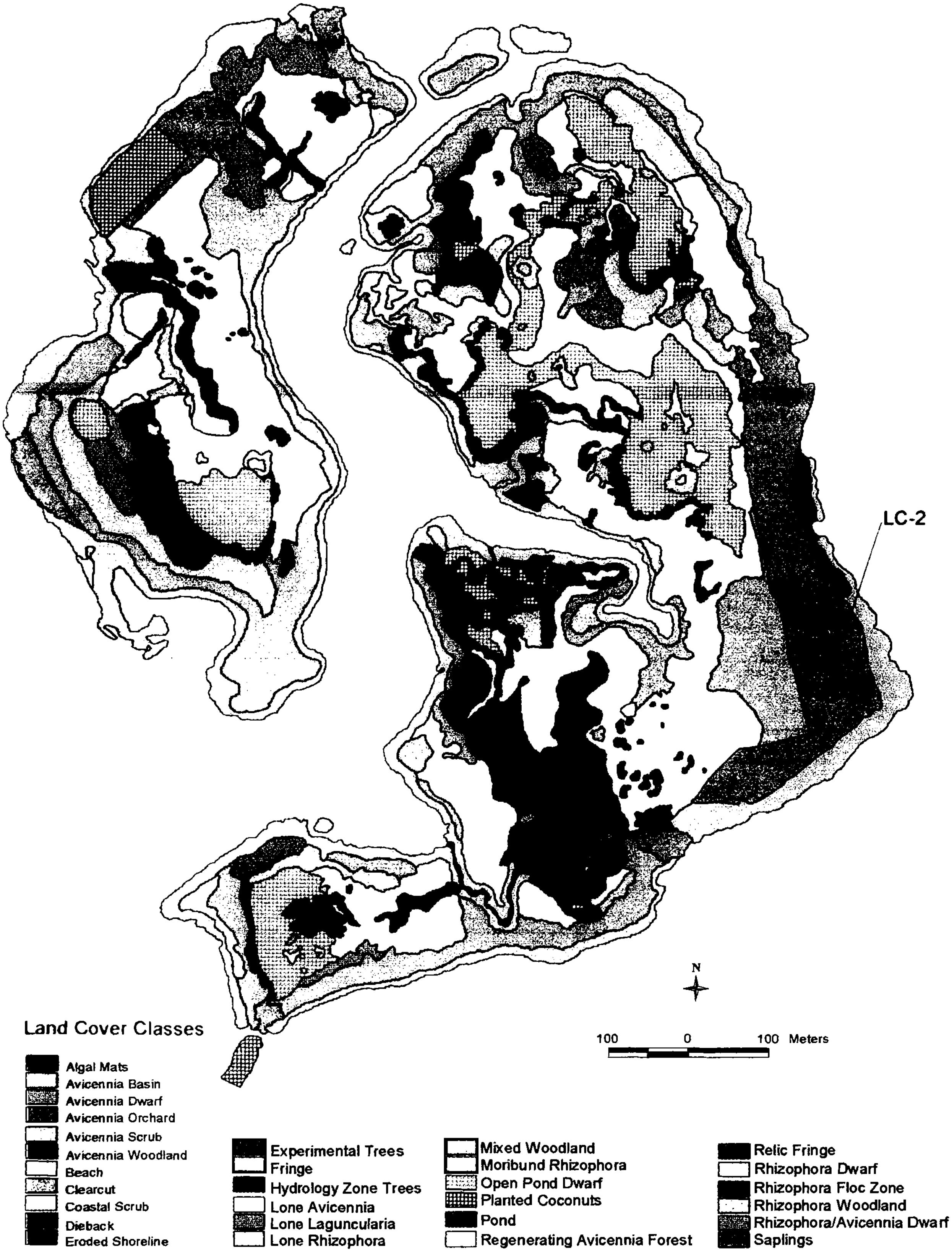


Figure 2. Classification of mangrove vegetation and land cover in Twin Cays, Belize.

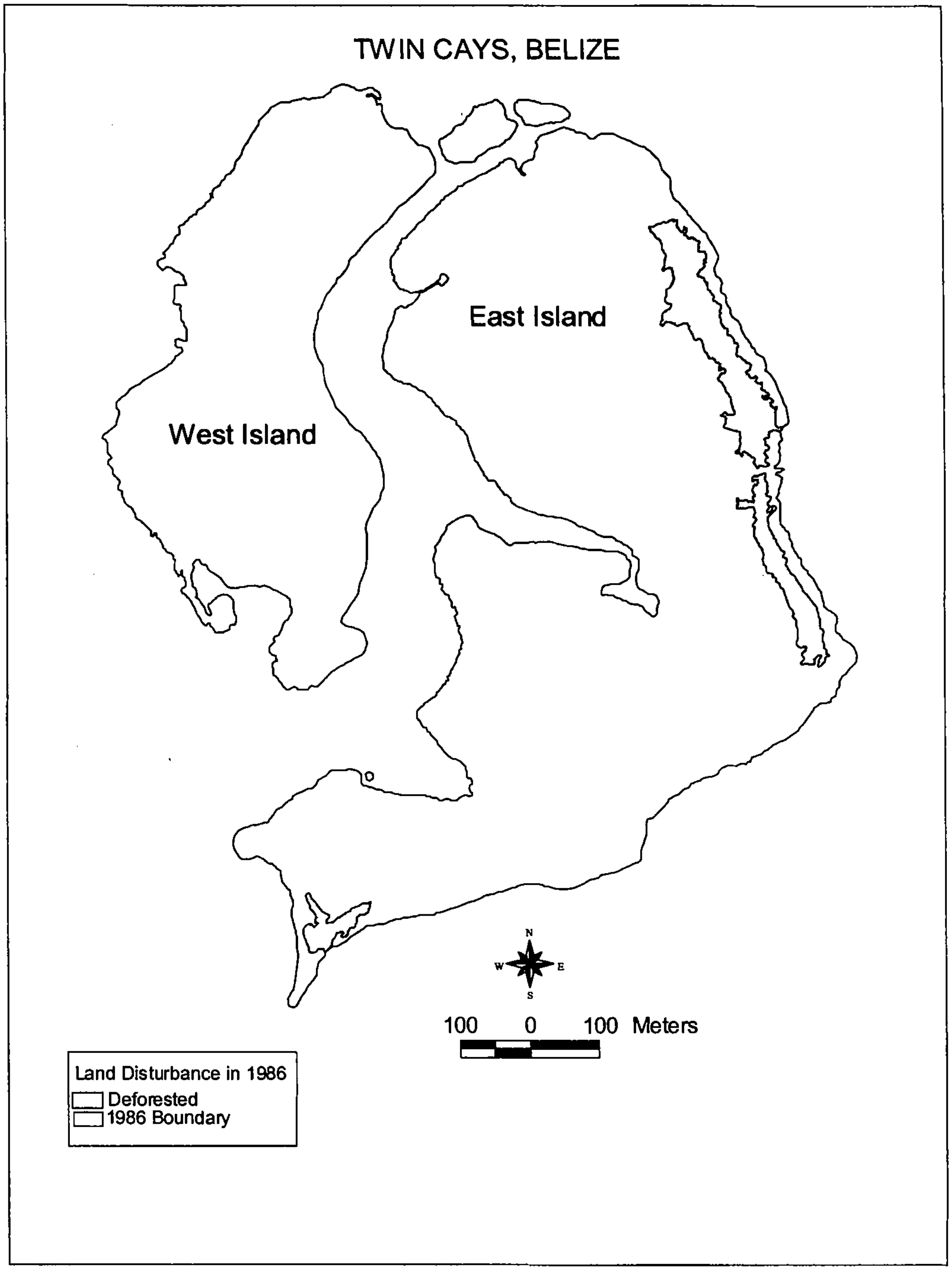


Figure 3. Spatial extent of land clearing in the east section of Twin Cays as quantified from a black-and-white photograph taken in 1986.

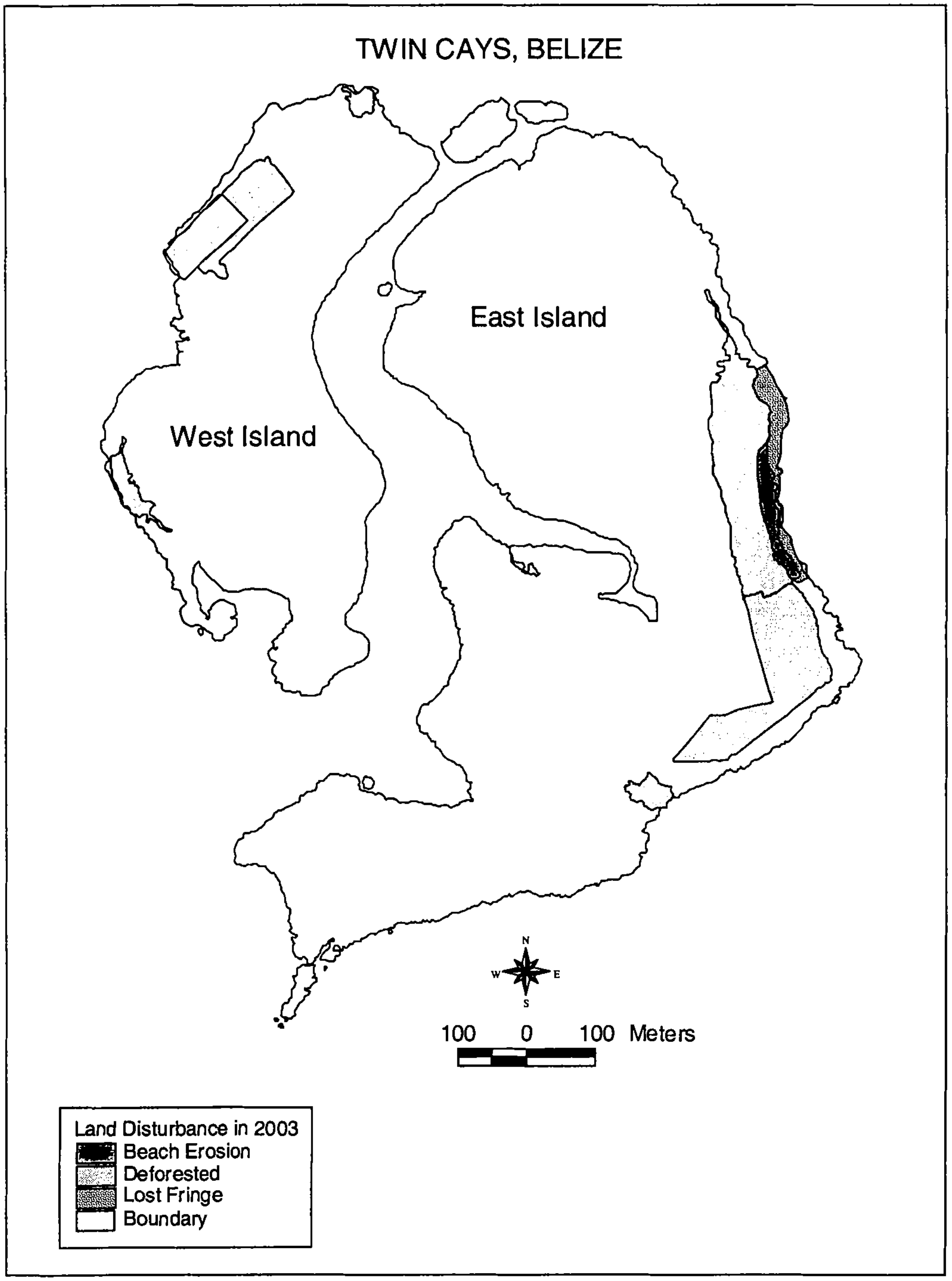


Figure 4. Spatial extent of land clearing, fringe loss, and beach erosion in Twin Cays as quantified from aerial photography (March 2003) and IKONOS satellite imagery (December 2003).

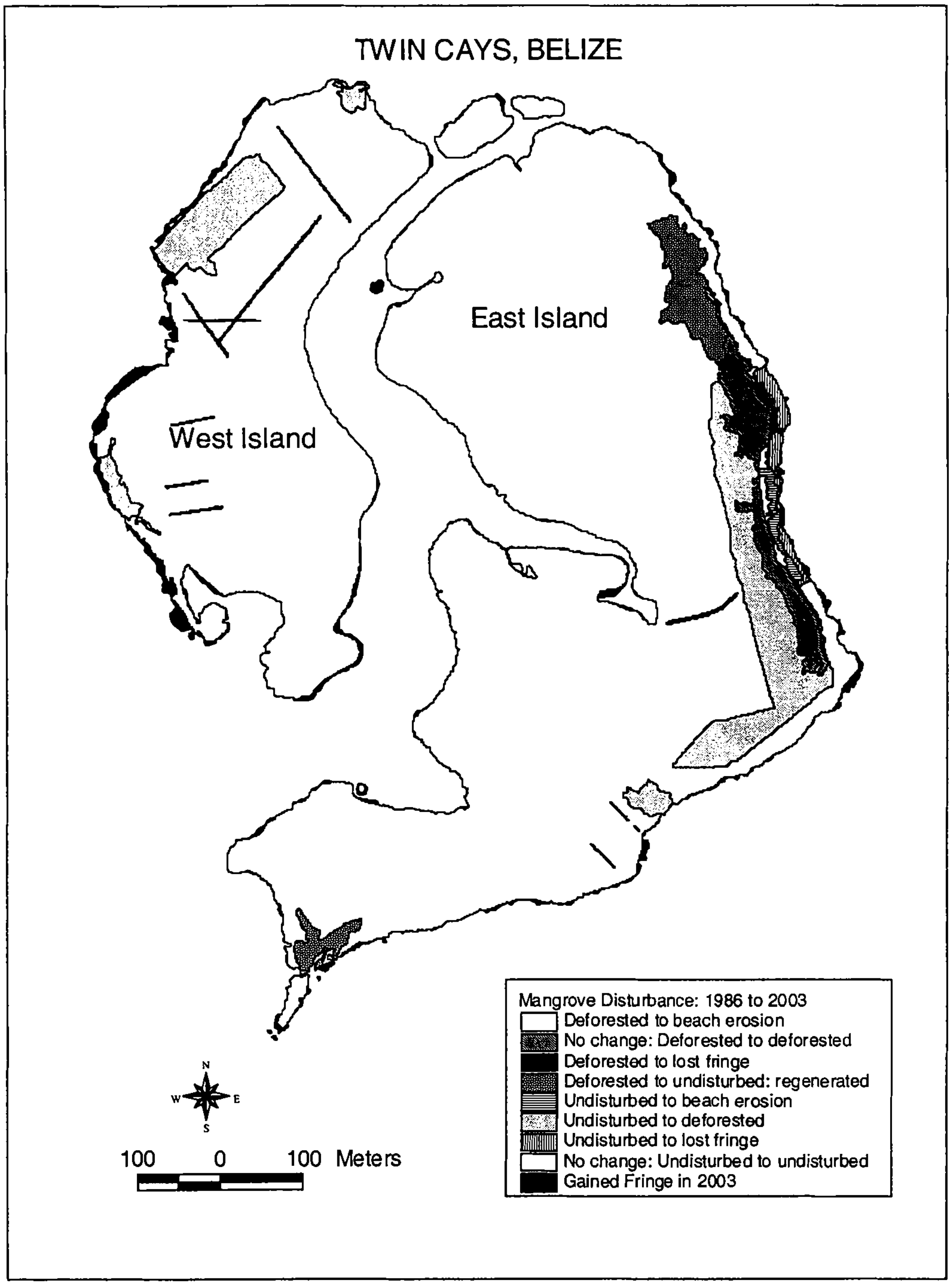


Figure 5. Spatial distribution of land-cover change at Twin Cays from 1986 to 2003. This analysis only considered the 'from-to' information from land cover classes of undisturbed and deforested mangrove forests from 1986 to undisturbed, deforested, beach erosion, and lost fringe classes in 2003.

REFERENCES

Anderson, J., E. Hardy, J. Roach, and R. Witmer
1976. *A land use classification system for use with remote-sensor data.* U.S. Department of Interior, U. S. Geological Survey Professional Paper 964, Washington, DC.

August, P. V., L. Iverson, and J. Nugranad
2002. Human conversion of terrestrial habitats. In *Applying Landscape Ecology in Biological Conservation*, edited by K. Gutzwiller, 198-224, Springer-Verlag, NY.

Blasco, F.
1988a. The international vegetation map (Toulouse, France). In. *Vegetation Mapping,* edited by A. W. Kuchler and I. S. Zonnefeld, 443-460, Junk Publishers, Amsterdam.

Blasco, F.
1988b. *Estudio Sobre los Manglares y la Vegetacion Tropical Utilizando Datos Proporcionados por Satellites.* Institute de la Carte Internationale de la Vegetation. University Paul Sabatier, Toulouse.

Chapin, F. S. III, E. S. Zavaleta, V. T. Eviner, R. L. Naylor, P. M. Vitousek, H. L. Reynolds, D. U. Hopper, S. Lavorel, O. E. Sala, S. E. Hobbie, M. C. Mack, and S. Diaz.
2000. Consequences of changing biodiversity. *Nature* 405:234-242.

Chapman, V. J.
1969. Lagoons and mangrove vegetation. In *Lagunas Costeras, un Simposio*, edited by A. Ayala-Castanares and F. B. Phleger, 504-514, UNAM-UNESCO, No. 28-30, Mexico.

Chauvaud, S., C. Bouchon, and R. Maniere
2001. Cartographie des biocenoses marines de Guadeloupe a partir de donnees SPOT (recifs corallines, phanerogames marines, mangroves). *Oceanologica Acta* 24: S3-S16.

Cowardin, L., V. Carter, F. Golet, and E. LaRoe.
1979. *Classification of Wetlands and Deepwater Habitats of the United States.* U.S. Department of Interior, U.S. Fish and Wildlife Service, Report No. FWS/OBS-79/31, Washington, DC.

Dial, G., H. Bowen, F. Gerlach, J. Grodecki, and R. Oleszczuk
2002. IKONOS satellite imagery, and products. *Remote Sensing of the Environment* 88:23-36.Douglas, I.
1999. Hydrological investigations of forest disturbance and land cover impacts in South–East Asia: a review, *Philosophical Transactions of the Royal Society of London, Series B,* 354:1725-1738.

ERDAS.
2003. *Earth Resources Data Analysis System.* Field Guide, ERDAS Inc., Atlanta, GA.

Feller, I. C.
1995. Effects of nutrient enrichment on growth and herbivory in dwarf red mangrove (*Rhizophora mangle*). *Ecological Monographs* 65:477-505.

Feller, I. C.
1996. Effects of nutrient enrichment on leaf anatomy of dwarf *Rhizophora mangle* L.

(Red Mangrove). Biotropica 28:13-22.

Feller, I. C., and W. N. Mathis
1997. Primary herbivory by wood-boring insects along an architectural gradient of *Rhizophora mangle* L. *Biotropica* 29:440-451.

Feller, I. C., K. L. McKee, D. F. Whigham, and J. P. O'Neill
2003a. Nitrogen vs. phoshphorous limitation across an ecotonal gradient in a mangrove forest. *Biogeochemistry* 62:145-175.

Feller, I. C., D. F. Whigham, K. L. McKee, and C. E. Lovelock
2003b. Nitrogen limitation of growth and nutrient dynamics in a disturbed mangrove forest, Indian River Lagoon, Florida. *Oecologia* 134:405-414.

Feller, I. C., C. E. Lovelock, K. L. McKee, M. C. Ball, and J. Ellis
2003c. Biocomplexity in mangrove forests: Indo-West pacific vs. Atlantic-East comparison of the effects on nutrient availability on growth and herbivory. *ERF 2003 Conference Abstracts,* September 14-19, 2003, Seattle, WA.

Forman, R. T. T., and M. Godron
1986. *Landscape Ecology,* John Wiley, NY.

Forman, R. T. T.
1995. *Land Mosaics: The Ecology of Landscapes and Regions.* Cambridge University Press, Cambridge.

Gill, A. M. and P. B. Tomlinson
1971. Studies on the growth of red mangrove (*Rhizophora mangle*). Part 3. Phenology of the shoot. *Biotropica* 3:109-124.

Herben, T., H. J. During and R. Law
2000. Spatio-temporal patterns in grassland communities. In *The Geometry of Ecological Interactions: Simplifying Spatial Complexity,* edited by U. Dieckman, R. Law, and J. A. J. Metz, 48-64. Cambridge University Press.

Ibrahim S., and I. Hashim
1990. Classification of mangrove forest by using 1:40 000 scale aerial photographs. *Forest Ecology and Management* 33:583-592.

Jensen, J. R.
1983. Urban-suburban land use analysis. In *Manual of Remote Sensing,* edited by R. Colwell, 1571-1666. American Society of Photogrammetry.

Jensen, J. R.
1996. *Introductory Digital Image Processing: A Remote Sensing Perspective.* Prentice-Hall, Inc.

Lyon, G. J.
2001. *Wetland Landscape Characterization: GIS, Remote Sensing, and Image Analysis.* Ann Arbor Press, MI.

Macintyre I. G., M. M. Littler, and D. S. Littler
1995. Holocene history of Tobacco Range, Belize, Central America. *Atoll Research Bulletin* 430:1-18.

McKee, K. L., I. C. Feller, M. Popp, and W. Wanek
2002. Mangrove isotopic fractionation (^{15}N and ^{13}C) across a nitrogen versus phosphorous limitation gradient. *Ecology* 83:1065-1075.

Penner, J. E.
1993. Atmospheric chemistry and air quality. In *Changes in Land Use and Land*

Cover: A Global Perspective, edited by W. B. Meyer and B. L.Turner II, 175-209. Cambridge University Press, Cambridge.

Ramirez-Garcia, P., J. Lopez-Blanco, and D. Ocana
1997. Mangrove vegetation assessment in the Santiago River Mouth, Mexico, by means of supervised classification using Landsat TM imagery. *Forest Ecology and Management* 105:217-229.

Running, S. W., G. J. Collatz, J. Washburne, S. Sorooshian, T. Dunne, R. E. Dickinson, W. J. Shuttleworth, C. J. Vorosmarty, and E. F. Wood
1999. Land ecosystems and hydrology. In *EOS Science Plan: The State of Science in the EOS Program,* edited by M. D. King, 197-257). Office of Earth Science, NASA Headquarters, Washington DC.

Rützler, K., and I. C. Feller
1988. Mangrove swamp communities. *Oceanus* 30:16-24.

Rützler, K, and I. C. Feller
1996. Caribbean mangrove swamps. *Scientific American* 274:94-99.

Sanchez-Azofeifa, G. A., G. C. Daily, A. S. P. Pfaff, and C. Busch
2003. Integrity and isolation of Costa Rica's national parks and biological reserves: examining the dynamics of land-cover change. *Biological Conservation* 109:123-135.

Singh, A.
1986. Change detection in the tropical rain-forest environment of Northeastern India using Landsat. In *Remote Sensing and Tropical Land Management,* edited by M. J. Eden and J. T. Parry, 237-254. John Wiley & Sons, London.

Singh, A,
1989. Digital change detection techniques using remotely-sensed data. *International Journal of Remote Sensing* 10: 989-1003.

Skole, D., and C. J. Tucker
1993. Tropical deforestation and habitat fragmentation in the Amazon: Satellite data from 1978 to 1988. *Science* 260:1905-1910.

Snedaker, S.
1993. Impact on Mangroves. In *Climatic Change in the Intra-Americas Sea: Implications of Future Climate on the Ecosystems and Socioeconomic Structure in the Marine and Coastal Regions of the Caribbean Sea, Gulf of Mexico, Bahamas, and the Northeast Coast of South America,* edited by G. A. Maul, 282-305. Chapman and Hall, Inc, NY.

USGS
1991. *Standards for Digital Line Graphs for Land Use and Land Cover Technical Instructions.* Referral STO-1-2. US Government Printing Office Washington, DC.

Vicente, V. P., N. C. Singh, and A. V. Botello
1993. Ecological implications of potential climate change and sea-level rise. In *Climatic Change in the Intra-Americas Sea: Implications of Future Climate on the Ecosystems and Socioeconomic Structure in the Marine and Coastal Regions of the Caribbean Sea, Gulf of Mexico, Bahamas, and the Northeast Coast of South America,* edited by G. A. Maul, 262-281. Chapman and Hall, Inc., NY.

Wicox, B. A. and D. D. Murphy

1985. Conservation strategy: the effects of fragmentation on extinction. *American Naturalist* 125: 879-887.

Woodroffe, C. D.

1995. Mangrove vegetation on Tobacco Range and nearby mangrove ranges, central Belize barrier reef. *Atoll Research Bulletin* 427:1-35.

Wright, R., D. Urish, and I. Runge

1991. The Hydrogeology of a Caribbean Mangrove Island. *Proceedings of the Coastlines of the Caribbean Coastal Zone* 1991 Conference, ASCE, Long Beach, CA.

Vitousek, P. M.

1994. Beyond global warming: ecology and global change. *Ecology* 75:1861-1876.

Zanoni, V. M., and S. N. Goward

2004. A new direction in Earth observations from space: IKONOS. *Remote Sensing of Environment* 88:1-2.