

TECHNICAL REPORT: IDENTIFICATION OF THREATENED AND RESILIENT MANGROVES IN THE BELIZE BARRIER REEF SYSTEM

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Abstract: Mangroves are an important component of the Belize Barrier Reef Complex, a mosaic of coral reef, sea grass, and mangrove ecosystems, and the world's second largest barrier reef system. Based on satellite imagery available through the Regional Visualization & Monitoring System (SERVIR), the extent of Belize's mangrove cover was assessed over a 30-year period to obtain a previously unavailable time-series of information on the status of these ecosystems. Using Zisman's (1998) mangrove extent data as a baseline, a multi-temporal remote sensing-based change detection study was conducted by performing spectral mixture analysis on Landsat satellite imagery for the years 1980, 1989, 1994, 2000, 2004, and 2010. This assessment indicates that from late 1980 through early 2010, Belize's mangrove cover declined from 188,417 acres (76,250 hectares), or 98.7% of the original extent, to 184,548 acres (74,684 ha.), or 96.7% of the original extent. Those figures equate to a net loss of approximately 3,900 acres of mangrove cover over roughly 30 years, a loss of 2% of the 1980 mangrove cover. The average annual net loss was estimated at 0.07%, or 125 acres. At the scale of 1:100,000, this assessment also reveals that land clearing resulted in fragmentation of some 2.1% of mangrove communities. In terms of the resilience of mangrove ecosystems, a mere 236 acres (96 ha.) of the area cleared between 1980 and 2010 was detected to have regrown. It is also assumed that widespread mangrove regrowth was likely not seen because land previously occupied by mangroves is permanently converted to other land uses such as infrastructure for housing. Whereas recent publications such as the 2010 World Mangrove Atlas indicate that a fifth of the world's mangrove cover had been lost since 1980, the loss of 2% of Belize's overall mangrove cover between 1980 and 2010 can be considered low.

Key words: Belize, mangrove, wetland, coastal zone, remote sensing, spectral mixture analysis, Landsat, ASTER

Mangroves, which are legally protected under Belize's *Forests Act* (GOB 2003), have been the subject of various studies that have highlighted their importance from both ecological and economic perspectives (Gray et al 1990, Zisman 1998, Murray et al 2003, McField & Kramer 2007, Cooper et al 2009). Among other characteristics, they provide important ecological services in terms of shoreline protection and serve as nurseries for reef fish. A large proportion of the country's mangroves are also intimately inter-connected with the Belize Barrier Reef Complex, the largest coral reef system in the Americas, and the second largest in the world after Australia's Great Barrier Reef (UNESCO 1996). Cooper et al (2009) found that mangroves contribute some US \$174-249 million per year to Belize's economy.

With conservation of Belize's mangroves thus being crucial, McField & Kramer (2007) highlighted the scarcity of information on the current extent of Belize's mangrove ecosystems. Well into the 2000s, the most accurate information available on the extent of Belize's mangroves was a national map of mangrove cover largely ~1990 data (Zisman 1998). In 2008, the *Healthy Reefs for Healthy People* initiative facilitated the updating of Zisman's data using satellite imagery from 2006-2007. To update Belize's national mangrove map to 2010 and to examine mangrove dynamics for 1980-2010, the current study was conducted by CATHALAC, with funding from the World Wildlife Fund (WWF). Extensive use was made of data available through the *Regional Visualization & Monitoring System* (SERVIR), a joint initiative of the U.S. Agency for International Development (USAID), NASA, CATHALAC, and other partners.

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I. BACKGROUND

Reasonably *accurate* information on the *current* extent of Belize's mangroves has been lacking. This is in spite of the fact that a number of data sources exist on mangrove cover. These have largely come from studies in recent years of Belize's overall land cover, which have included the following: Fairweather & Gray 1994, Iremonger & Brokaw 1995, White et al 1996, Meerman & Sabido 2001, Meerman 2005, Meerman et al 2010. However, as these studies have been produced through different methods and for different purposes, estimates of mangrove cover from those studies invariably differ, in many cases significantly (Zisman 1998).

In his doctoral dissertation, Simon Zisman – an expert on Belize's mangroves – provides a comprehensive review of all of the then-existing national-level sources of mangrove data for Belize. In terms of maps of Belize's mangrove cover, Zisman reviewed the following:

- (i) Provisional 1:50,000 topographic map series (1948-1953)
- (ii) E-755 1:50,000 topographic map series (1995)
- (iii) National vegetation map (Wright et al 1959)
- (iv) National land cover map (Fairweather & Gray 1994)
- (v) Natural vegetation map (Iremonger & Brokaw 1995)

Zisman's conclusion was that the maps previously developed all fell short of comprehensively mapping Belize's mangroves. Even though those maps all included mangroves, since their objective was not specifically the mapping of mangrove ecosystems, they were all subject to varying degrees of errors of commission and errors of omission (i.e., not including mangroves or erroneously mapping other vegetation as mangrove, respectively).

Generation of a Baseline for National Mangrove Cover

In 1989, Belize's first national map specific to mangrove cover was released, based on Landsat imagery from 1987 (Gray et al 1989). This was subsequently revised under the United Kingdom-funded Forest Planning and Management Project, the FPMP (Zisman 1993). In 1998, with the publication of his dissertation, Zisman released a third and final edition of the national mangrove cover map, revised through an exhaustive process, where he comprehensively re-mapped Belize's mangrove cover based on aerial photography (from 1988, 1990, and 1992), Landsat 5 satellite imagery (captured on January 4, 1987), and field surveys carried out in the 1990s. Zisman's field surveys (and interviews of residents of coastal communities) also served to identify areas which he postulated had once been covered by mangrove but had been cleared due to human settlement (for instance much of what is now Belize City). Zisman left three maps of Belize's mangrove, which are explained in detail in his brief report, "Explanatory Notes for the Zisman Mangrove Map" (Zisman 1999):

- (i) National mangrove cover, nominally for 1990
- (ii) National mangrove cover, updated to 1992 for the Belize City area only
- (iii) National mangrove cover, original pre-settlement (see **Figure 1**)

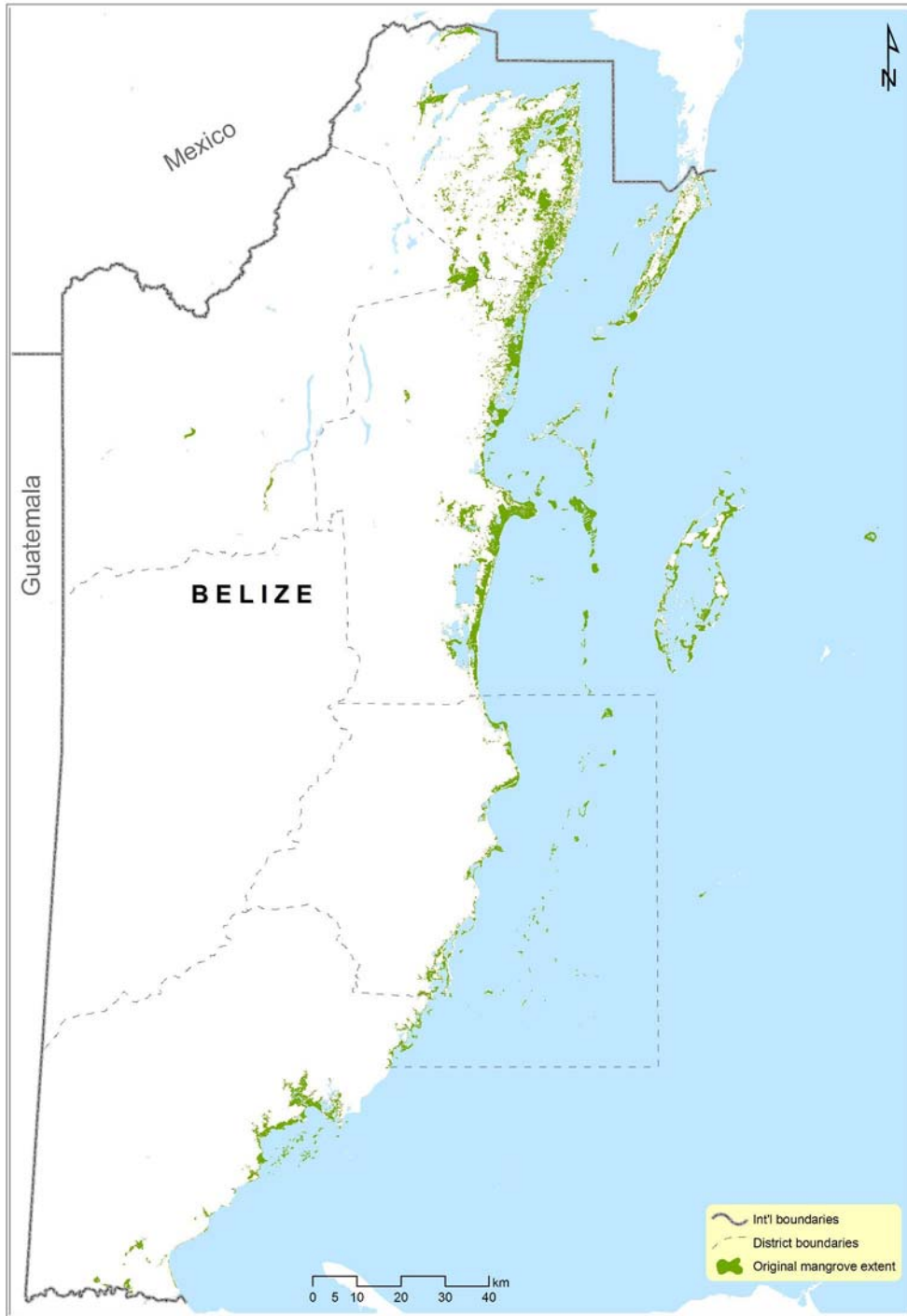


Figure 1: Belize’s original, pre-settlement mangrove cover, after Zisman (1998)

Zisman not only mapped Belize’s mangrove ecosystems, but classified them physiographically into five main groups: (i) sparse mangroves in open water, (ii) mangrove savannas, (iii) dwarf mangrove scrubs, (iv) communities of mangroves of medium height, and (v) tall mangrove formations. Zisman 1998 and Murray et al (2003) give detailed descriptions of those classes; **Figure 2** illustrates their geographic distribution.

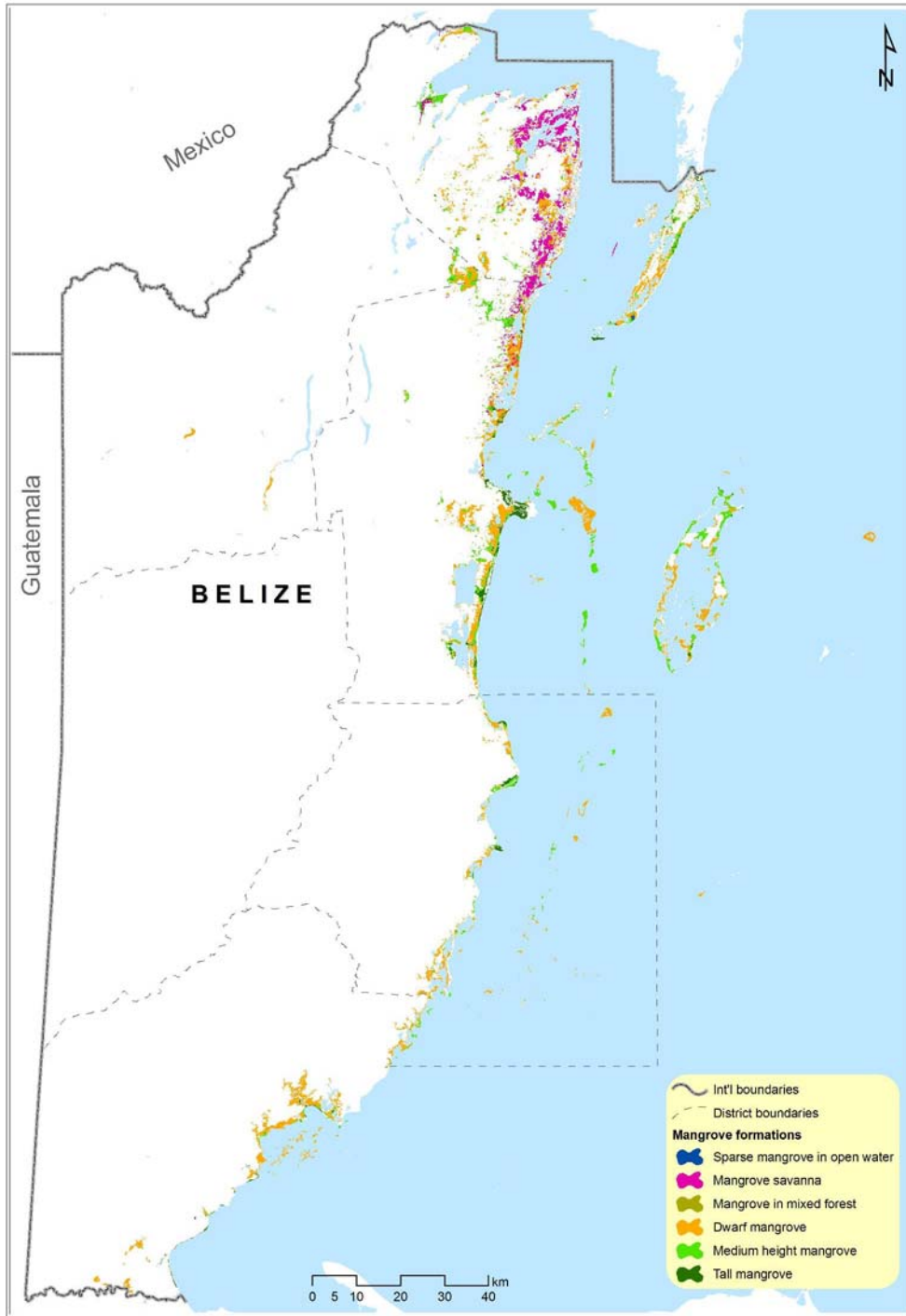


Figure 2: Belize’s mangrove formations, based on Zisman (1998)

It should also be recognized that accuracy – ultimately where a map coincides with the reality on the ground – is an important consideration (Lillesand et al 2007). It is important to note that Zisman developed the third version of the national mangrove map through targeted revisions of the two earlier versions of the map, based on extensive field work. While his estimate is not based directly on the collection of field data for a quantitative assessment of accuracy, Zisman

estimated the overall accuracy of his 1990 map to be 85-95%, with accuracy of mapping the height classes to be “within the 50-80% range” (Zisman 1998: Appendix 6, page 9). Nevertheless, based on the robustness of his approach, Zisman’s data for 1990 can thus be considered an authoritative baseline regarding Belize’s mangrove cover. One of Zisman’s (1998) recommendations was that the national map should be updated regularly. Nine years later, this was echoed by McField & Kramer (2007: 41) who made three specific recommendations for “regularly tracking mangrove forest extent,” for “sharing information in a readily accessible database,” and for “basic monitoring by remote sensing coupled with field-based ground truthing.”

Mangrove Mapping post-Zisman

In the intervening years since Zisman (1998), data on mangrove cover for Belize became available from a number of sources. A few of these are national land cover maps, which have included a mangrove class, while other mapping projects have specifically targeted the mapping of mangroves. These are:

- (i) Meerman & Sabido’s (2001) national ecosystems map
- (ii) Meerman’s (2005) revision of the national ecosystems map
- (iii) EarthSat’s (2005) GeoCover LC global-level land cover maps
- (iv) World Resources Institute’s (2008) map of Belize’s mangroves¹
- (v) DIVERSITY’s (2008) maps of the Mesoamerican Reef mangrove ecosystems
- (vi) SERVIR’s (2008) map of Belize’s mangroves
- (vii) Meerman et al (2010)’s map of Belize’s forest cover²

There are, however, factors which limit the utility of most of the datasets listed above. For instance, where Iremonger & Brokaw’s (1995) map was the basis for the ecosystem maps of Meerman & Sabido (2001), and Meerman (2005), one would assume that discrepancies present within Iremonger & Brokaw (1995) would have been propagated in the legacy datasets. Internal assessments conducted by CATHALAC in 2008 indicated various errors in the mangrove maps developed by WRI and the data developed under European Space Agency (ESA)-funded DIVERSITY project, likewise limiting their ultimate usefulness.

For instance, where the DIVERSITY project developed maps of mangrove cover based on radar imagery for 1996 and for 2007, an accuracy assessment conducted by CATHALAC indicated respective class accuracies for mangroves of 26% and 51%. The assessment of the WRI data indicated that the analysis undertaken was complicated by high cloud cover in the images utilized. The EarthSat GeoCover LC maps for circa 1990 and circa 2000 were likewise assessed to bear little resemblance to the existing maps of mangrove, likely due to their being generated through the process of unsupervised classification.

¹ This unpublished dataset was developed from Landsat 7 data for 2000-2002 for use in its Oak Foundation-supported economic valuation of the Belize Barrier Reef System (Cooper et al 2009).

² This data was not available at the outset of this project and was therefore not assessed.

The underlying thread of six of the seven studies listed above is that they re-mapped Belize's mangroves in lieu of utilizing what the remote sensing parlance refers to as a change detection study (Lillesand et al 2007). In a change detection study, one evaluates changes from a pre-set baseline. In 2008, in the framework of SERVIR and funded by the Smithsonian Institution's *Healthy Reefs for Healthy People* initiative, CATHALAC and NASA utilized Zisman's data as a baseline to conduct a change detection in order to assess mangrove cover for the period 2006-2007, based on satellite imagery from the Landsat 7 satellite's ETM+ sensor and the Terra satellite's ASTER sensor. The study had the shortcoming of not its results verified through ground-truthing, and in terms of currency of the data, in 2010 its findings are obsolete.

II. OBJECTIVES

Acknowledging that the wider Mesoamerican Reef eco-region in which the Belize Barrier Reef lies is vulnerable to climate change and other anthropogenic factors, the current project was formulated to assess the status of Belize's mangrove ecosystems by utilizing the synoptic perspective afforded by satellite imagery.³ The objective of this study was thus to update and extend the earlier evaluation of Belize's coastal mangrove cover conducted in the context of SERVIR, by more comprehensively assessing recent changes in mangrove extent. While the overarching objective of this project was to map the current extent of the mangrove ecosystems of the Belize Barrier Reef System⁴, the specific objectives of this project were:

- (i) to utilize remote sensing to map Belize's mangrove ecosystems, stratified by physiographic classes at a scale of 1:100,000 for the years 1980, 1989, 1994, 2000, 2004 and, the 2010, utilizing imagery available from the Landsat series of satellites and supplemented where necessary by imagery from the ASTER sensor, compared against the baseline established by Zisman (1998),
- (ii) to identify areas of change (i.e. loss, colonization and regeneration) in mangrove ecosystems since 1980, and
- (iii) to identify mangrove areas potentially at risk of being cleared.

Making the information on Belize's mangrove cover available for decision-making was also an underlying objective of this study. In addition to making the outputs available, the various inputs utilized in the analysis were also placed in the public domain (via SERVIR, see hyperlinks in the following sections) to allow the methodology to be replicated at a later date using updated satellite imagery.

³ The oldest source of satellite imagery is the US' Landsat series of satellites. The first Landsat satellite (Landsat-1) was launched almost 40 years ago in 1972, and the seventh satellite in the series, Landsat-7 continues to provide imagery of Belize and the globe every 16 days, cloud cover notwithstanding (Lillesand et al 2007). Hundreds of satellite images for Belize from the 1970s through present are available free-of-charge from the USGS.

⁴ The Belize Barrier Reef System constitutes the largest portion of the Mesoamerican Reef eco-region.

III. METHODOLOGY

The analysis can generally be divided into pre-processing, processing, and post-processing phases. These also included the development of indices related to the canopies of mangrove forests, and ecosystem fragmentation.

Pre-Processing of Satellite Imagery

As the object of the study was to map changes from Zisman's 1990 baseline (i.e. 1994, 2000, 2004, and 2010) and also to map cover prior to 1990 (i.e. 1980, 1989), some processing needed to be done to Zisman's data in order to harmonize it with other ancillary datasets at the project's disposal. As relatively large offsets were detected between islands identified by Zisman (1998) and those islands' locations in orthorectified satellite imagery, those boundaries had to be adjusted using the 30m-derived boundaries for offshore cayes extracted from the SRTM Water Body Dataset (SWBD) obtained from the elevation data collected during STRM, the Shuttle Radar Topography Mission (Jarvis et al 2008). Zisman's data was also converted from shapefile format to raster format to coincide spatially with the satellite data, which was in raster format.

In terms of processing the satellite images, twenty-six (26) individual Landsat satellite images were acquired and "mosaicked" together to produce six sets of images (1980, 1989, 1994, 2000, 2004, 2010) covering all of Belize's territory. Standard image corrections were then applied to the data to removal random noise, and the images were "radiometrically registered" to each other to facilitate comparison (see Aranoff 2005, Jensen 2007, Lillesand et al 2007). A detailed methodology of the pre-processing utilized to prepare the satellite images is presented in Cherrington et al (2010: 9-10). The Landsat images utilized are listed in **Table 1**.

Table 1: Landsat scenes used in the analysis, and their characteristics

Mosaic	Satellite	Sensor	Spatial res.	Spectral res. (µm)	Reference		Location	Date
					Path	Row		
1: 1980	Landsat-3	MSS	60m	0.5 - 0.8	19	47	north	November 14, 1980
	Landsat-3	MSS	60m	0.5 - 0.8	19	48	central	February 14, 1979
	Landsat-3	MSS	60m	0.5 - 0.8	19	48	central	November 14, 1980*
	Landsat-3	MSS	60m	0.5 - 0.8	19	49	south	November 14, 1980
2: 1989	Landsat-5	TM	30m	0.45 - 2.35	19	47	north	December 27, 1989
	Landsat-5	TM	30m	0.45 - 2.35	19	48	central	December 28, 1989
	Landsat-5	TM	30m	0.45 - 2.35	19	49	south	December 29, 1989
3: 1994	Landsat-5	TM	30m	0.45 - 2.35	19	47	north	March 28, 1994
	Landsat-5	TM	30m	0.45 - 2.35	19	48	central	March 28, 1994
	Landsat-5	TM	30m	0.45 - 2.35	19	49	south	March 28, 1994
4: 2000	Landsat-5	TM	30m	0.45 - 2.35	19	47	north	March 28, 2000
	Landsat-5	TM	30m	0.45 - 2.35	19	48	central	March 28, 2000
	Landsat-5	TM	30m	0.45 - 2.35	19	49	south	March 28, 2000
5: 2004	Landsat-7	ETM+	30m	0.45 - 2.35	19	47	north	February 28, 2004
	Landsat-7	ETM+	30m	0.45 - 2.35	19	48	central	January 27, 2004
	Landsat-7	ETM+	30m	0.45 - 2.35	19	48	central	February 12, 2004
	Landsat-7	ETM+	30m	0.45 - 2.35	19	49	south	January 27, 2004
6: 2010	Landsat-7	ETM+	30m	0.45 - 2.35	19	47	north	January 11, 2010
	Landsat-7	ETM+	30m	0.45 - 2.35	19	47	north	February 12, 2010
	Landsat-7	ETM+	30m	0.45 - 2.35	19	47	north	February 28, 2010
	Landsat-7	ETM+	30m	0.45 - 2.35	19	48	central	January 11, 2010
	Landsat-7	ETM+	30m	0.45 - 2.35	19	48	central	February 12, 2010
	Landsat-7	ETM+	30m	0.45 - 2.35	19	48	central	February 28, 2010
	Landsat-7	ETM+	30m	0.45 - 2.35	19	49	south	January 11, 2010
	Landsat-7	ETM+	30m	0.45 - 2.35	19	49	south	February 12, 2010
	Landsat-7	ETM+	30m	0.45 - 2.35	19	49	south	February 28, 2010

* Primary scene utilized for 1980

For public access, the image mosaics for each study year (and their corresponding metadata) have been published in the SERVIR Data Portal (<http://www.servir.net/>) and are available from the following URLs:

- 1980: http://maps.cathalac.org/downloads/data/landsat/landsat3_reflectance_bz_1980-11-14_wgs84.zip
- 1989: http://maps.cathalac.org/downloads/data/landsat/landsat5_reflectance_bz_1989-12-27_wgs84.zip
- 1994: http://maps.cathalac.org/downloads/data/landsat/landsat5_reflectance_bz_1994-03-28_wgs84.zip
- 2000: http://maps.cathalac.org/downloads/data/landsat/landsat5_reflectance_bz_2000-03-28_wgs84.zip
- 2004: http://maps.cathalac.org/downloads/data/landsat/landsat7_reflectance_bz_2004-jan-feb_wgs84.zip
- 2010: http://maps.cathalac.org/downloads/data/landsat/landsat7_reflectance_bz_2010-jan-feb_wgs84.zip

Detection of Changes in Mangrove Cover

The study's main objective of change detection relied upon identifying visible indicators of such change, which determined the type of image processing that was utilized, among a variety in existence. Soil exposition and the presence of impervious surfaces are characteristic of the removal of mangrove and its replacement with infrastructure. Identification of these indicators has been achieved through the automated image processing techniques of "supervised" and "unsupervised" classification, both utilized by CATHALAC in respective analyses of Belize's forest cover (Cherrington et al 2010) and of Panama's mangrove cover (Trejos et al 2008). As Zisman's data could be used as a baseline for the change detection, those techniques were not deemed as optimal.⁵ Thus, the technique known as "spectral mixture analysis" (SMA) – also referred to as spectral mixture modeling or spectral unmixing – was employed since principally both mangrove clearing and regrowth needed to be detected. SMA has been used extensively in the mapping of exposed soil and impervious surfaces (see Lu et al 2002, Braun & Herold 2003, and Tiruveedhula et al 2009). Through its ability to detect vegetative cover, SMA also allowed for identification of the regrowth of mangrove vegetative cover.

As such, a linear SMA algorithm was applied on each of the six Landsat image mosaics⁶, resulting in the generation of three datasets (fractional images) for each image mosaic (i.e. 1980, 1989, 1994, 2000, 2004, and 2010):

- Soil exposure (0-100%)
- Green vegetation content (0-100%)
- Shadowing (0-100%)

As such, each Landsat pixel (equivalent to 0.22 acres) was quantified in terms of the amount of soil, green vegetation, and shadow that it possesses. The utility of such information is that, as indicated in a variety of research studies on SMA, forests and other land cover types generally exhibit predictable patterns in terms of their satellite-derived properties of soil exposure and vegetation cover, as compared to bare land (Lu et al 2002, Braun & Herold 2003, Tiruveedhula et al 2009). Forests, for instance, usually display very low levels of soil exposure from a satellite perspective because looking from above, the soil beneath forests' canopies are covered. Provided those forests are not deciduous and undergoing senescence, they should also display high chlorophyll reflectance, caused by the abundance of leaves in their canopies. Bare land in Belize, often the result of clearing of naturally occurring vegetation for development purposes, on the other hand, shows high levels of soil exposure and very low levels of chlorophyll (caused by traces of grass, perhaps). **Figure 3** for instance illustrates the different fractional images generated for an area with mangroves near Belize City.

⁵ While the Belize forest cover data (Cherrington et al 2010) could be used as reference, it must be recalled that, as noted in Murray et al (2003), Belize's mangrove ecosystems not only fall into the category of "forests" – for instance, closed-canopied formations of trees over 5m in height, into whose definition some medium-height mangrove and all tall mangrove formations would fit - but also closed formations of dwarf mangroves (below 3m in height) and savannas and areas of open water where mangroves are sparse.

⁶ To support follow-on research, the spectral signature "endmembers" utilized for bare soil, green vegetation, and shadow are publicly available at: http://maps.cathalac.org/downloads/data/landsat/bz_endmembers_rois_1980-2010.zip. These are readable in the RSI ENVI® remote sensing package.

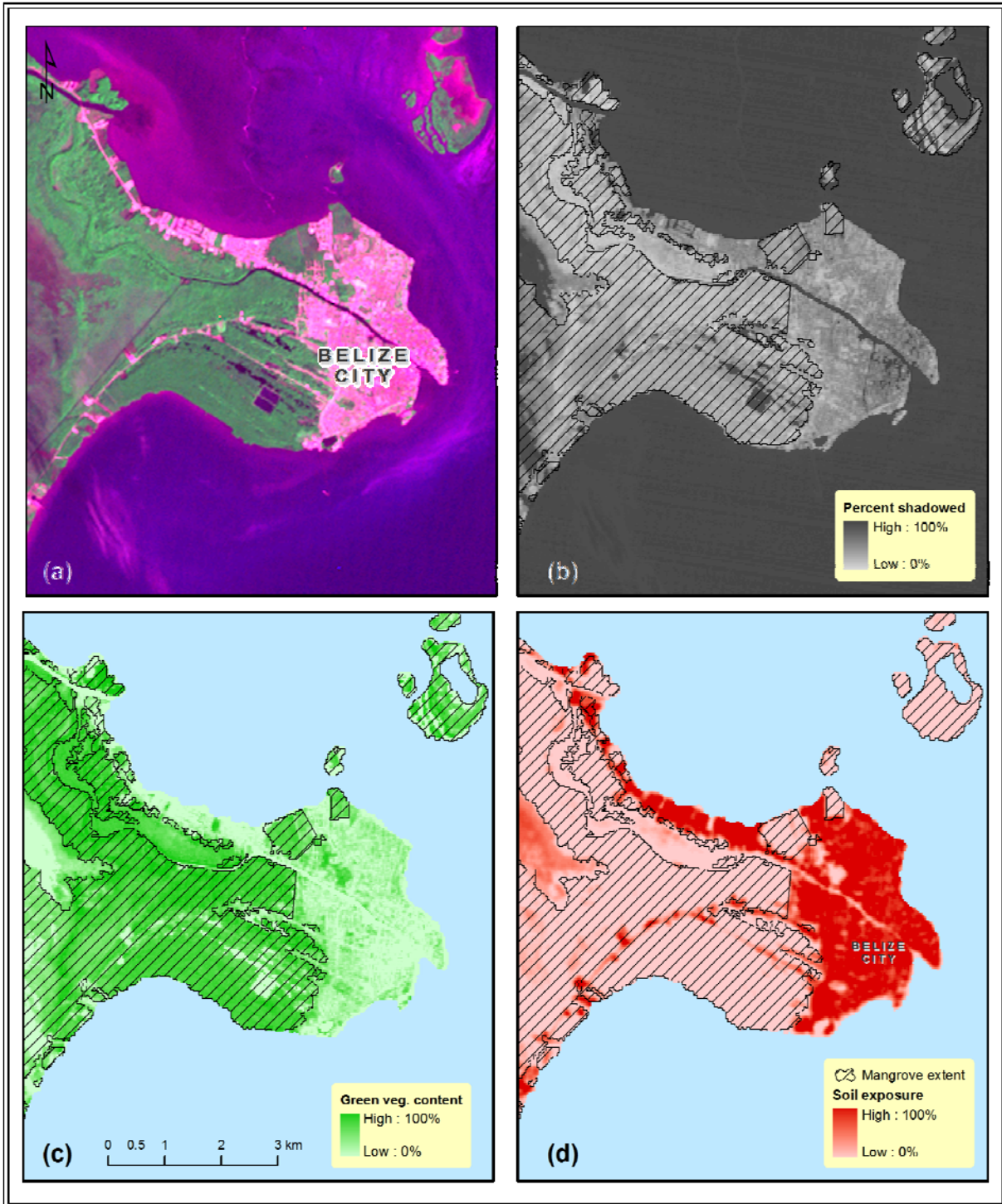


Figure 3: Spectral mixture analysis for the Belize City area, showing that areas devoid of mangrove exhibit high soil exposure and low vegetation content. (a) false color Landsat image captured December 27, 1989; (b) Shadow fraction image; (c) Green vegetation fraction image; (d) Soil fraction image.

In addition to having performed linear SMA on the Landsat images, to hone in on finer details of mangrove change particularly in the offshore cayes, the SMA results from Landsat were complemented by data from the ASTER⁷ satellite sensor, which provides 15m-resolution imagery in the green, red, and near-infrared parts of the electromagnetic spectrum (Jensen 2007, Lillesand et al 2007). An ASTER image mosaic corresponding to March 25, 2010 was acquired through SERVIR to be used to identify different vegetation types. SMA was not applied because of the lack of mid-infrared imagery from ASTER due to a pre-existing sensor malfunction.⁸ Thus, the Normalized Difference Vegetation Index (NDVI) was calculated from the ASTER imagery and used to identify bare land utilizing values below 0.2.

Generation of a Forest Canopy Index

Based on the satellite-derived fractional images generated through SMA, a simple *Forest Canopy Index* (FCI) was devised as follows, utilizing the fractional images of soil exposure and green vegetation cover:

$$\text{FCI} = [\text{Green vegetation content} + (100 - \text{Soil exposure})] / 2$$

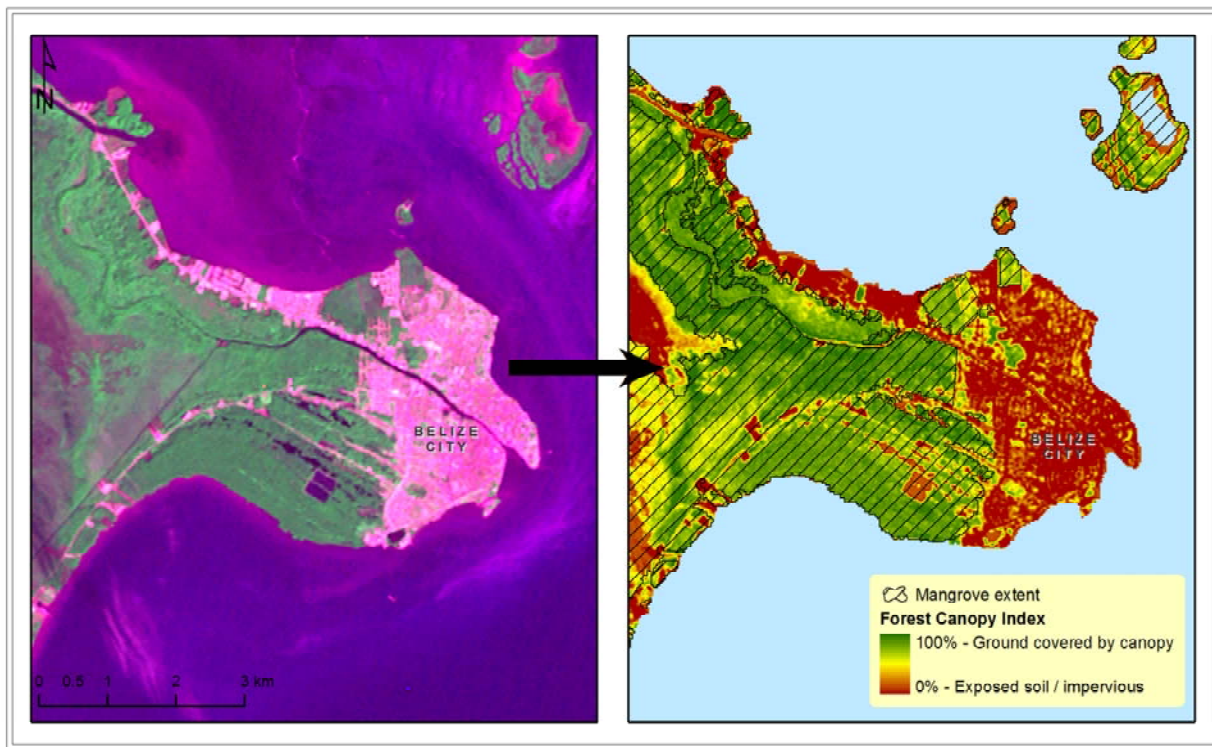


Figure 4: The Forest Canopy Index generated from the 1989 image (*Landsat image on left courtesy of USGS / NASA*)

⁷ ASTER is a joint asset of NASA and the Japanese Space Agency, JAXA, onboard the US satellite Terra (Jensen 2007, Lillesand et al 2007).

⁸ ASTER possesses three cameras: one for capturing visible and near infrared (VNIR) imagery, another for short-wave infrared (SWIR) imagery, and another for capturing thermal infrared (TIR) imagery (Jensen 2007, Lillesand 2007). The SWIR camera suffered a permanent malfunction in April 2008 (<http://asterweb.jpl.nasa.gov/swir-alert.asp>).

As illustrated in **Figure 4**, this provided an index scaled between 0 and 100, which provided vital information on the density of canopy cover in each image pixel. Through index calibration, an FCI threshold of 70% was selected for identifying medium to tall mangrove forests, as areas beneath such a threshold have at most moderate levels of green vegetation, and moderate levels of soil exposure. As such, for the areas identified by the Zisman baseline as mangrove, it was identified whether an area consisted of (i) cleared land, (ii) dwarf mangrove, or (iii) medium to tall mangrove.

The six FCI maps (i.e. 1980, 1989, 1994, 2000, 2004, and 2010) were subsequently combined into a single binary dataset to express whether or not an area was covered by mangrove in any given period. By merging these six FCI maps with Zisman's baseline data, a dynamic of how each pixel had changed between 1980 and 2010 was obtained. It could be assessed, for instance, whether a given pixel had been converted from medium-height mangrove in 1989 to bare land in 1994. Mangrove extent was thus quantified for the six years, and changes in the periods in between were likewise assessed (principally mangrove clearing or mangrove regrowth).

Generation of Fragmentation Indices

Additionally, within the geographic information systems (GIS) environment of ESRI ArcGIS 9.2®, metrics of mangrove fragmentation were calculated. In addition to having identified via remote sensing those mangrove patches which had been cleared outright, or which had regrown, the GIS allowed the identification of mangrove patches whose areal extents had been altered. In some cases, the process of clearing had broken mangrove patches into multiple fragments; in other cases, the patch sizes had merely been reduced. This was evaluated over time and used to develop a separate dataset indicating the history of fragmentation.

Further regarding fragmentation, utilizing the work of Tremblay-Boyer & Anderson (2007), an index of the theoretical fragmentation potential of Belize's mangroves was also generated, based on the shape of each mangrove patch. Tremblay-Boyer & Anderson (2007)'s "Ecosystem Patch Irregularity Index" (EPII, otherwise denoted as EVCC₂) indicated how easy it is for an ecosystem patch to become fragmented due to its inherent geometry. "Thinner" patches with large perimeter to area ratios, for instance, are more likely to become fragmented than more "compact" patches with lower perimeter to area ratios. The EPII was generated through the following equation:

$$EPII = \frac{Patch\ perimeter}{(2\pi \times \sqrt{Patch\ area/\pi})}$$

The EPII values were subsequently ranked in terms of the theoretical fragmentation potential.

Post-processing

As explained in greater detail in the following section, post-processing involved extensive visual assessment of the outputs against the source imagery, allowing for correction of errors as encountered.

IV. VALIDATION

Field validation of this study is slated for late 2010, after the release of this technical report. Where maps of mangrove cover for six periods have been developed, it should likewise be recognized that field validation will only allow for quantitative assessment of the accuracy of the 2010 map. Quantitative accuracy assessment of the 1980, 1989, 1994, 2000, and 2004 maps would require access to any of the three sources for each of the respective dates:

- (i) Field surveys taken within and outside of areas with mangrove,
- (ii) Ortho-rectified aerial photography (ortho-photos), or
- (iii) High resolution (2.5m or better) satellite imagery.

It is likely, for instance, that much of the field data (with accompanying coordinates) for the periods identified *do not exist* even though mangrove monitoring data was registered in ~2004-2007 in the Regional Environmental Information System (REIS) established under the now-defunct Mesoamerican Barrier Reef Systems (MBRS) project. That information could hence not be accessed. While aerial photography for Belize exists and was utilized by Zisman in his mapping effort, aerial photography in an ortho-rectified format which could be manipulated in a geographic information system (GIS) could not be located, even though aerial photography is being collected by a US-based group called CAVU (Nadia Bood, personal communication). High-resolution satellite imagery – available only at cost – could likewise not be acquired within the constraints of this project.

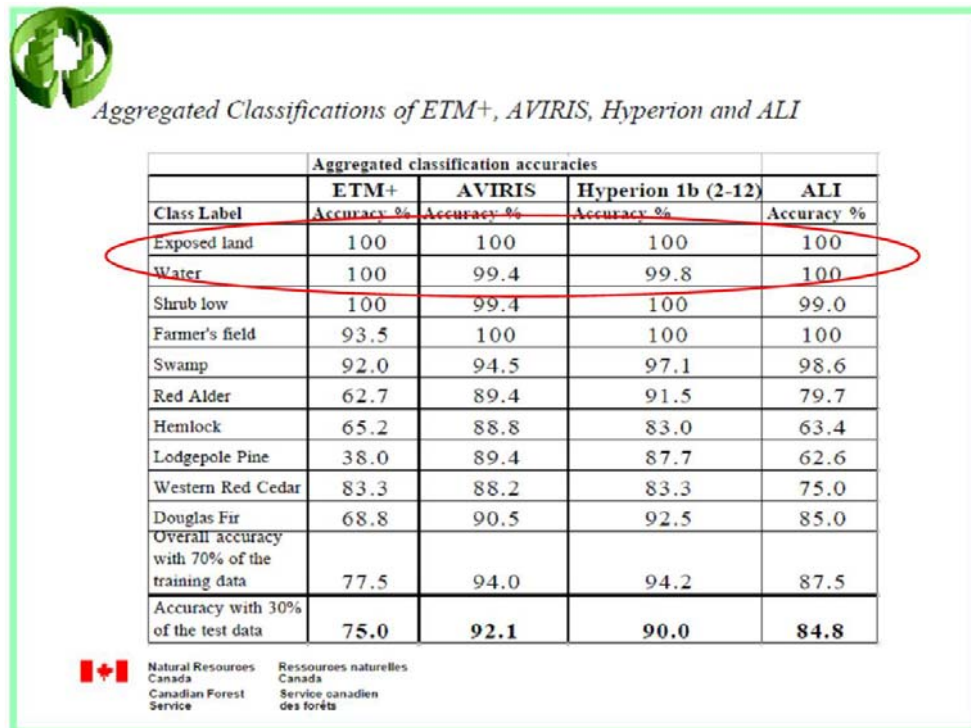


Figure 5: Accuracy assessments of classifications of different types of imagery, showing that both exposed land and water are routinely mapped with almost absolute accuracy (*source: Goodenough et al 2002*)

Nonetheless, there is much reason to suspect that this study’s results should enjoy a high overall level of accuracy, based on the changes being detected. According to sources in the literature such as Goodenough et al (2002), impervious surfaces and exposed soils appear quite distinct from other land cover features such as forest; hence they can be identified with a high degree of accuracy. As demonstrated in **Figure 5**, Goodenough et al (2002) were able to identify exposed land with an accuracy of 100% utilizing four different sensors. **Figure 3** in the previous section likewise shows how well the spectral mixture analysis performed in assessment of Belize City’s impervious surfaces and exposed soil.

The maps generated were also subjected to extensive verification against the source satellite imagery (both Landsat and ASTER), in addition to ASTER imagery for other periods that CATHALAC had access to through SERVIR. The process of revising the areas identified as changed allowed for the identification of areas erroneously identified as changed, which it is expected should contribute to an overall high degree of accuracy in this study’s outputs. While some errors are inevitable, it is anticipated that this study’s results should be quite accurate overall at the scale of its intended use (i.e. 1:100,000). Nevertheless, it is also expected that this report will be updated after completion of the field validation exercises.

V. RESULTS

Based on Zisman (1998)’s estimation of Belize’s original mangrove cover, it is concluded that mangroves once covered some 191 thousand acres (3.5%) of the country’s land surface (see **Figure 1**, and **Table 2**). Mangroves are found on much of the coast of the mainland, and much of the area of the offshore islands,⁹ as well as a few areas far inland, to a limited extent. The present study indicates that Belize’s mangrove cover in mid-November 1980 stood at 188 thousand acres, or 98.7% of the original coverage. This study likewise estimates that as of early 2010, national mangrove cover had declined to 185 thousand acres, or 96.7% of the original cover, following a process of widespread mangrove clearing and extremely limited regrowth (see **Figure 6**). Some 1,100 individual clearings of mangrove were detected for the period between 1980 and 2010, to the tune of a net¹⁰ annual clearing of 125 acres being cleared annually, but with an average clearing size of 3.48 acres. The average size per mangrove clearing on the offshore cayes was 3.8 acres, compared to 3.38 acres for mainland mangrove clearings.

Table 2: Mangrove cover, 1980-2010

Year	Area		% Mangrove cover	% Land cover
	Acres	Hectares		
pre-1980	190,897	77,254	100%	3.5%
1980	188,417	76,250	98.7%	3.4%
1989	187,458	75,862	98.2%	3.4%
1994	186,736	75,570	97.8%	3.4%
2000	186,318	75,400	97.6%	3.4%
2004	185,582	75,103	97.2%	3.4%
2010	184,548	74,684	96.7%	3.4%

⁹ Zisman (1998) estimated that mangroves are found on some 60-80% of Belize’s offshore cayes.

¹⁰ Total average annual clearing was 132 acres / year; factoring in regeneration, net loss was 125 acres / year.

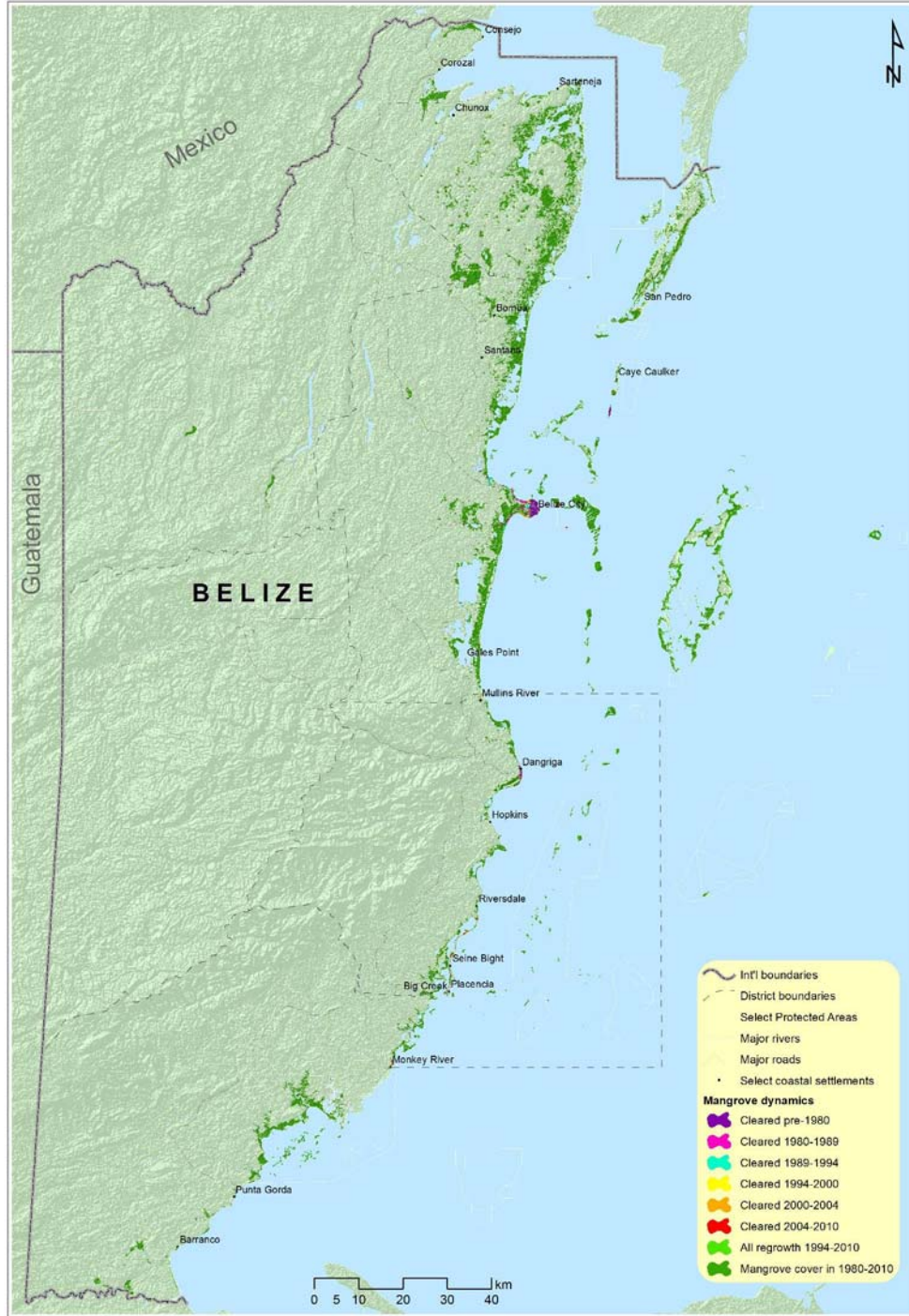


Figure 6: Mangrove dynamics, 1980-2010

Nevertheless, while mangrove cover did decline from 98.7% of its original cover in 1980 to 96.7% of its original cover in 2010, as **Table 2** also illustrates, the overall percentage of Belize’s land cover covered by mangrove ecosystems remained at 3.4% over the almost 30-year period. As indicated in **Table 3**, and in line with Zisman (1998), in 2010 dwarf mangrove communities represented the largest single physiographic mangrove class, representing over a half of overall mangrove cover. Mangroves of medium height represented slightly over a fifth of overall

mangrove cover in 2010, while tall mangroves represented only one-twentieth of mangrove cover. Clearance of mangrove savanna and sparse mangrove in open water was negligible.

Table 3: Distribution of mangrove communities in 2010

Type	Area		
	Acres	Ha.	%
Sparse mangrove in open water	320	130	0.2%
Mangrove in mixed forest	112	45	0.1%
Mangrove savanna	31,309	12,670	17.0%
Dwarf mangrove	103,119	41,731	55.9%
Medium height mangrove	39,769	16,094	21.5%
Tall mangrove	9,919	4,014	5.4%
TOTAL	184,548	74,684	100%

Mangrove Dynamics

With regard to overall mangrove dynamics, earlier estimates of mangrove loss have been revised to a total clearance of 3,868 acres of mangrove over almost 30 years (i.e. November 1980 – March 2010). This amounts to a relative loss of only 2% of the 1980 mangrove cover, or an average annual net loss of 0.07%, or 125 acres. The overall trend has thus been a very gradual decline in mangrove cover, although as indicated in **Table 4**, regeneration of mangrove ecosystems was also detected (also see the section on *Mangrove Resilience*). Analysis of mangrove clearing by region, for instance, indicates that overall over a quarter of all mangrove clearings between 1980 and 2010 occurred on Belize’s offshore cayes (see **Table 4**). In the period 2000-2004, however, clearing of mangrove on the offshore cayes (i.e. Belize’s offshore islands) slightly *exceeded* clearing on the mainland. Continuing this trend, in the period 2004-2010, offshore mangrove clearing represented almost two-fifths of all clearings.

Table 4: Mangrove dynamics, 1980-2010

Description	Mainland		Offshore		All	Change / yr
	Acres	%	Acres	%	Acres	Acres
Cleared pre-1980	2,204	88.9%	277	11.1%	2,480	
Cleared 1980-1989	905	94.4%	53	5.6%	959	-105.3
Cleared 1989-1994	595	96.8%	20	3.2%	615	-144.6
Cleared 1994-2000	304	70.6%	127	29.4%	430	-71.7
Cleared 2000-2004	332	48.1%	358	51.9%	690	-176.0
Cleared 2004-2010	718	61.1%	457	38.9%	1,175	-195.8
Regrowth 1994-2000	12	100.0%	0	0.0%	12	1.9
Regrowth 1994-2004	95	100.0%	0	0.0%	95	9.6
Regrowth 2004-2010	129	100.0%	0	0.0%	129	21.5
Mangrove cover (1980-2010)	136,896	74.3%	47,416	25.7%	184,312	
Original extent	142,190	74.5%	48,707	25.5%	190,897	

The period 2004-2010 was also the one with the highest rate of clearing, with almost 200 acres of mangrove cleared per year, even as some 21.5 acres of mangrove were being regenerated per year during that same period. The clearing rate in 2004-2010 was almost twice that of the clearing rate in the decade following Belize’s Independence from Great Britain.

Table 5: Mangrove dynamics 1980-2010, with respect to physiographic classes

Mangrove class	Period	Description	Acreage
Dwarf mangrove	pre-1980	Cleared pre-1980	-17
Medium height mangrove		Cleared pre-1980	-95
Tall mangrove		Cleared pre-1980	-2,369
Dwarf mangrove	1980-1989	Cleared 1980-1989	-96
Mangrove savanna		Cleared 1980-1989	-50
Medium height mangrove		Cleared 1980-1989	-41
Tall mangrove		Cleared 1980-1989	-773
Dwarf mangrove	1989-1994	Cleared 1989-1994	-58
Mangrove savanna		Cleared 1989-1994	-6
Medium height mangrove		Cleared 1989-1994	-59
Tall mangrove		Cleared 1989-1994	-492
Dwarf mangrove	1994-2000	Cleared 1994-2000	-100
Mangrove savanna		Cleared 1994-2000	-5
Medium height mangrove		Cleared 1994-2000	-153
Tall mangrove		Cleared 1994-2000	-173
Tall mangrove		Regrowth 1994-2000	12
Tall mangrove	1994-2004	Regrowth 1994-2004	95
Dwarf mangrove	2000-2004	Cleared 2000-2004	-290
Medium height mangrove		Cleared 2000-2004	-217
Tall mangrove		Cleared 2000-2004	-183
Dwarf mangrove	2004-2010	Cleared 2004-2010	-571
Medium height mangrove		Cleared 2004-2010	-460
Tall mangrove		Cleared 2004-2010	-143
Tall mangrove		Regrowth 2004-2010	129
Net change	1980-2010		-3,633
Net change / year	1980-2010		-124

Examining change in mangrove cover through the perspective of the physiographic classes utilized by Zisman (1998) and Murray et al (2003) is also helpful in understanding how mangrove cover has changed. Between 1980 and 2010, for instance, there was a net loss of over 1,500 acres of tall mangroves, a greater change than in any other mangrove class. Net loss of dwarf mangrove was estimated at over 1,100 acres over the study period, and net loss in mangroves of medium height at almost 1,000 acres. Loss of mangrove savanna was estimated at 60 acres between 1980 and 2010.

‘Hotspots’ of Change

A key finding of this study is that mangrove clearing does not occur uniformly across region. Neither is it random, nor should one expect it to be. The destruction of mangroves was definitely related to the nearness of areas of mangrove to either road networks or to marine transport routes. This would seem logical in that accessibility would lend to mangroves being found in prime areas for infrastructural development which leads to their eventual clearing. **Table 7** elaborates on this somewhat, in presenting an analysis of change in Belize’s mangroves by thirteen geographic zones that are based very loosely on the Belize Coastal Zone Management Authority & Institute (CZMAI)’s ‘coastal planning regions’ (see **Figure 7**).

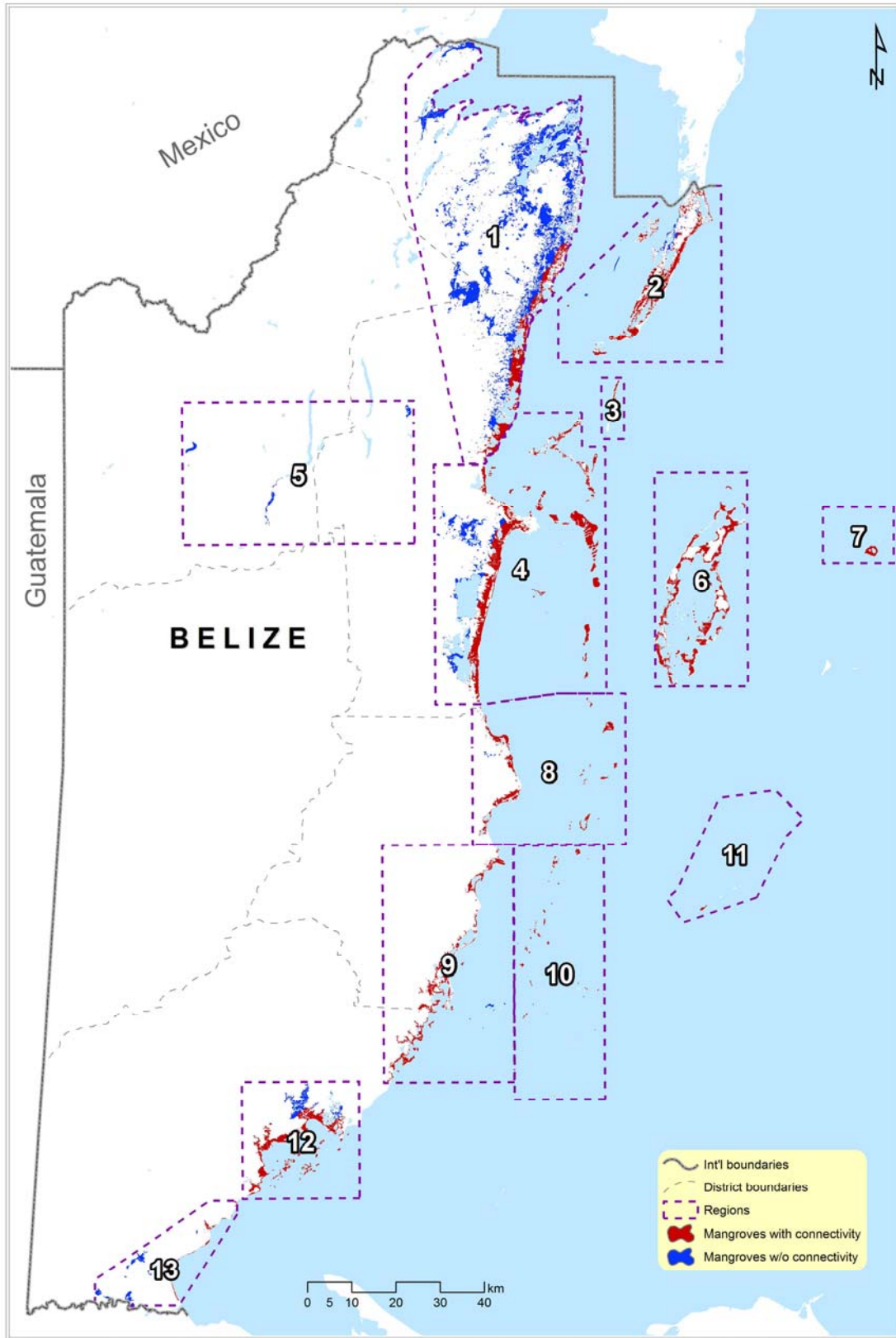


Figure 7: Mangrove connectivity and geographic regions where Belize’s mangroves are found

Table 7: Mangrove change by zone, 1980-2010 (ordered north-south)

No.	Zone	Change 1980-2010 (acres)	% of clearings
1	Corozal + northern Belize District	-231	-6.0%
2	Ambergris Caye area	-455	-11.8%
3	Caye Caulker & Caye Chapel	-102	-2.6%
4	Belize City + nearby cayes	-2,074	-53.8%
5	Far inland mangroves	0	0.0%
6	Turneffe Atoll	-17	-0.4%
7	Lighthouse Reef	0	0.0%
8	Dangriga + nearby cayes	-385	-10.0%
9	Placencia + nearby cayes	-471	-12.2%
10	Pelican Cayes range	-105	-2.7%
11	Glover's Reef	0	0.0%
12	Punta Ycacos & Port Honduras	0	0.0%
13	Sarstoon-Temash	-19	-0.5%
TOTAL		-3,858	

It was thus found that almost 90% of all clearings between 1980 and 2010 occurred in only four principal zones, in the following order of magnitude of clearing: (i) the Belize City area (including surrounding cayes), (ii) the Placencia peninsula and surrounding cayes, (iii) Ambergris Caye and nearby islands, and (iv) the Dangriga area and nearby cayes. More than half of all mangrove clearings from 1980-2010 occurred near Belize City. In other areas like the Punta Ycacos / Port Honduras area, Glover's Reef, Lighthouse Reef, and in the case of the mangroves located far inland, no change at all was registered over the study period.

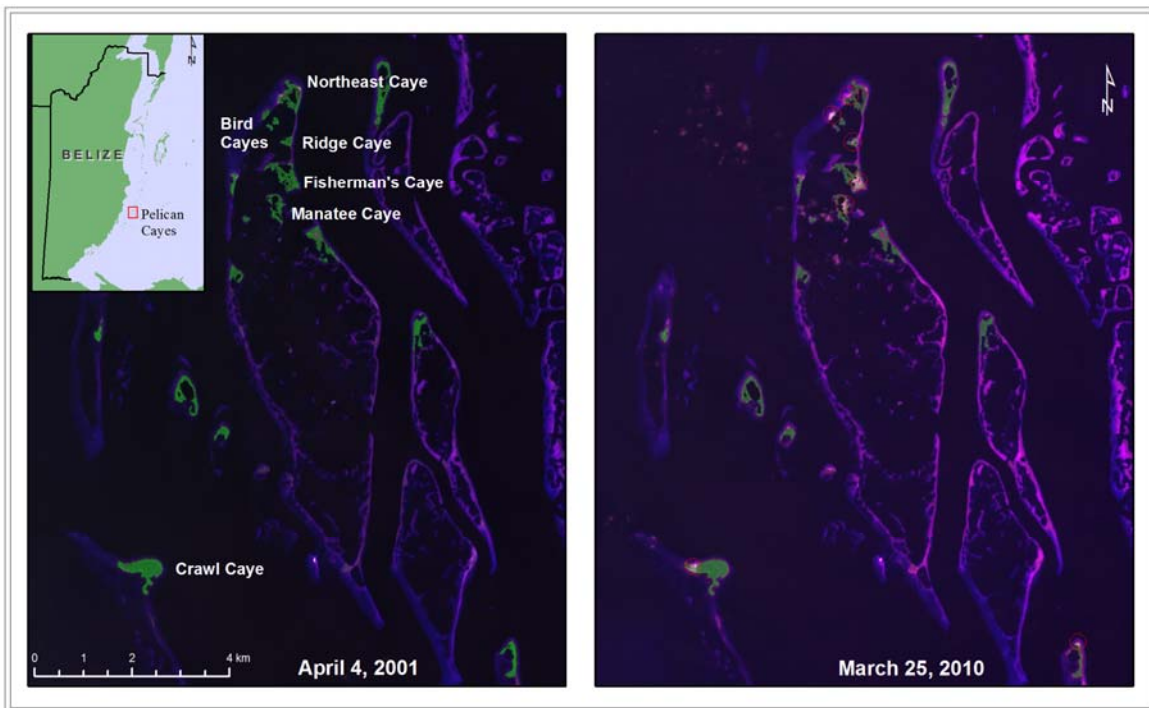


Figure 8: Mangrove clearing in the Pelican Cayes, 2001-2010 (ASTER images courtesy of JAXA / NASA)

Figure 8 highlights one of those zones experiencing change, namely the case of mangrove clearings in the Pelican Cayes range, which was the subject of intense scrutiny in 2008 (MNREI 2010). GIS analysis indicates that some 28 acres (11 ha.) of the range’s 692 acres of mangrove cover had been cleared between 2004 and 2010 (another ~3 acres had been cleared between 1994 and 2004). This amounted to the loss of merely 4% of the range’s overall mangrove cover.

Marine Connectivity

The Government of Belize’s ambitious 2004-2005 *National Protected Areas Policy & System Plan* (NPAPSP) utilized the concept of marine connectivity in examining the distribution of Belize’s mangroves in relation to seagrass beds and coral reef. As such, those mangroves within a 2.5km distance of seagrass and reef were considered the most ecologically important and thus (NPAPSP 2005). The mangroves which possess such marine connectivity are also the ecosystems which can be considered integral to the functioning of the *Belize Barrier Reef Complex*, along with the seagrass and coral reefs that these mangrove ecosystems interface with. Both **Figure 7** and **Table 6** thus illustrate that with respect to those mangrove ecosystems possessing marine connectivity, from 1980-2010, their overall representation declined from 55.2% of all mangroves in 1980 to 54.5% in 2010. Of significant note is that of the 3,868 acres of mangroves cleared from 1980-2010, 3,517 acres of mangroves with marine connectivity were cleared, representing 90.9% of all mangrove clearing.

Table 6: Marine connectivity of mangroves, 1980-2010

Year	All mangroves	Mangroves w/ marine connectivity	
	(acres)	(acres)	%
pre-1980	190,897	106,537	55.8%
1980	188,417	104,087	55.2%
1989	187,458	103,241	55.1%
1994	186,736	102,602	54.9%
2000	186,318	102,198	54.9%
2004	185,582	101,527	54.7%
2010	184,548	100,569	54.5%

Mangrove Resilience

In terms of mangrove ecosystems’ resilience, only small areas of regrowth of mangrove were detected, all of these areas near Belize City. In total, some 236 acres of regrowth was detected near Belize City, including a large 129-acre area which had regrown from a larger clearing of ~260 acres (see **Figure 9**). The mangrove in that area had been cleared in 2002 for the development of cruise tourism facilities. It is suspected that the main reason that mangrove regeneration was not detected in other locations is that upon clearance, the land previously occupied by mangroves is then likely converted to specific land uses (e.g. housing infrastructure) which are then maintained, unlike the case of tropical rainforest, which might regrow (GOFCC-GOLD 2009). The case of the cruise tourism facility, which incidentally was never built, is a rare example of mangrove being cleared followed by the land being left largely idle, even though the eastern half of the cleared parcel – on which *some* infrastructure sat in March 2010 – did *not* regenerate.

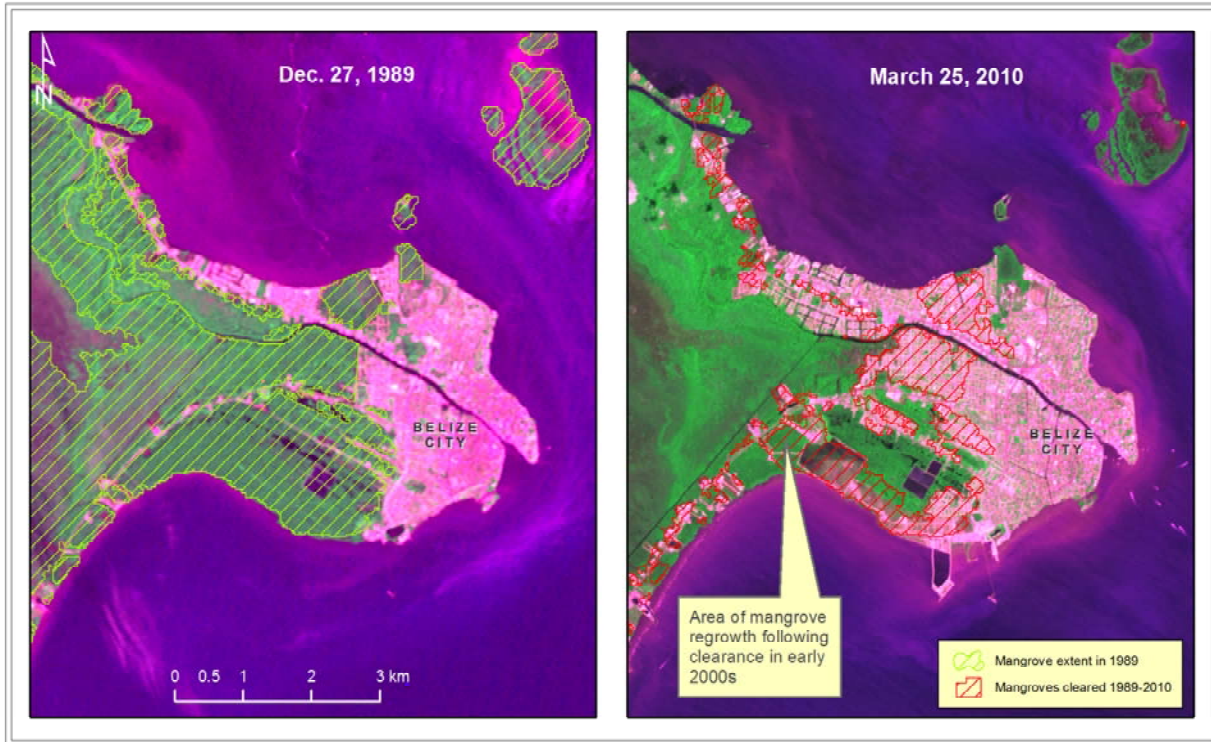


Figure 9: Mangrove cover and change near Belize City, 1989 vs. 2010 (*Landsat image on left courtesy of USGS / NASA; ASTER image on right courtesy of JAXA / NASA*)

Ecosystem Fragmentation

The data on fragmentation of mangrove ecosystems are also quite illustrative. In addition to “fragmentation,” in terms of the overall perspective, the results of this study also indicate that clearing land subjects mangrove ecosystems to three main processes / outcomes:

- (i) outright destruction of entire mangrove communities,
- (ii) fragmentation of mangrove communities, or
- (iii) reduction of the areal extent of mangrove communities.

From the 1:100,000 scale of this study’s mapping, it was assessed that in 1980, Belize’s mangroves existed in approximately 6,515 patches (stratified by structure) exceeding 1 acre in size. By 2010, that number had declined to 6,402 patches, although mere comparison of the two statistics masks what has occurred. With regard to risk of future fragmentation, **Figures 10-11** examine both the ease of fragmentation and the history of fragmentation, and indicate that the mangrove ecosystems (both mainland and offshore) near Belize City and San Pedro Town had the highest overall fragmentation risk, in line with the previously explored ‘hotspot’ analysis. **Figure 10** also illustrates that in general, most of Belize’s mangrove communities have areal extents that make them susceptible to fragmentation. **Figure 11** also indicates that while fragmentation has been greatest near Belize City and San Pedro Town, fragmentation has also occurred near all major coastal settlements. Areas where mangrove ecosystems have been fragmented have also generally experienced outright clearing of entire mangrove communities. In the case of both Belize City and San Pedro, there have been both high levels of fragmentation

as well as high levels of outright clearing; in Dangriga and the Placencia peninsula, there have likewise been high levels of outright clearing. In the case of Placencia peninsula, however, with its small relative extent, fragmentation has not been high. This is because, according to the data, outright clearing of small swaths of mangrove in certain parts of the Peninsula has reduced the extent of (rather than fragmenting) those mangroves.

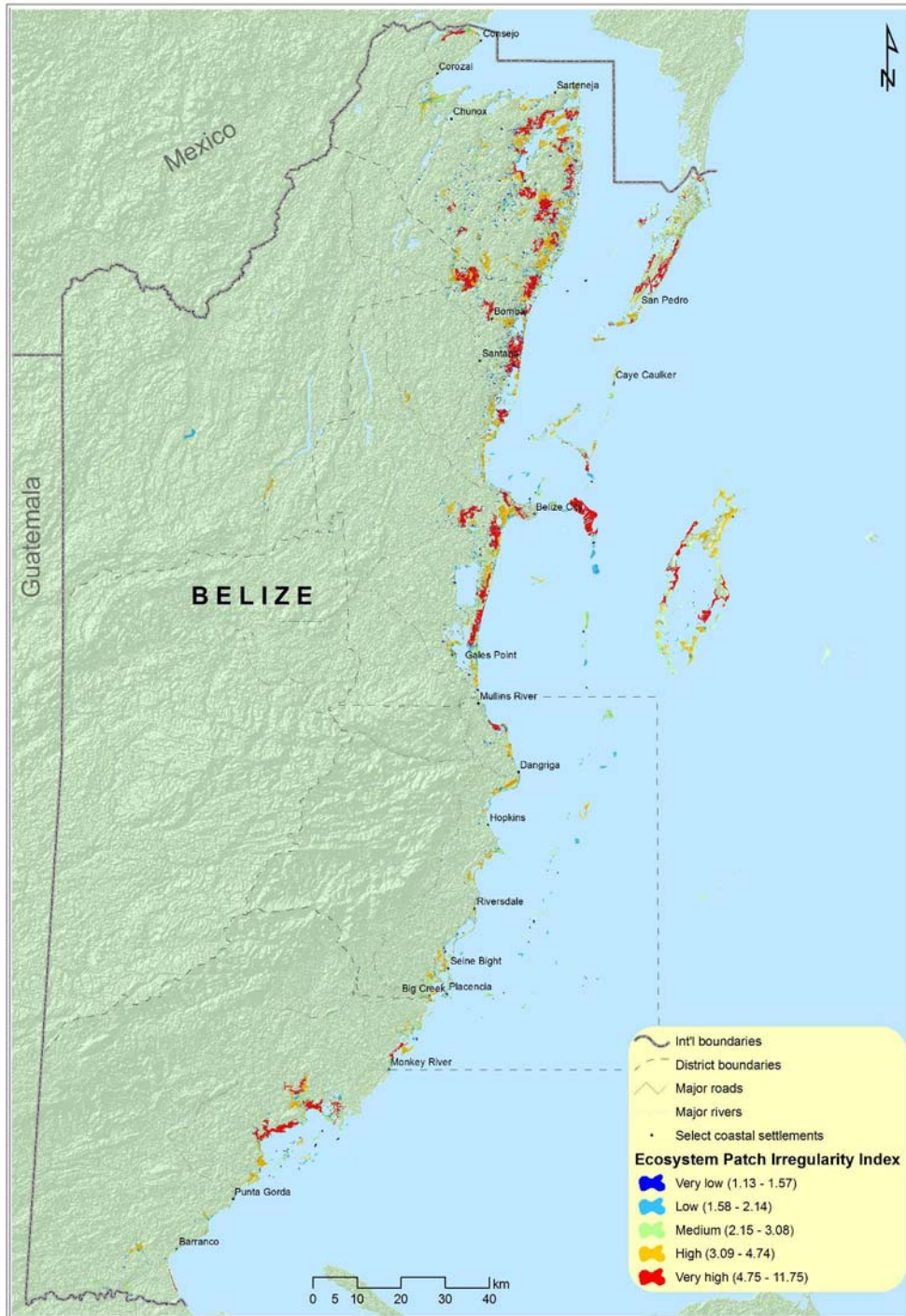


Figure 10: Ease of fragmentation of Belize's mangroves in 2010

In terms of the overall analysis, of the 6,515 mangrove communities (patches) which existed in 1980, 335 such communities were destroyed by outright clearing. Another 226 communities were fragmented into 458 patches. Those fragments represented merely 2.1% of total mangrove cover. In terms of the effect of mangrove clearing on mangrove connectivity, almost a quarter of the clearings between 1980 and 2010 resulted in fragmentation of mangrove communities.

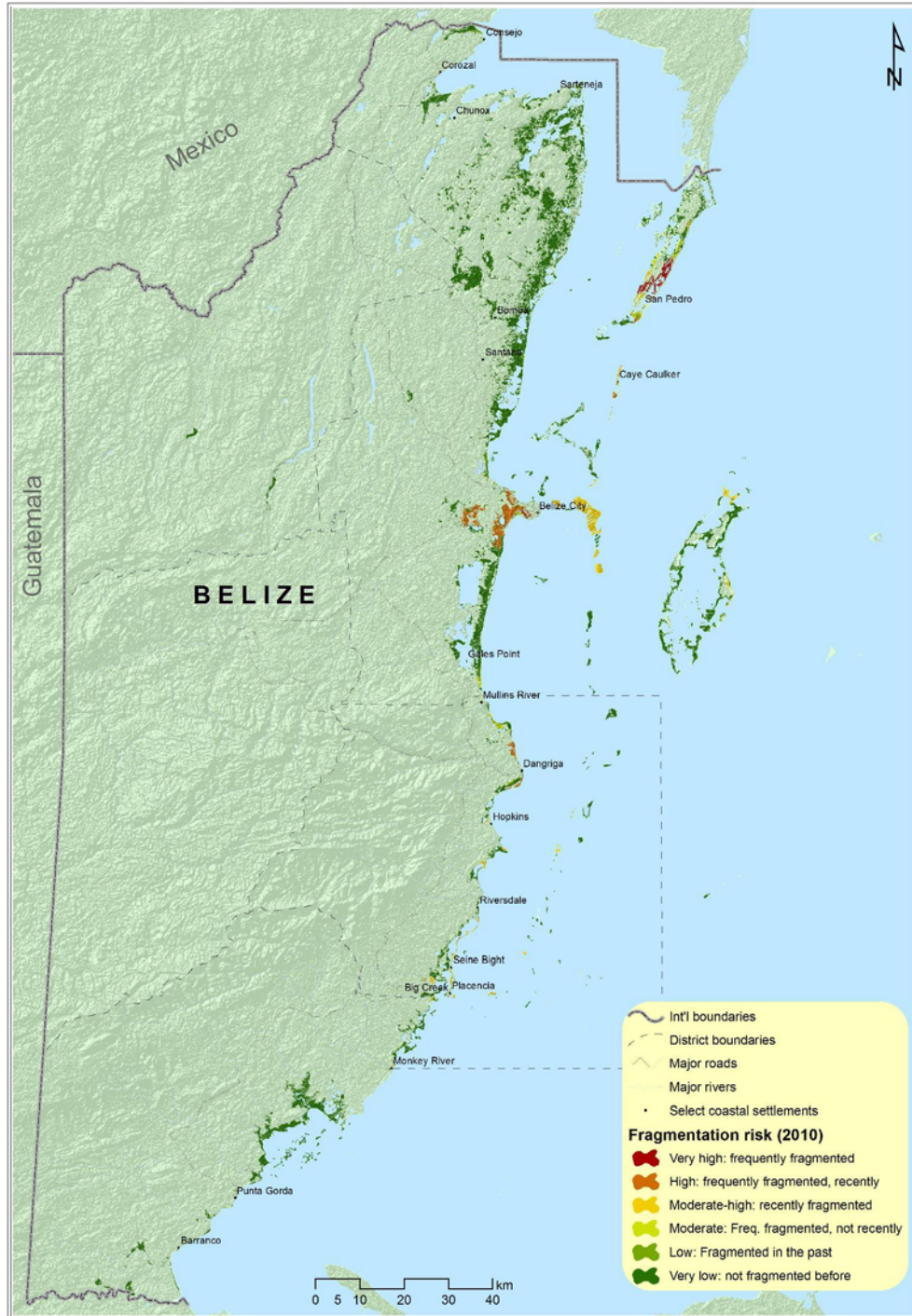


Figure 11: Susceptibility of fragmentation of Belize’s mangroves, 2010

Whereas less than a percent of clearings were “clean sweeps” which destroyed entire mangrove communities, almost 75% of clearings resulted in the reduction of the areal extent of mangrove communities (i.e. “trimming” / patch size reduction). This analysis also indicated, however, that on average, 91.6% of the mangrove communities were unaffected by anthropogenic alteration between 1980 and 2010. Additionally, analysis of fragmentation risk and fragmentation history indicates that the areas of highest risk of fragmentation lie near coastal urban areas, specifically near Belize City and near San Pedro. Beyond fragmentation risk in those areas, mangrove communities there were also at risk of being cleared completely for infrastructural expansion.

Data Availability

In line with the recommendation of McField & Kramer (2007) for “sharing information in a readily accessible database,” in order to facilitate further research, the results of this study have been datasets have been uploaded to SERVIR and are available from the following links:

- http://maps.cathalac.org/Downloads/data/bz/bz_mangroves_cathalac_1980-2010_v1.zip
(mangrove cover for pre-1980, 1980, 1989, 1994, 2000, 2004, and 2010; mangrove dynamics for pre-1980-1980, 1980-1989; 1989-1994; 1994-2000; 2000-2004; 2004-2010)
- http://maps.cathalac.org/Downloads/data/bz/bz_mangrove_frag_risk_cathalac_v1_2010.zip
(degree of mangrove fragmentation, and risk of fragmentation)

VI. DISCUSSION

This study has a variety of implications, from the national to international levels. These implications also translate to a variety of opportunities for future research. Nonetheless, in examining this study’s implications, it is worth framing the results of this analysis in terms of recently-published global trends of mangrove loss. It is also necessary to consider this study in the context of the need for an agreed-upon national baseline for mangrove cover. First and foremost, however, the drivers of mangrove clearing in Belize need to be considered.

Drivers of Change

With regard to the drivers of change in Belize’s mangrove ecosystems, an unpublished, internal study conducted by Belize’s CZMAI (Cherrington 2005) noted that land cover change in Belize was largely due to four principal processes:

- (i) agricultural expansion,
- (ii) urban expansion,
- (iii) the development of coastal infrastructure, and
- (iv) aquaculture development.

Although the current study did not specifically address the drivers of mangrove loss, it can be speculated – supported by the literature (e.g. Zisman 1998, Murray et al 2003) – that two of the above factors were *not* responsible for mangrove loss. That is to say, it has not been noted that agricultural expansion has contributed to the clearing of mangroves, even though Giri et al (2007) point out that in Asia, 81% of mangrove loss from 1975-2005 was caused by agricultural

encroachment. Murray et al (2003) also point out that the establishment of ponds for aquaculture in Belize had largely been constrained to inland savanna. This leaves one to suspect that the main drivers of the mangrove loss noted in this study to thus be related to the expansion of settlements (e.g. Belize City, San Pedro), and the development of tourism-related infrastructure on the coast. While that thus seems like a logical conclusion, it might be worthwhile nevertheless to conduct further research to examine the current land use on lands formerly occupied by mangrove, even as Zisman (1998) likewise concluded that most of the mangroves cleared from 1990-1992 were replaced with housing developments. In fact, Zisman (1999: 4-5), lists the main land uses that mangroves have been converted to as:

- (i) **Housing developments:** “Former mangrove areas that has been replaced by housing” ranging from low to high density
- (ii) **Industrial & commercial uses:** “Former mangrove areas that have been replaced by industry (e.g. storage yards, factories, etc.) or businesses like shops, banks, etc.”
- (iii) **Institutional uses:** “Former mangrove areas that have been replaced by waste dumps and sewage treatment works”
- (iv) **Waste disposal:** “Former mangrove areas that have been replaced by some other form of use. This includes the cemetery, for instance.”
- (v) **Other uses:** “Former mangrove areas that have been replaced by waste dumps and sewage treatment works”
- (vi) **Open water:** “Former mangrove areas that have been eroded and removed, as a result of dredging that led to increased erosion. The only place so far identified where this happened is at New Brighton / Yarborough, Belize City.”

This is reason, nevertheless, to suspect that tourism-related development is driving mangrove clearing. While no mention is made in Zisman (1998), Zisman (1999) or Murray et al (2003) to the conversion of areas with mangroves, the recent joint national report of the Ministry of Natural Resources and the Environment and the United Nations Environment Programme (UNEP), in the context of UNEP’s *Global Environmental Outlook*, does make reference to mangrove-altering coastal development “infrastructure to attract tourism and increasingly retirees from the developed world” in addition to “infrastructure for local populations in the forms of businesses, homes and roads” (MNRE 2010: 108). The same report, nonetheless, also highlights that “coastal development for tourism usually involves the clearing of mangroves” (MNRE 2010: 108).

The Ministry of Natural Resources and the Environment’s 2010 report also explored the issue of clearing of mangroves in the context of Belize’s *Forests Act*, whose 1989 “Protection of Mangroves” Regulations establishes a legal process for altering / removing mangroves (GOB 2003). That report found that from 2000-2007, 452.7 acres of mangroves were registered as altered (MNRE 2010: 109). When extrapolated out to 2010 to cover two of the periods assessed in the present study, that figure is 770.4 acres, or 41.3% of the 1,864.6 acres of mangrove detected by the current assessment as cleared from 2000-2010. This would thus seem to indicate that more than half of the mangrove clearing which occurred from 2000-2010 was done without legal permits. A noteworthy example of this is that while the clearance of only 1.2 acres of mangrove was approved for 2002 (MNRE 2010: 109), that same year ~260 acres of mangrove near the Port of Belize had been cleared (see **Figure 7**) – apparently without legal permit.

Belize's Mangroves in the Global Context

The situation of Belize's mangroves in the global context should also be noted. In mid-July 2010, UNEP and The Nature Conservancy (TNC) announced the publication of an update to the *World Mangrove Atlas*, indicating that a fifth of the world's mangrove cover had been lost since 1980 (TNC 2010a). By comparison, for Belize it is estimated that between 1980 and 2010, only 2% of the 1980 mangrove cover had been lost. Analysis of Zisman's data on Belize's "original" mangrove cover would indicate that as of early 2010, 96.7% of Belize's original mangrove cover still remains. The annual rate of mangrove loss – 0.07% – is less than Belize's estimated annual deforestation rate – 0.6% (Cherrington et al 2010). This is in stark contrast to the estimate that globally, mangroves are cleared at four times the rate of other forests (TNC 2010b). Overall, the clearing of an average of 125 acres of mangrove per year can likely be considered low. With both Belize's national report to the *Global Environmental Outlook* and McField & Kramer (2007) noting the scarcity of data on mangrove clearing in Belize, this study thus helps to frame the issue of clearing (and regrowth) by quantifying rates of clearing. This study also responds to the need expressed in Belize's national report to the *Global Environmental Outlook* for "clear data that shows the actual extent of mangrove [loss]" (MNRE 2010: 110).

Further regarding framing Belize's mangroves in the global context, it can be anticipated that this study will only be truly consolidated through *sustained monitoring* of Belize's mangrove cover. In addition to the capacities of the *Regional Visualization & Monitoring System* (SERVIR), whose capacities have been brought to bear in the development of this assessment, it should be noted that the Government of Belize is also a member of the intergovernmental Group on Earth Observations (GEO). Membership in GEO facilitates access to imagery, algorithms and capacity-building among its members. In the context of the *Global Earth Observation System of Systems* (GEOSS) whose development GEO is leading, there are two initiatives that are particularly relevant to the current work, the *GEO Biodiversity Observation Network* (GEO BON), and the *GEO Forest Carbon Tracking Task* (GEO FCT). These initiatives respectively advocate for the continued collection of observations of ecosystems and forests, while the latter initiative seeks to support countries in monitoring their forests and has called for the establishment of a *Global Forest Monitoring Network* (GEO 2008, GEO 2010).

The GEO FCT has a demonstration site (<http://www.geo-fct.org/national-demonstrators/browser>) and it might thus be useful to include Belize as a demonstration country under the GEO FCT, making use of the data large time-series of data developed under the present study. Further regarding the issue of sustained monitoring of Belize's mangroves, it is also anticipated that SERVIR will be able to support such activities. Linking SERVIR's work in Belize to both GEO BON and the GEO FCT could potentially provide additional satellite data resources for monitoring. From a 'forest carbon' perspective, field research by the U.S. Geological Survey (USGS) and the Smithsonian Institution (McKee & Faulkner 2000, McKee 2004) have shown that Belize's mangroves sit on carbon-rich peat deposits. This is significant in the context of the emerging *Reducing Emissions from Deforestation and Forest Degradation* (REDD+) initiative occurring in the framework of the United Nations Framework Convention on Climate Change (UNFCCC). Belize's potential involvement in REDD+ would likewise imply that its mangrove ecosystems would need to be regularly monitored, even as this study indicates that pressures on mangroves may not be as high as pressures on Belize's other forests.

Agreeing Upon a Baseline

Quantitatively assessing the situation with respect to Belize's mangroves also highlights the need to have an agreed-upon baseline for Belize's mangrove cover. In light of the absence of any other studies looking at changes in Belize's mangrove cover, it is thus hoped that this study can indeed serve as the needed baseline. Where this assessment has shown mangrove cover to have declined, albeit at a low rate, from 1980-2010, at least one recent published report has indicated that Belize's mangrove cover has increased in the recent past, even as there is a significant body of evidence to contradict such a claim. This therefore highlights the need to utilize datasets with high levels of accuracy / confidence. As elaborated in this report's *Background* section, various studies have arrived at different estimates of mangrove cover for Belize, even as a definitive baseline has not yet been agreed upon by the relevant national authorities. It is the premise of this study that the data from Zisman (1998) should be treated as the baseline for mangrove cover for Belize because of the rigorous manner through which it was generated. The current study, in fact, builds off of and draws conclusions based on Zisman's data.

The lack of an agreed-upon baseline for mangrove cover can also lead to confusion when examining global sources of data on Belize's mangroves which do not take local data into consideration. Those global sources of data can also contradict each other. For instance, the GeoCover LC product from EarthSat indicates that mangrove cover in Belize circa 2000 was merely 43,948 acres (a mere 58.2% of what this study indicated). By contrast, the recently-released Belize national report for the 2010 *Global Forest Resources Assessment* (FRA 2010) of the Food & Agriculture Organization (FAO) of the United Nations, estimates that Belize's mangrove cover in 2010 was 104,064 hectares (FAO 2010). That figure is 39% more than what this study estimates, and thus likewise higher than what Zisman estimated for 1990. It is quite unlikely that Belize's mangrove cover has increased by two-fifths when various other studies have indicated an opposite trend, that of *decreasing* mangrove cover. A plausible explanation for such findings, as elaborated in Cherrington et al (2010), is that such discrepancies are likely caused by global studies' (i) not utilizing local inputs in their mapping efforts, and (ii) using different methodologies for defining their targets. A 2010 study by the U.S. Geological Survey (USGS), and based on Landsat imagery, likewise arrived at 12.3% lower estimate of global mangrove cover than the FAO's estimate (Giri et al 2010). It would also be useful to compare Giri et al (2010)'s Belize estimates with those of the present study.

Further regarding agreement upon a baseline, it should be noted that in terms of caveats, the results of the present study have not yet been verified in the field, although field verification activities are planned for implementation prior to the end of 2010. Nevertheless, it is anticipated based on previous research that this study's results should possess a high degree of accuracy based on the methodology employed. Previous studies such as Goodenough et al (2002) have shown that as impervious surfaces / exposed soils appear quite distinct from other land cover features such as forest, and are not only easier to identify, but can also be identified with high if not *absolute* accuracy. This study's results were also filtered through rigorous visual assessment. In terms of alteration of Belize's mangroves, it should also be recalled that the present study did not contemplate assessment of *degradation* of mangrove ecosystems, which may or may not be on a greater scale than the outright destruction of ecosystems. It would thus be recommended that future satellite-based studies be conducted to examine not only the areal extent of mangrove

ecosystems, but also how their densities or health may be changing over time. While some errors are inevitable, it is thus anticipated that this study's results should be accurate overall at the scale of its intended use (i.e. 1:100,000).

It is also noted that the analyses presented in this study are not *exhaustive*. With the public availability of this study's data, there exist various opportunities to analyze the data from other perspectives (e.g. examining mangrove cover across protected areas or by land tenure), as well as to follow-up this work in the future based on the detailed methodology presented here and in Cherrington et al (2010). Such analyses and follow-up research could be worthwhile endeavors for institutions in Belize (e.g. the University of Belize's Environmental Research Institute, MNRE's LIC, Belize Audubon Society, etc.). As mangroves are also found elsewhere in Latin America and the Caribbean, this study could easily be expanded. It is hoped that this study's results will inform national-level decision-making on the use of Belize's natural resources.

VII. CONCLUSIONS

Leveraging the USAID- and NASA-supported *Regional Visualization & Monitoring System* (SERVIR), this study has demonstrated the utility of satellite imagery for monitoring one of Belize's critical ecosystems. Mangroves – whose annual contribution to Belize's economy is estimated at US \$174-249 million per year – are likewise a key component of the mosaic of ecosystems known as the Belize Barrier Reef Complex, the world's second largest barrier reef system (UNESCO 1996, Cooper et al 2009). This study reveals that from November 1980 through March 2010, Belize's mangrove cover declined from 188,417 acres (76,250 ha.) or 98.7% of the original extent to 184,548 acres (74,684 ha.) or 96.7% of the original extent. That equates to a net loss of almost 3,900 acres of mangrove cover over roughly 30 years, and a loss of 2% of the 1980 mangrove cover. The average annual net loss was estimated at 0.07%, or 125 acres. In contrast, it has been estimated that Belize's forests are cleared at a rate of 25,000 acres per year – an annual deforestation rate of 0.6% (Cherrington et al 2010).

With a significant proportion of Belize's mangroves interfacing with the Belize Barrier Reef Complex' coral reefs and seagrass, this assessment also revealed that 90.9% of mangroves cleared from 1980-2010 were those very ecologically important mangroves with 'marine connectivity.' It was also estimated that almost 90% of all mangrove clearing occurred in four main areas: (i) the Belize City area and surrounding cayes, (ii) the Placencia peninsula and surrounding cayes, (iii) Ambergris Caye and nearby islands, and (iv) the Dangriga area and nearby cayes. At the scale of 1:100,000, this assessment also revealed that land clearing resulted in fragmentation of some 2.1% of mangrove communities. In terms of resilience of mangrove ecosystems, a mere 236 acres (96 ha.) of the area cleared from 1980-2010 was detected to have regrown. In terms of this study's implications for local conservation efforts, while recent publications such as the *World Mangrove Atlas* indicate that a fifth of the world's mangrove cover had been lost since 1980, the loss of only 2% of Belize's overall mangrove cover between 1980 and 2010 can probably be considered low. This work likewise provides a partial picture of coastal development and land use patterns in the broader Mesoamerican Reef ecoregion. A more full picture of those patterns will be presented in the soon to be released second edition of the *Report Card for the Mesoamerican Reef* (HRI in press) whose 2010 *Coastal Development Index* was partially calculated using the results of this study.

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REFERENCES

- Aronoff, S. 2005. Remote Sensing for GIS Managers. First Edition. ESRI Press. 487 pp.
- Braun, M. and M. Herold. 2003. "Mapping Imperviousness using NDVI and Linear Spectral Unmixing of ASTER Data in the Cologne-Bonn Region (Germany)." Proceedings of the 10th International Symposium on Remote Sensing. Barcelona, Spain. 11 pp. Available online: www.geogr.uni-jena.de/~c5hema/pub/spie_paper_mhfinal_4.pdf
- Cherrington, E.A. 2005. "Drivers of Land Use Change Adjacent to the Mesoamerican Reef: A Preliminary Review." Internal, unpublished project document. Belize Coastal Zone Management Authority & Institute / ICRAN-MAR Project. 13 pp.
- Cherrington, E.A., Ek, E., Cho, P., Howell, B.F., Hernandez, B.E., Anderson, E.R., Flores, A.I., Garcia, B.C., Sempris, E., and D.E. Irwin. 2010. "Forest Cover and Deforestation in Belize: 1980-2010." Water Center for the Humid Tropics of Latin America and the Caribbean. Panama

City, Panama. 42 pp. Available online: http://www.servir.net/servir_bz_forest_cover_1980-2010.pdf

Cooper, E., Burke, L., and N. Bood. 2009. "Coastal Capital: Belize. The Contribution of Belize's Coral Reefs and Mangroves." WRI Working Paper. World Resources Institute, Washington, DC. 53 pp. http://pdf.wri.org/working_papers/coastal_capital_belize_wp.pdf

Earth Satellite Corporation (EarthSat). 2005. "EarthSat GeoCover LC Overview." Dataset based on Landsat GeoCover imagery, for periods circa 1990 and circa 2000. Report available online: <http://www.mdafederal.com/geocover/geocoverlc/gclcoverview>

Fairweather, P.N. & D.A. Gray. 1994. "The Land Use of Belize: 1989/92." Land Information Centre, Ministry of Natural Resources. Belmopan, Belize. 15 pp.

Food & Agriculture Organization (FAO). 2010. "Global Forest Resources Assessment 2010: Country Report: Belize." Rome, Italy. 39 pp. Available online: <http://www.fao.org/forestry/20262-1-171.pdf>

GeoVille Group / DIVERSITY project (GeoVille / DIVERSITY). 2008. "Belize / Mexico Mangrove map 2007." Dataset developed by GeoVille under the European Space Agency-supported DIVERSITY project, and based on ENVISAT ERS-1 and ERS-2 imagery. Report available online: http://www.geoville.com/diversity/products/pdf/DIVERSITY_More_Information_P4_Mangrove_Maps.pdf

Giri, C., Zhu, Z., Tieszen, L.L., Singh, A., Gillette, S., and J. A. Kelmelis. 2007. "Mangrove forest distributions and dynamics (1975-2005) of the tsunami-affected region of Asia." *Journal of Biogeography*, DOI:10.1111/j.1365-2699.2007.01806.x

Giri, C., Ochieng, E., Tieszen, L. L., Zhu, Z., Singh, A., Loveland, T., Masek, J. and N. Duke. 2010. "Status and distribution of mangrove forests of the world using earth observation satellite data." *Global Ecology and Biogeography*, DOI: 10.1111/j.1466-8238.2010.00584.x.

Global Observation of Forest and Land Cover Dynamics (GOF-C-GOLD) Secretariat. 2009. "A Sourcebook of Methods and Procedures for Monitoring and Reporting Anthropogenic Greenhouse Gas Emissions and Removals caused by Deforestation, Gains and Losses of Carbon Stocks in Forests remaining Forests, and Forestation." GOF-C-GOLD Report version COP15-1. Alberta, Canada. 197 pp. Available online: http://www.gofc-gold.uni-jena.de/redd/sourcebook/Sourcebook_Version_Nov_2009_cop15-1.pdf

Goodenough, D.G., Hollinger, A., Hall, R., Leckie, D., Dyk, A., Miller, J., Niemann, O., Iisaka, J., Staenz, K., Zwick, H., Pearlman, J., Han, T., Chen, H., McDonald, S., West, C., Thompson, C. and G. Wilson. 2002. "Report on the Evaluation and Validation of EO-1 for Sustainable Development (EVEOSD) Project." Report to NASA EO-1 Science Team. Available online: http://eo1.gsfc.nasa.gov/new/validationReport/Technology/Documents/Tech.Val.Report/Science_Summary_Goodenough.pdf

Government of Belize (GOB). 2003. "Forests Act Subsidiary Laws." Chapter 213 in: Substantive Laws of Belize. Revised Edition 2003. Government Printer: Belmopan, Belize. 137 pp. Available online at: <http://www.belize.gov.bz/lawadmin/PDF%20files/cap213s.pdf>

Gray, D., Zisman, S., and C. Corves. 1990. "Mapping of the Mangroves of Belize." Technical report. University of Edinburgh. Edinburgh, United Kingdom.

Group on Earth Observations (GEO). 2008. "GEO BON Concept Document." Document 20 of the GEO-V Plenary. Geneva, Switzerland. 43 pp. Available online: http://www.earthobservations.org/documents/geo_v/20_GEO%20BON%20Concept%20Document.pdf

_____. 2010. "Report on the Concept Phase for Developing a Global Forest Monitoring Network." Report of the Forest Carbon Tracking Task team, June 17, 2010 draft. Geneva, Switzerland. 22 pp.

Healthy Reefs Initiative (HRI). In press. "Report Card for the Mesoamerican Reef." Smithsonian Institution. Belize City, Belize.

Iremonger, S. & N.V.L. Brokaw. 1995. "Vegetation Classification for Belize." In: Wilson, R. (Ed.) 1995. "Toward a National Protected Areas Systems Plan for Belize." Synthesis report. Programme for Belize. Belize City, Belize. 114 pp.

Jarvis, A., Reuter, H.I., Nelson, A., and E. Guevara. 2008. "Hole-filled seamless SRTM data V4." International Centre for Tropical Agriculture (CIAT). Cali, Colombia. Available online: <http://srtm.csi.cgiar.org>.

Jensen, J.R. 2007. Remote Sensing of the Environment: An Earth Resource Perspective. Second Edition. Prentice Hall. 592 pp.

Lillesand, T.M., Kiefer, R.W., and J.W. Chipman. 2007. Remote Sensing & Image Interpretation. Sixth Edition. Wiley & Sons. 756 pp.

Lu, D., Batistella, M., and E. Moran. 2002. "Linear Spectral Mixture Analysis of TM Data for Land-Use and Land Cover Classification in Rondonia, Brazilian Amazon." Symposium on Geospatial Theory, Processing and Applications, Ottawa, Canada. 6 pp. Available online: http://www.machadinho.cnpem.embrapa.br/pdf/anais_de_congresso/APC_SGTPA02_LINEAR_MB.pdf

McField, M. and P. Richards Kramer (Eds.) 2007. "Healthy Reefs for Healthy People: A Guide to Indicators of Reef Health and Social Well-being in the Mesoamerican Reef Region." Smithsonian Institution. 208 pp. Available online: http://www.healthyreefs.org/index.php?option=com_docman&task=doc_download&gid=19&Itemid=54&lang=en

McKee, K.L. and P.L. Faulkner. 2000. "Mangrove Peat Analysis and Reconstruction of Vegetation History at the Pelican Cays, Belize." Smithsonian Institution. Atoll Research Bulletin No. 468. 14 pp. Available online: <http://si->

pddr.si.edu/dspace/bitstream/10088/5001/1/00468x.pdf

McKee, K.L. 2004. "Belowground Dynamics in Mangrove Ecosystems." USGS Fact Sheet 2004-3126. United States Geological Survey. Reston, Virginia. 4 pp. Available online: <http://www.nwrc.usgs.gov/factshts/2004-3126.pdf>

Meerman, J.C. & W. Sabido. 2001. "Central American Ecosystems Map: Belize." Volumes I. Programme for Belize. Belize City, Belize. 28 pp. Available online: http://biological-diversity.info/Downloads/Volume_Iweb_s.pdf

Meerman, J.C. 2005. "Belize Ecosystems Map: 2004 update." Dataset. National Protected Areas Policy & Systems Plan. Available online: www.biodiversity.bz

Ministry of Natural Resources and the Environment (MNREI). 2010. "GEO Belize 2010." Ministry of Natural Resources and the Environment / United Nations Environment Programme – Regional Office for Latin America and the Caribbean. 197 pp.

Murray, M.R., Zisman, S.A., Furley, P.A., Munro, D.M., Gibson, J., Ratter, J., Bridgewater, S., Mity, C.D., and C.J. Place. 2003. "The Mangroves of Belize: Part 1. Distribution, Composition and Classification." *Forest Ecology and Management* 174: 265–279

Strand, H., Hoft, R., Strittholt, J., Miles, L., Horning, N., Fosnight, E., and W. Turner. 2007. "Sourcebook on Remote Sensing and Biodiversity Indicators." Technical Series no. 32. Secretariat of the Convention on Biological Diversity, NASA-NGO Biodiversity Working Group, World Conservation Monitoring Centre of the United Nations Environment Programme. Montreal, Canada. ISBN: 92-9255-072-8. 203 pp.

The Nature Conservancy (TNC). 2010a. "'World Atlas of Mangroves' Highlights the Importance of and Threats to Mangroves: Mangroves among World's Most Valuable Ecosystems." Press release. Arlington, Virginia. Available online: <http://www.nature.org/pressroom/press/press4573.html>

_____. 2010b. "The Mystery of Mangroves." *Nature Conservancy Magazine*, Summer 2010. Available online: <http://www.nature.org/magazine/summer2010/features/art31631.html>

Tiruveedhula, M.P., Fan, J., Sadasivuni, R.R., Durbha, S.S., and D.L. Evans. 2009. "Biomass and Health Based Forest Cover Delineation Using Spectral Un-Mixing." Proceedings of the 2009 annual conference of the American Society of Photogrammetry and Remote Sensing. 11 pp. Available online: <http://www.asprs.org/publications/proceedings/baltimore09/0095.pdf>

Tremblay-Boyer, L. and E.R. Anderson. 2007. "Preliminary Analysis of Ecosystem Vulnerability to Climate Change in Panama." Senior undergraduate research project, School of Environment, McGill University, Montreal, Canada. Available online: <http://evcc-panama.mcgill.ca>

Trejos, N., Moran, M., Smith, O. and M. Morales. 2008. “Diagnósticos del Estado Actual de los Manglares, Su Manejo y Su Relación con la Pesquería en Panamá: Biofísico, Institucional-Legal, Socioeconómico y Línea Base del Bosque de Manglar del Golfo de Chiriquí, Provincia de Chiriquí.” Technical report by CATHALAC to the National Authority on Aquatic Resources of Panama (ARAP) and the Natura Foundation. ISBN 978-9962-8941-3-1. 133 pp. Available online: http://www.cathalac.org/dmdocuments/2008/chiriqui_manglares.pdf

United Nations Educational, Scientific, and Cultural Organization (UNESCO). 1996. “Report: World Heritage Committee Twentieth Session.” Report of the twentieth session of the UNESCO World Heritage Committee. Paris, France. WHC-96 / CONF. 201 / 9. 207 pp. Available online: <http://whc.unesco.org/document/884>

Water Center for the Humid Tropics of Latin America and the Caribbean (CATHALAC). 2008. “Assessment of ESA DIVERSITY Project Mangrove Data for Belize and the Mesoamerican Reef (MAR) Region.” SERVIR internal report. 6 pp.

World Bank & the CCAD. 2001. “Ecosystems of Central America (ArcView regional map files at 1:250,000).” World Bank, Central American Commission on Environment and Development (CCAD), World Institute for Conservation and Environment (WICE), and the Centro Agronómico Tropical de Investigación y Enseñanza (CATIE), Washington, DC. Available online: <http://www.worldbank.org/ca-env>

World Resources Institute (WRI). 2008. “Mangroves of Belize.” Dataset developed by WRI contractor Temilola Fatoyinbo based on 2000-2002 Landsat GeoCover ortho imagery. Facilitated to Healthy Reefs Initiative by Lauretta Burke.

Zisman, S.A. 1993. “Mangroves in Belize: Their Characteristics, Use and Conservation.” Consultancy report number 3. Forest Planning and Management Project. Forest Department, Ministry of Natural Resources. Belmopan, Belize.

Zisman, S.A. 1998. “Sustainability or Status Quo: Elite Influence and the Political Ecology of Mangrove Exploitation in Belize.” Doctoral dissertation, Department of Geography, University of Edinburgh. Edinburgh, Scotland.

Zisman, S.A. 1999. “Explanatory Notes for the Zisman Mangrove Map.” Presentation to the Belize Coastal Zone Management Project. 6 pp.