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# Climate Change versus Human Population and Development: Hurricanes, Urbanization, and Tourism Impacts on Land Change in the Tropical Island Ecosystems of Roatán, Honduras

A Thesis submitted in partial satisfaction of the requirements for the degree of Master of Arts in Geography

By

Cascade P Tuholske

Committee in charge:

Professor David López-Carr, Chair

Professor Dar Roberts

Professor Susan Cassels

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The thesis of Cascade P Tuholske is approved.

Dar Roberts

Susan Cassels

David López-Carr, Committee Chair

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ABSTRACT

Climate Change versus Human Population and Development: Hurricanes, Urbanization, and Tourism Impacts on Land Change in the Tropical Island Ecosystems of Roatán, Honduras

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Relatively little scholarship has compared the ecological impact of acute climate-related events versus chronic human pressures. Despite mounting pressures from climate change and rapid tourism development across the Caribbean, even less research has assessed the relative impacts of biophysical versus anthropogenic pressures on the region's island landscapes. We compare the effects of an extreme climate event in the years immediately following Hurricane Mitch in 1998 relative to thirty years of rapid urbanization and tourism development on Roatán, Honduras. Results from a random forest classifier applied to thirteen Landsat Thematic Mapper (TM) and Operational Land Imager (OLI) scenes, indicate that between 1985 and 2015 urban area increased by 982.8 ha (227.7%), with 224.1 ha (-19.1%) of mangroves converted to urban areas. This compares to a 37% (384.9 ha) decrease in mangroves immediately following Hurricane Mitch. Mangroves in protected areas have fully recovered since Mitch, demonstrating their resiliency. Despite being illegal, mangrove deforestation across all unprotected areas accelerated to accommodate increasing urban area. Given that mangroves provide vital protection to an island's coastline and represent a major carbon-sink, and that extreme hurricanes in the Caribbean are projected to double in the coming decades due to climate change, this research suggests that rapid urbanization and tourism development in the Caribbean may decrease island ecosystem resiliency to environmental stressors.

## Introduction

Valuable and vulnerable, Caribbean tropical islands remain among the most ecologically diverse places on the planet (Cassels *et al.* 2005; Hammond *et al.* 2015). While abundant ecological splendor offers a boon for Caribbean island economies, linked terrestrial-marine ecosystems face mounting anthropogenic and biophysical threats. Climate change stands to exacerbate a host of environmental threats, while rapid urbanization and tourism development further compound chronic pressures on Caribbean island environments (Klein *et al.* 1999; Belle & Bramwell 2005, Stonich 2008). While a growing literature discusses many aspects of climate change and human impacts on the environment (e.g. An and López-Carr 2012), little is yet known to what extent anthropogenic pressures compare to environmental impacts on Caribbean ecosystems (Bremner *et al.* 2010).

The latest climate models suggest that Atlantic hurricanes will increase in intensity and frequency as sea surfaces warm, indicating that category 4 and 5 storm incidence may double by the end of the 21st century (Webster *et al*. 2005; Bender *et al*. 2010). Sea-level rise will further compound the damage hurricanes cause to Caribbean islands. Global mean sea-level rose 1.5 to 1.9 mm $yr^{-1}$ from 1901 – 2010 and is projected to rise 26 to 98 cm $yr^{-1}$ by 2100 (Church *et al*. 2013), aggravating storm damage to terrestrial and marine Caribbean island ecosystems (Doiron & Weissenberger 2014). Such sea-level rise enhances inundation of low-lying coastal land, accelerates coastal erosion, and leads to salt water intrusion of freshwater aquifers (Belle & Bramwell 2005). Marine ecosystems face similar threats from rising sea-level and increased storm severity, with coral reefs being exceptionally vulnerable to severe hurricanes (Gardner *et al*. 2005). Warming sea-surface water temperatures have already increased coral reef bleaching in the Caribbean and will continue to worsen in the coming decades (McWilliams *et al.* 2005; Eakin *et al.* 2010).

Tourism has long been hailed as an economic boon for the Caribbean (Stonich 1998). The region has become among the most tourism-dependent regions on the planet, with 28.7 million stopover tourists and 24.4 million cruise passengers visiting the region in 2015 (European Commission 2002; Caribbean Tourism Organization 2015). These 50 million visitors injected $51.9 billion into the Caribbean's economy in 2014, providing 13% of total regional employment (Turner 2015). However, the sustainability of the Caribbean tourism industry is increasingly questioned (Stonich 1998; Stonich 2008; Stonich *et al.* 2008; Doiron & Weissenberger 2014). The coupled terrestrial and marine ecological splendor that draws tourists to Caribbean islands contends with heightened stress due to the rapid growth of the tourism industry itself. Tourism development represents a risk of $350 - $870 million per year in lost revenue due to damage to reefs, a decline in dive tourism, and lost shoreline protection (Burke & Maidens 2004). In-migration and urbanization competes for bounded island coastlines, rendering Caribbean islands among the most densely populated and urbanized places in the world (Hinrichsen 1998; United Nations 2015).

Anthropogenic pressures on Caribbean island terrestrial ecosystems cascade into surrounding marine environments. While coral reefs provide immense economic, social, cultural and environmental benefits to island communities, urbanization and development of Caribbean island landscapes threatens over 60% of the Caribbean's reefs (Spalding *et al*. 2001). Urbanization and tourism development harms Caribbean marine ecosystems through overfishing, the introduction of invasive species, wastewater and irrigation runoff, and alteration of island coastlines through development, erosion, increased sediment and coastal deforestation (Burke & Maidens; Hall 2010). Coastal development threatens reefs, which reduces coastal protection and increases damage to islands from storm surges and tsunamis.

Mangrove forest degradation illustrates a foremost environmental and human threat to Caribbean island terrestrial and marine ecosystems. Ecologically, mangroves provide habitat for juvenile coral reef fish species and remain vital to overall coral ecosystem function, fisheries productivity and reef resilience (Mumby *et al.* 2004). A bulwark against climate change, mangroves are among the most carbon-rich tropical forests and mangrove deforestation may contribute to as much as 10% of global annual carbon emissions (Donato *et al.* 2011). Economically, the United Nations Environmental Program (UNEP) estimates that, worldwide, mangroves deliver hundreds of billions dollars of economic, social, and environmental benefits to coastal communities and for the planet (Ajonina *et al.* 2014). Citing evidence from Central Africa, UNEP estimates that mangrove protection of coastal communities and ecosystems from storm surges and hurricanes at $11,286/ha in seawall replacement, $7,142/ha in overall protection for rural communities and $151,948/ha for urban infrastructure. UNEP estimates a low-end social benefit of reduced carbon at $15,588/ha to $151,983/ha of mangroves. Notwithstanding that mangroves are protected under international treaty and national laws in the Caribbean, migration and urbanization to coastal areas rank among the most important drivers of tropical forest loss, including mangroves, over-multi-decade time scales (Lambin *et al.* 2003; Singh *et al.* 2014). Climate change further burdens Caribbean mangroves, with sea-level rise noted as the perhaps the greatest threat (Gilman *et al.* 2008).

Researchers have long used remote sensing to measure land use-cover change (LUCC) in terrestrial ecosystems, ranging from studies of deforestation in Latin America

(Aide et al. 2010), the Amazon (Roberts *et al*. 2002; Nunes *et al.* 2015) and large tropical islands (Harper *et al*. 2007) to urbanization (Seto *et al.* 2011). However, remote sensing has rarely been applied to Caribbean islands. Notably, researchers have mapped mangrove cover of continental Caribbean coastlines (Murray *et al.* 2003) and urban land cover of Puerto Rico (Martinuzzi *et al*. 2007). Remote sensing of LUCC offers the opportunity to investigate local patterns and processes that are key to understanding human-environment dynamics in small bounded areas as characterized by tropical islands (Bremner *et al.* 2010). Such local-scale temporal analysis of LUCC not only allows for the investigation of coupled human-environment systems, but also assists in the prediction of future LUCC (Lambin *et al.* 2003). While a limited body of literature has examined the potential effects of climate change and tourism development on Caribbean islands (Uyarra *et al.* 2005; Belle & Bramwell 2005; Moore 2010; Scott *et al.* 2012; Doiron & Weissenberger 2014), no research has leveraged remote sensing to compare the impacts of a major climatic event versus rapid urbanization and tourism development on a Caribbean island's landscape, much less assessed how such pressures may affect mangroves.

Roatán, Honduras, presents a compelling opportunity to quantitatively decouple the relative effects of humans versus an extreme climate event on a Caribbean's island landscape. Like all Caribbean islands, Roatán copes with anthropogenic and biophysical threats to its coupled terrestrial-marine ecosystem. While Roatán's tourist development did not launch in earnest until the 1990s, tourism and population have ballooned on the island since the late 1990s (see Stonich *et al.* 2008). Fewer than 13,000 people lived on Roatán in the 1970s and as many as 100,000 people inhabit the island today, with much of this growth coming from in-migration from mainland Honduras (Stonich 1998; Bay Island Voice 2014).

Today, the island is a melting pot of ethnic groups from Caracol, Garifuna, Afro-Caribbean, Hispanics, and expatriates.

Tourism to Roatán boomed from 15,000 tourists in 1998 to 1.2 million tourists in 2011 (Stonich 1998; Kendal 2012). In 2015, tourism comprised 16% of Honduras's GDP (Turner 2015). The Bay Islands account for by far the most tourist visits to Honduras: of the nearly 2 million tourists that visited Honduras in 2013, ~700,000 disembarked as cruise ship passengers in Roatán alone (Ministry of Tourism 2014). The increase in tourism can largely be attributed to two cruise ship terminals, Port Mahogany Bay and Port Roatán and the establishment of Roatán as a free trade zone, *Zona Libra Touristica* (Zolitur) in 2006 (Stonich *et al.* 2008). The opening of the Mahogany Bay terminal increased cruise ship passenger visits by 86% between 2009 and 2010, adding 373,800 visitors in 2010 compared to 2009 (Ministry of Tourism 2009, 2014).

Climate change threatens Roatán's fragile marine and terrestrial ecosystems (Doiron & Weissenberger 2014). While the effects of climate change remain unclear, Hurricane Mitch, the eighth strongest and second deadliest Atlantic hurricane on record (National Climatic Data Center 2004; Rochelau 2015), offers a striking example of the damage that can be inflicted by an extreme weather event. The category 4 storm passed 40 km east of Roatán hurricane, exposing Roatán to hurricane force winds from 27 – 29 October 1998 (Cahoon *et al.* 2003). Wind speeds peaked at an estimated 180 km $hr^{-1}$ and a tidal surge inundated Roatán's northern and eastern coasts (Doyle *et al.* 2003). Because much of the affected areas lay inside Saint Helena Wildlife Refuge and Barbareta Marine Reserve, both protected from development, we can measure how Roatán's landscape recovered since Hurricane Mitch to more accurately gauge the comparative acute impact of Hurricane Mitch versus rapid urbanization and tourism development on the island.

Scientists continue to debate the independent and combined impact of biophysical and human impacts on global ecosystems under duress from human encroachment and climate change. Despite a significant body of literature highlighting both human and environmental threats to Caribbean islands, to our knowledge no published research has quantitatively compared environmental impacts with human impacts on a tropical island's landscape. This case study offers to fill this gap by utilizing remote sensing to measure and map LUCC on Roatán from 1985 to 2015 to examine what happens when an extreme weather event and anthropogenic pressures collide in an island ecosystem. We quantify LUCC from 1985 – 2015, comparing the effects of hyper urbanization—defined here as urban land area expansion (Seto *et al.* 2011)—and tourism development on LUCC with the acute damage of a Hurricane Mitch. We specifically document land conversation rates of mangroves to urban areas, and compare this with the immediate loss and eventual regrowth of mangroves following Hurricane Mitch. By evaluating the relative impact of both human and environmental impacts on Roatán's mangroves we take an important initial step to understanding the relative contribution of each threat independently and interactively. Given mangroves' key roles in climate change mitigation as carbon sinks, as island protection from hurricanes, and as key species for marine ecosystem vitality, this case study suggests tourism and development exacerbate the potential for decline in Caribbean ecosystem resiliency.

## Methods

### *Study Site*

Located atop the Mesoamerican Reef, a UNESCO World Heritage site, Roatán provides an exceptional location to investigate climatic and anthropogenic drivers of LUCC on a tropical island. The largest of the Bay Islands, Roatán sits ~50 km from Honduras' northern coast. The island, including Santa Elena and Barbareta islets, is approximately 40 km long and 5 km across at its widest point, encompassing ~130 km$^2$. A serpentine ridge runs west-east along the center of the island, with a maximum elevation of 244 m, and contains a few exposed rock outcrops of serpentinite, amphibolite, biotite, chlorite schist, and gneiss (McBirney and Bass 1969; Sutton 2015).

The island's coastline is mostly vegetated or urbanized, though several palm-lined white sand beaches bound sections of the island. Exposed alluvium, phytokarst, and coastal boundstone form portions of the northwestern coast (Sutton 2015). The island averages 2,000 mm of precipitation annually, with the preponderance falling during a rainy season in October and November (Stonich 1998). Less than 100 mm of rain falls during the dry season from January to June. The western side of the island receives more rain compared to the east, resulting in southeastern coastline covered in sparse vegetation of mixed shrubs and grassland (Tomczyk 2010).

Due to conservation efforts by Roatán Marine Park and the Bay Island Conservation Association, the surrounding coral reefs rank among the healthiest across the Mesoamerican Reef (Healthy Reefs for Healthy People 2015). Roatán has a high rate of herbivore biomass and coral cover compared to the rest of the Mesoamerican reef. The reef supports over 70 species of corals, 41 species of sponge, 185 coral fish and large-vertebrates such as whale sharks, sea turtles, bottlenose dolphins, rays, pilot whales and orcas (Doiron & Weissenberger 2014).

Roatán is bisected by two municipalities: Roatán in the west and José Santos Guardiola in the east. The preponderance of tourism development has been concentrated on the western portion of the island in municipality of Roatán. José Santos Guardiola boasts all of the island's terrestrial protected areas, including: Port Royal Wildlife Refuge (850 ha), Saint Helena Wildlife Refuge (1,422 ha) and the Barbareta Marine Reserve (10,108 ha) (Tomczyk 2010). The largest tract of mangroves (~400 ha) is found inside the St. Helene and Barbareta Marine Reserve. Red mangroves are most abundant on Roatán, with lesser amounts of black, white, and buttonwood mangroves present (Cahoon *et al.* 2003). Cutting mangroves is illegal under Honduran law (Doiron & Weissenberger 2014).

*Preprocessing and data selection*

Fifteen cloud free images collected by Landsat 5 Thematic Mapper (TM) and Landsat 8 Optical Land Imager (OLI) and accessed from the USGS Earth Explorer website were used. The USGS TM and OLI Land Surface Reflectance Products were atmospherically corrected using the Landsat Ecosystem Disturbance Adaptive Processing System (LEDAPS) (see Masek *et al.* 2006) and L8SR algorithm (USGS 2016). We recognize that USGS's LEDAPS products are still provisional and that sensor differences between the TM and OLI scenes may bias our results. All scenes, save the 2015 scene, were acquired between February and March to reduce phenological impacts. The 2015 scene was selected to closest match in-situ ground reference points collected with a Garmin handheld GPS from August – September, 2016.

Bands 1-5 and 7 for TM and bands 1-5, 7 and 8 for the OLI images were combined with a Shuttle Radar Topography Mission SRTM digital elevation model and stacked into a single image using Exelis Visual Information Solutions (ENVI) 5.2 software. The 2015 OLI image was subsampled to contain only our study area. All other images were found to be free of co-georegistration errors by visual inspection and were subsampled to the 2015 scene.

From the 2011 TM and the 2015 OLI scene, we manually selected 150 pixels to serve as training data for the following five land cover classes: tropical forest, mixed agriculture and tropical forest (MAF), urban, mangroves, and soil/non-photosynthetic vegetation (NPV). Because TM and OLI satellites collect different spectral data, two separate datasets were created. Criteria considered for each class included spectral reflectance, relationship to in-situ GPS-collected ground reference points, spatial pattern, and visual reference to Digital Globe high resolution imagery available from Google Earth. Transects from Roatán's airport, Coxen Hole, and French Harbor provided a majority of the urban training data. Tropical forest training data were selected based on higher near-infrared reflectance and lower reflectance in the short-wave infrared (1650 to 2300 nm) due to liquid water absorption.

MAF proved to be the most challenging class in terms of training data. We relied on high resolution images available from Google Earth for both 2011 and 2015 to help discriminate MAF from tropical forest and on in-situ ground reference points. Mangrove training data were selected from Saint Helena Wildlife Refuge and the Barbareta Marine Reserve (Cahoon *et al.* 2003), and confirmed with geo-referenced photographs during a 2016 summer field visit. Most soil/NPV training data came from the steep, arid hills on the Port Royal Wildlife Reserve.

*Classification*

The 2011 and 2015 images and their respective datasets were classified using the Random Forest (RF) algorithm (Breiman, 2001) in R (R Development Core Team 2010 version 2.12.2) statistical software. Random Forest is an ensemble classifier based on the

Classification and Regression Tree (CART) and has been shown to be a highly accurate and robust classifier of Landsat TM and OLI, with less noise compared to single CART classifiers (Breiman *et al.* 1984; Belgiu and Dragut, 2016). In RF a predetermined number of CART trees are fed training data via bootstrapping (sampling from the total set of training data with replacement). At each tree node only a user-defined subset of features are used. In this classification, standard values were used. When encountering new data, the algorithm uses the average determination of the trees. Separate classifications were performed for the TM and OLI scenes with training data from the 2011 and 2015 scenes used, respectively.

*Accuracy Assessment & Post Classification*

Because the RF algorithm selects training data via bootstrapping, approximately two thirds of the training data proved sufficient to train each individual tree. These data are referred to as the in-bag samples. The remaining one-third of the data, referred to as out-of-bag sample (OOB), can be used to perform internal cross validation for estimating the RF performance (Breiman 2001). Several remote sensing studies have shown that OOB error is a reliable measure of classification accuracy (Lawerence *et al.* 2006; Zhong *et al.* 2014). In this study, our overall OOB error was 6.8% (93.2% correctly classified) and 3.2% (96.8% correctly classified) for the 2011 and 2015 images, respectively.

After classifying each scene's land cover, we masked the ocean to avoid misclassification of terrestrial land cover classes. Next, pixels classified as mangroves above 25m, the maximum elevation of a red mangrove canopy, were masked as unclassified areas. Several post-classified scenes were removed from our final analysis. The TM scene from 1991 was removed due to a high degree of misclassification of fire scars, which were common due to slash and burn agriculture prevalent on Roatán at the time, as urban. The

2000 image and both 2014 images were removed from our analysis because the images contained an unusually large number of physically impossible classification anomalies. Due to sediment blanketing the island after Hurricane Mitch (Cahoon *et al*. 2003), the RF algorithm misclassified damaged mangroves as urban (Fig. 1) for the scene from 1999. However, we retained this scene for our results to assess how mangroves were affected by the hurricane. Following scene classification, we calculated total land cover change between each image and overall change between 1985 and 2015. Finally, we calculated how each land cover class transitioned between time points and between the first and last scene.

**Results**

Between 1985 and 2015, tropical forest area varied considerably throughout our study period (Table 1), with an overall increase of 271 ha, or 4.3%. Substantial variation in the extent of tropical forest persisted throughout the 1990s. Similarly, the total area of MAF oscillated through the 1990s. Overall, MAF decreased 19.9% (917.3 ha) between 1985 and 2015, suggesting a notable decline in agriculture (Table 1), consistent with 2016 field observations. During the same period, Soil/NPV remained largely unchanged.

***Table 1*** Total land cover classification results from a random forest classification algorithm for each land cover class. Using the 1985 results as a baseline, total (ha), present, annual, and percent annual change in land cover classes between 1985 and 2015.

| *Date* | *Forest (ha)* | *MAF (ha)* | *Urban (ha)* | *Mangroves (ha)* | *Soil/NPV (ha)* |
|---|---|---|---|---|---|
| 2/1/1985 | 6377.31 | 4610.61 | 431.55 | 1171.08 | 423.45 |
| 3/8/1986 | 4204.44 | 6095.88 | 784.26 | 999.18 | 931.32 |
| 2/26/1994 | 6091.74 | 4761.18 | 736.20 | 1079.28 | 346.41 |
| 2/13/1995 | 6598.44 | 4263.57 | 835.47 | 1034.73 | 278.82 |
| 4/4/1996 | 5310.72 | 5303.25 | 870.48 | 962.55 | 568.08 |
| 2/2/1997 | 7126.20 | 3866.58 | 720.72 | 1036.44 | 263.07 |
| 2/5/1998 | 6220.44 | 4495.86 | 985.14 | 1036.44 | 273.87 |
| 3/12/1999 | 5393.61 | 5244.93 | 1280.97 | 651.51 | 444.78 |
| 3/1/2001 | 6280.83 | 4540.77 | 1085.67 | 766.98 | 341.10 |

| | | | | | |
|---|---|---|---|---|---|
| 12/4/2009 | 7367.67 | 3440.61 | 1044.99 | 992.16 | 169.02 |
| 2/25/2011 | 6379.29 | 4043.70 | 1305.90 | 920.43 | 365.67 |
| 9/26/2013 | 8155.08 | 2787.12 | 1030.59 | 865.53 | 172.98 |
| 9/16/2015 | 6648.30 | 3693.33 | 1414.35 | 841.77 | 416.70 |
| | | ***1985 – 2015*** | | | |
| Total Change (ha) | 270.99 | -917.28 | 982.80 | -329.31 | -6.75 |
| Total % Change | 4.25 | -19.89 | 227.74 | -28.12 | -1.59 |
| Annual Change (ha) | 98.18 | -332.33 | 356.07 | -119.31 | -2.45 |
| % Annual Change | 0.14 | -0.65 | 7.43 | -0.92 | -0.05 |

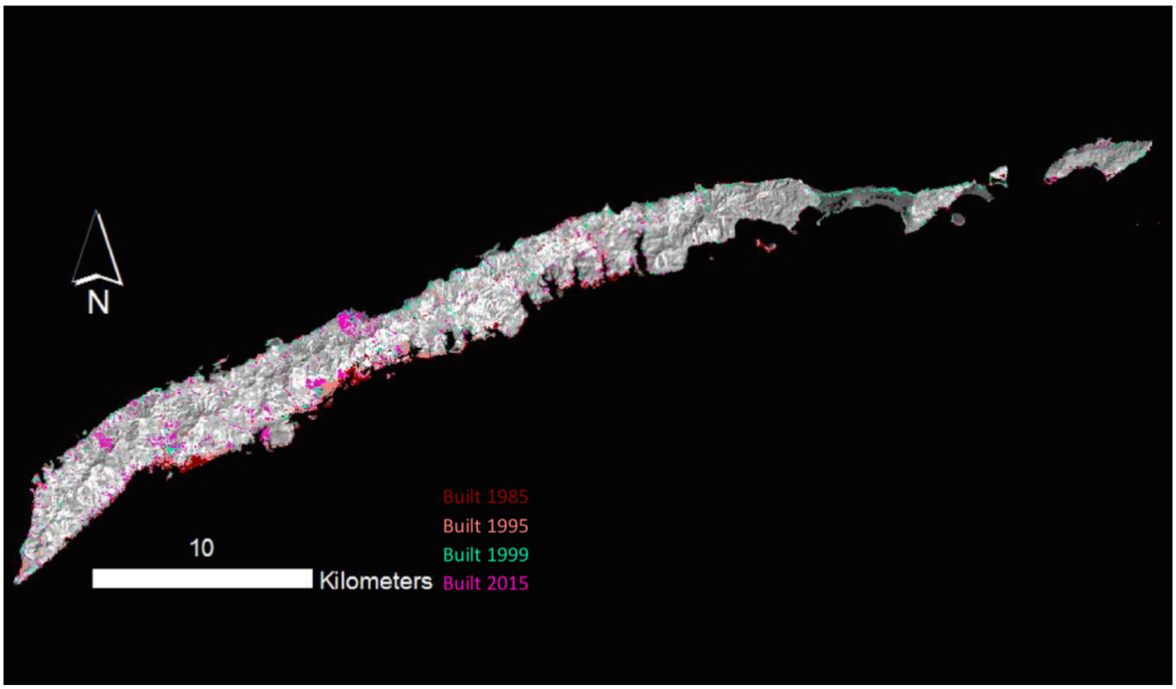


***Figure 1*** Total built area for 1985, 1995, 1999, and 2015. The built area in 1999 in northeastern Roatán reveals how, immediately following Hurricane Mitch, damaged mangroves are misclassified as urban area.

Results indicate a 223% (928.8 ha) increase in urban area (Table 2), corresponding to a normalized annual urban growth rate of 7%. Urbanization was concentrated on the western edge of Roatán, though urban encroachment into higher elevations and the south eastern portion of Roatán are also evident (Fig 1). Urbanization accelerated between 1985 and 1995 (Fig. 2), increasing 404 ha, and then plateaued through the late 1990s. From 2009 to 2015, urbanization boomed again, increasing 369.4 ha or 35% over six years.

***Table 2*** Using 1985 as baseline, land conversion to urban from between 1985 and 2015.

| ***Urban Conversion 1985 - 2015*** | ***Total (ha)*** | ***% Change*** |
|---|---|---|
| Forest to Urban | 352.98 | 5.5% |
| MAF to Urban | 486.54 | 10.6% |
| Mangroves to Urban | 224.10 | 19.1% |
| Soil/NPV to Urban | 30.24 | 7.1% |

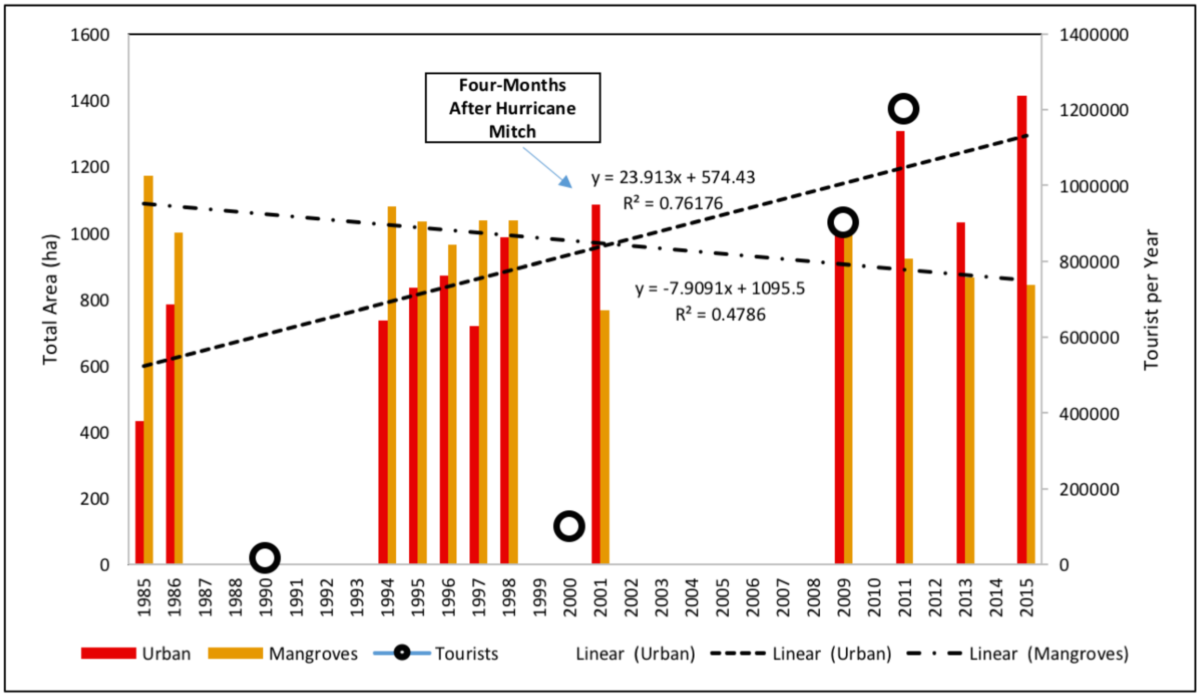


***Figure 2*** Total urban and mangrove area by year, with simple linear regression overlaid for both land cover classes. Tourism numbers were adopted from Doiron & Weissenberger (2014).

Using 1985 as a baseline land cover map, from 1985 – 2015 19.1% (224.1 ha) of mangroves were converted to urban area (Table 2). Visually, urban encroachment into mangroves is evident (Fig 3). The conversion of 486.5 ha of MAF to urban area reveals the conversion of formal agriculture areas to urban development. Roatán's tropical forest remains less effected by urbanization. Only 4.3 (271 ha) of the tropical forest in 1985 was converted to urban areas by 2015. Results capture the extent of the damage of Hurricane Mitch on Roatán's mangrove forest (Fig. 3). Roatán's 1998 mangrove coverage of 1036.4 ha remained relatively static throughout the mid-1990s but dropped to 651.5 ha in 1999. This

37% decrease in mangroves is consistent with other post-hurricane field studies (Cahoon *et al.* 2003). Mangroves in eastern Roatán rebounded throughout the 2000s (Fig. 4), but continued to decrease on the island overall to 841.8 ha (Table 1).

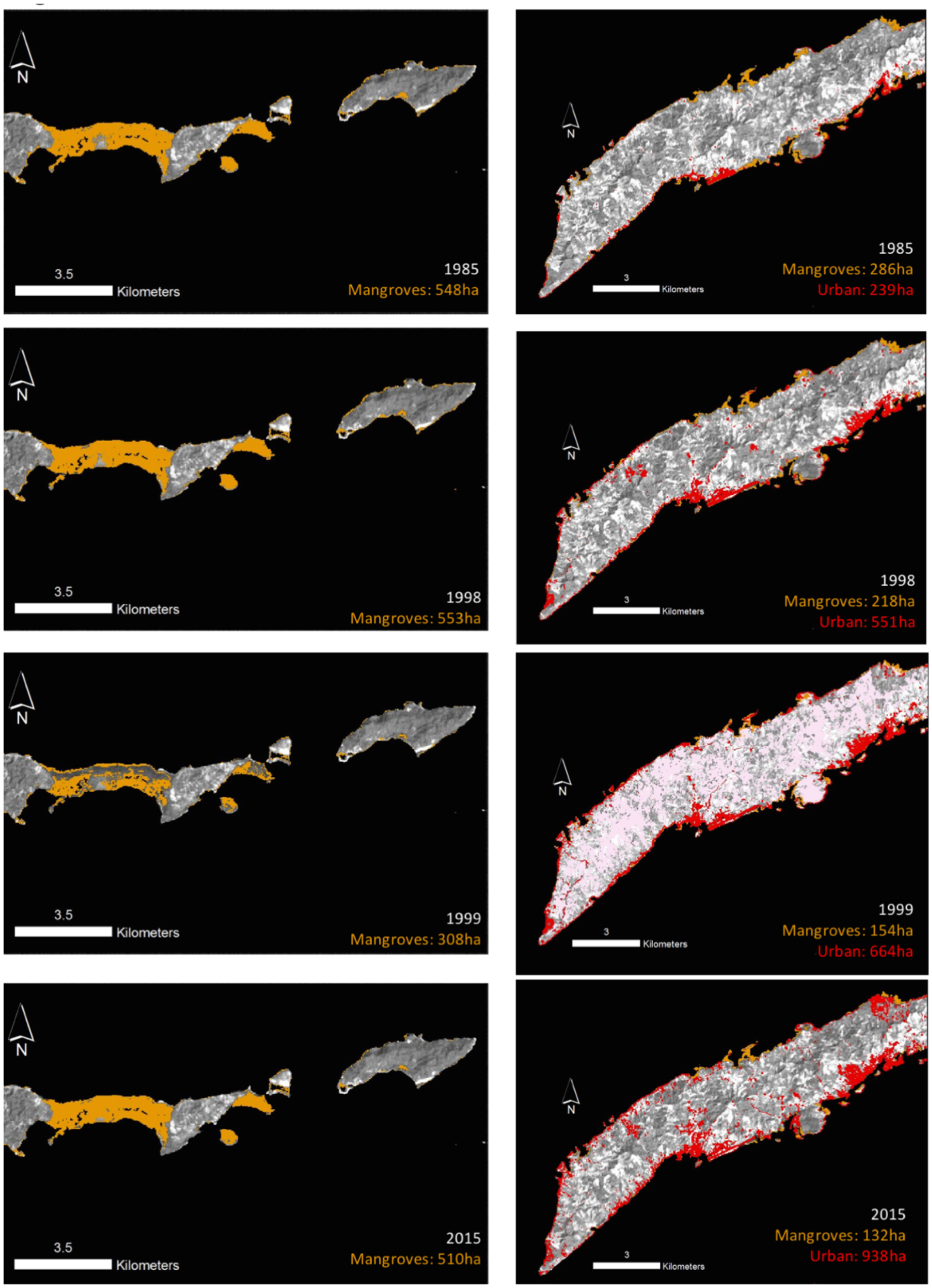


***Figure 3*** Total mangrove area (left) in eastern Roatán's Saint Helena Wildlife Refuge and the Barbareta Marine Reserve recovered after Hurricane Mitch to near the 1985 baseline

levels (urban area is excluded for ease of viewing of mangrove loss and recovery). In Western Roatán (right), hyper urbanization and tourism development has led to illegal mangrove deforestation.

## Discussion

Our results suggest that land use cover change in Roatán over the past thirty years is characterized by two spatial trends. The eastern portion of the island faced significant damage due to an extreme weather event. With limited human interference the terrestrial ecosystem rebounded and mangroves in the eastern half of the island today cover nearly the same area as they did in 1985 (Fig. 3). Conversely, the western end reveals the recent legacy of population growth and tourism development impressed on the island's landscape. While results suggest less overall urbanization compared to our preliminary analysis of two Landsat scenes from 1985 and 2014 respectively (Tuholske *et al.* 2016), urbanization rates in Roatán over recent decades are comparable to China's often cited rapid growth rates (Seto *et* al. 2011). Mangroves have been cut illegally (often with impunity) for coastal development (Fig. 4). And, while the eastern end of the island remains relatively pristine, in the fall of 2015 Zolitur, the government body charged with zoning the island, released a new zoning plan, *Plan de Ordenamiento Territorial de Islas de la Bahía*, which promises to further accelerate coastal and inland residential and tourism development. Should recent trends continue framed within Zolitur's new zoning regulations, the future of Roatán's terrestrial ecosystem appears bleak: nearly the entire eastern portion of the island is zoned for residential or tourist development, including the entirety of Barbareta, which is currently protected from development. While Hurricane Mitch decimated Roatán's mangroves, the mangrove forest in the Saint Helena Wildlife Refuge and the Barbareta Marine Reserve have since recovered.

Yet with category 4 and 5 hurricanes slated to increase in frequency, Roatán's mangroves may not have the necessary recovery time to regenerate in the near future.

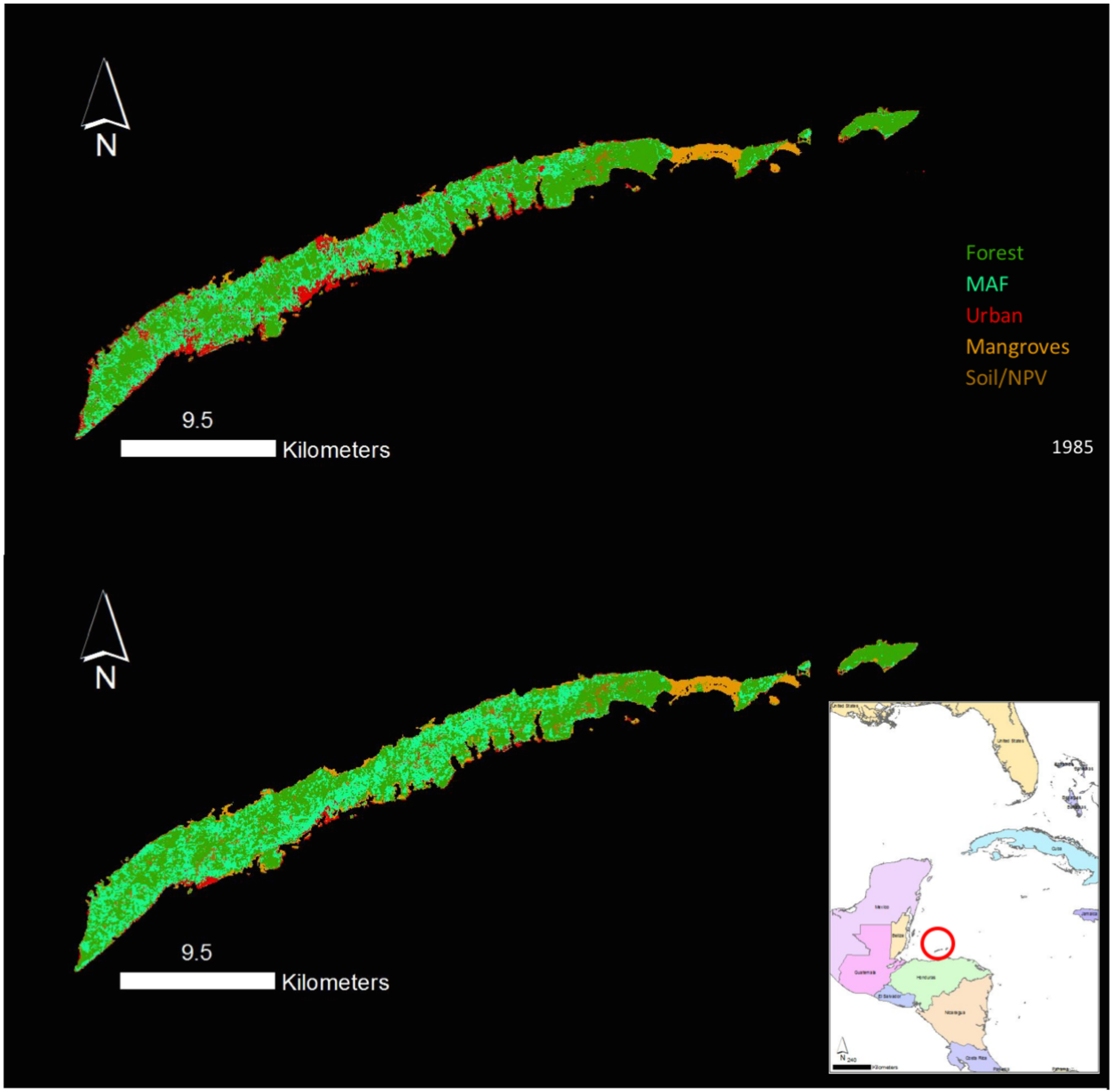


***Figure 4*** Land cover classification results from a random forest classification algorithm for 1985 and 2015.

Rapid urban land expansion in Roatán is replacing mangroves and former agricultural areas at globally high rates. For comparison, East Asia and East Africa are often cited in development literature as having exceedingly high rates of rates of urbanization (United

Nations 2015), with mean urban land area expansion rates between 1970 and 2000 hovering at ~7% in China and ~4% in Africa (Seto *et al*. 2011). Roatán's explosive rate of 7.8% between 1985 and 2015 matches or exceeds the pace of urbanization of even the most rapidly urbanizing regions, with the 35% increase from 2009 to 2015 far eclipsing rates observed in most regions. This rapid pace of urban growth, without commensurate water and sanitation development, places an extreme burden on Roatán's fresh water supply with damaging implications for the near shore marine environment. The loss of mangroves, combined with increased runoff, burdens coral ecosystem. Scholars have already documented how the island's hyper development has negatively affected human health, particularly increasing risk among low-income and marginalized groups (Stonich 1998). Unfortunately, the development of Roatán's coastlines is not cheap, nor are its costs equally shared. Using the UNEP estimates of the economic benefits of mangroves, we approximate a combined social and ecological cost of mangrove loss to urban areas on the island to be nearly $70 million since 1985. This estimate was calculated by adding the UN estimate economic benefit of mangroves for urban infrastructure ($151,948/ha) to the high end economic benefit of reduced carbon ($151,983/ha) and multiplying the sum by the total reduction of mangroves on the island between 1985 and 2015 (224.1 ha).

Researchers have highlighted poor development regulation in Roatán, yet note that with suitably financed and integrative planning, the Bay Islands could become an economical and environmentally friendly model for Caribbean tourism development (Forest 1997). This has yet to happen. The post-Mitch tourism boom in Roatán was largely fueled by foreign land developers who morphed Roatán's coastline into large-scale resorts and luxury housing (Stonich 2008). Indeed, Hurricane Mitch may have helped catalyze urbanization and tourism development policy incentives which, in turn, perversely subsidized the production of greenhouses gases contributing to the island's increased vulnerability to more frequent and extreme hurricanes. Following the storm, the Honduran Government instituted a variety of reforms to spur post-hurricane development and reconstruction. For example, following Hurricane Mitch in 1998, the government opened foreigner and foreign company land ownership of coastal lands, including in the Bay Islands, which had formally been illegal, to spur foreign investment and post-Hurricane reconstruction (Stonich 2008).

Mangrove loss and subsequent recovery illustrates that, while extreme weather events cause short term damage, without human encroachment, Roatán's terrestrial landscape would remain remarkably resilient with substantial ecosystem and economic benefits. Urbanization and tourism development, however, create a feedback loop whereby the felling of mangroves further heightens the risks to damage by hurricanes through mangrove conversion and simultaneously contributes to the increased likelihood of hurricanes vis-a-vis increased carbon emissions. With reduced mangroves and weakening barrier reefs encircling the island, we wonder what will happen when the next category 4 hurricane slams into the island. Further research is needed measure to what extent anthropogenic threats compare and contrast to environmental threats in other coastal and terrestrial systems globally under dual human and climate change pressures.

**References:**

Aide, T. M., Clark, M. L., Grau, H. R., López-Carr, D., Levy, M. A., Redo, D., ... & Muñiz, M. (2013). Deforestation and reforestation of Latin America and the Caribbean (2001–2010). *Biotropica* **45**: 262-271.

Ajonina, G. J. G. Kairo, G. Grimsditch, T. Sembres, G. Chuyong, D. E. Mibog, A. Nyambane and C. FitzGerald 2014. Carbon pools and multiple benefits of mangroves in Central Africa: Assessment for REDD+. 72pp.

An, L. and López-Carr, D., 2012. Understanding human decisions in coupled natural and human systems. *Ecological Modelling* **229**: 1-4.

Belle, N., & Bramwell, B. (2005). Climate change and small island tourism: Policy maker and industry perspectives in Barbados. *Journal of travel research* **44**: 32-41.

Bender, M. A., Knutson, T. R., Tuleya, R. E., Sirutis, J. J., Vecchi, G. A., Garner, S. T., & Held, I. M. (2010). Modeled impact of anthropogenic warming on the frequency of intense Atlantic hurricanes. *Science*, **327**: 454-458.

Bremner, J., López-Carr, D., Suter, L., & Davis, J. (2010). Population, poverty, environment, and climate dynamics in the developing world. *Interdisciplinary Environmental Review* **11**: 112-126.

Burke L., & Maidens J. (2004). Reefs at Risk in the Caribbean (report). Washington, D.C: World Resources Institute.

Church, J.A., P.U. Clark, A. Cazenave, J.M. Gregory, S. Jevrejeva, A. Levermann…and A.S. Unnikrishnan (2013). Sea Level Change. In: Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P.M. Midgley (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Cassels, S., Curran, S., & Kramer, R. (2005). Do Migrants Degrade Coastal Environments? Migration, Natural Resource Extraction and Poverty in North Sulawesi, Indonesia. *Human Ecology* **33**: 329-363.

Caribbean Tourism Organization. (2015). State of The Tourism Industry Report 2015. St. Michael, Barbados: 1 pp. http://www.onecaribbean.org/wp-content/uploads/FINAL-CTO-2016-News-Conference-Infographic-.pdf&hl=en_US

Cahoon, D. R., Hensel, P., Rybczyk, J., McKee, K. L., Proffitt, C. E., & Perez, B. C. (2003). Mass tree mortality leads to mangrove peat collapse at Bay Islands, Honduras after Hurricane Mitch. *Journal of ecology* **91**: 1093-1105.

Donato, D. C., Kauffman, J. B., Murdiyarso, D., Kurnianto, S., Stidham, M., & Kanninen, M. (2011). Mangroves among the most carbon-rich forests in the tropics. *Nature Geoscience* **4**: 293-297.

Doiron, S., & Weissenberger, S. (2014). Sustainable dive tourism: Social and environmental impacts—The case of Roatán, Honduras. *Tourism Management Perspectives* **10**: 19-26.

Eakin, C. M., Morgan, J. A., Heron, S. F., Smith, T. B., Liu, G., Alvarez-Filip, L., ... & Brandt, M. (2010). Caribbean corals in crisis: record thermal stress, bleaching, and mortality in 2005. *PloS one* **5**: e13969.

European Commission (2002) The Caribbean and the European Union. Luxembourg, Luxembourg: Office for the Official Publications of the European Communities: 17 pp.

Forest, N. B. (1998). Assessment of coastal regulations and implementation: case study of Roatan, Bay Islands, Honduras. *Coastal Management* **26**: 125-155.

Gardner, T. A., Cote, I. M., Gill, J. A., Grant, A., & Watkinson, A. R. (2008). Hurricanes and Caribbean coral reefs: impacts, recovery patterns, and role in long-term decline. *Ecology* **86:** 174-184.

Gilman, E. L., Ellison, J., Duke, N. C., & Field, C. (2008). Threats to mangroves from climate change and adaptation options: a review. *Aquatic botany* **89**: 237-250.

Hammond, D. S., Gond, V., Baider, C., Florens, F. B. V., Persand, S., & Laurance, S. G. W. (2015). Threats to environmentally sensitive areas from peri-urban expansion in Mauritius. *Environmental Conservation* **42**: 256-267.

Harper, G. J., Steininger, M. K., Tucker, C. J., Juhn, D., & Hawkins, F. (2007). Fifty years of deforestation and forest fragmentation in Madagascar. *Environmental Conservation* **34**: 325-333.

Healthy Reefs for Healthy People (2015). Mesoamerican Reef: An Evaluation of Ecosystem Health 2015 Report Card. Available: http://www.healthyreefs.org/

Hinrichsen, D. (1998). Coastal Waters of the World: Trends, Threats, and Strategies. Island Press Washington, DC

Kendall, B (2012, Feburary 11). A new Pete Dye golf course isn't all that's waiting for you in Roatán The Globe and Mail (2012, February 11). Retrieved from: http://www.theglobeandmail.com

Klein, R. J., & Nicholls, R. J. (1999). Assessment of coastal vulnerability to climate change. *Ambio*, 182-187.

Lawrence, R. L., Wood, S. D., & Sheley, R. L. (2006). Mapping invasive plants using hyperspectral imagery and Breiman Cutler classifications (RandomForest). *Remote Sensing of Environment* **100**: 356-362.

Martinuzzi, Sebastian, William A. Gould, and Olga M. Ramos González. (2007). "Land development, land use, and urban sprawl in Puerto Rico integrating remote sensing and population census data." *Landscape and Urban Planning* **79**: 288-297.

McBirney, A. R., & Bass, M. N. (1969). Geology of bay islands, Gulf of Honduras. In: *Tectonic Relations of Northern Central America and the Western Caribbean—The Bonacca Expedition*, pp 229-243. American Association of Petroleum Geologists.

McWilliams, J. P., Côté, I. M., Gill, J. A., Sutherland, W. J., & Watkinson, A. R. (2005). Accelerating impacts of temperature-induced coral bleaching in the Caribbean. *Ecology* **86**: 2055-2060.

Ministry of Tourism, Republic of Honduras (2009). Tourism Statistics Bulletin 2004 – 2008 (report). Retrieved from: http://www.iht.hn/files/tourism-statistic-bulletin-20042008.pdf

Ministry of Tourism, Republic of Honduras (2014). Tourism Statistics Bulletin 2009 – 2013 (report). Retrieved from: http://transparencia.iht.hn/?q=system/files/Boletin%20de%20Estadisticas%20Turisticas%20 2009-2013.pdf

Moore, W. R. (2010). The impact of climate change on Caribbean tourism demand. *Current Issues in Tourism* **13**: 495-505.

Mumby, P. J., Edwards, A. J., Arias-González, J. E., Lindeman, K. C., Blackwell, P. G., Gall, A., ... & Wabnitz, C. C. (2004). Mangroves enhance the biomass of coral reef fish communities in the Caribbean. *Nature* **427**: 533-536.

Murray, M. R., Zisman, S. A., Furley, P. A., Munro, D. M., Gibson, J., Ratter, J., ... & Place, C. J. (2003). The mangroves of Belize: Part 1. distribution, composition and classification. *Forest Ecology and Management*, **174**: 265-279.

National Climatic Data Center (2004). "Mitch: The Deadliest Atlantic Hurricane Since 1780". United States National Oceanic and Atmospheric Administration's National Environmental Satellite, Data, and Information Service. Retrieved May 23, 2016.

Nunes, S. S., Barlow, J., Gardner, T. A., Siqueira, J. V., Sales, M. R., & SOUZA, C. M. (2015). A 22 year assessment of deforestation and restoration in riparian forests in the eastern Brazilian Amazon. *Environmental Conservation* **42**: 193-203.

Roberts, D. A., Numata, I., Holmes, K., Batista, G., Krug, T., Monteiro, A., ... & Chadwick, O. A. (2002). Large area mapping of land-cover change in Rondonia using multitemporal spectral mixture analysis and decision tree classifiers. *Journal of Geophysical Research: Atmospheres, 107(D20)*.

Roatán Population Tops 100,000 Up Four-Fold Since Last Official Census in 2001. (n.d.). Retrieved from http://www.bayislandsvoice.com/Roatán-population-tops-100000-up-four-fold-since-last-official-census-in-2001-201405079774

Rochelau, M. (2015, October 23). 10 strongest hurricanes ever recorded in the Western Hemisphere. Boston Globe. Retrieved from http://www.bostonglobe.com.

Scott, D., Simpson, M. C., & Sim, R. (2012). The vulnerability of Caribbean coastal tourism to scenarios of climate change related sea level rise. *Journal of Sustainable Tourism* **20**: 883-898.

Seto, K. C., Fragkias, M., Güneralp, B., & Reilly, M. K. (2011). A meta-analysis of global urban land expansion. *PloS one*, ***6***: e23777.

Singh, S. K., Srivastava, P. K., Gupta, M., Thakur, J. K., & Mukherjee, S. (2014). Appraisal of land use/land cover of mangrove forest ecosystem using support vector machine. *Environmental earth sciences* **71**: 2245-2255.

Spalding M.D., Ravilious C. and Green E.P. (2001). World Atlas of Coral Reefs. Prepared at the UNEP World Conservation Monitoring Centre. University of California Press, Berkeley, USA.

Stonich, S. C. (1998). Political ecology of tourism. *Annals of tourism research* **25**: 25-54.

Stonich, S. C., Stronza, A., & Durham, W. H. (2008). Ecotourism and marine protected areas in a time of climate change. *Ecotourism and conservation in the Americas*, 51-65.

Stonich, S. (2008). International Tourism and Disaster Capitalism. Capitalizing on Catastrophe: Neoliberal Strategies in Disaster Reconstruction. In *Capitalizing on Catastrophe Neoliberal Strategies in Disaster Reconstruction (Globalization and the Environment)*, ed. N. Gunewardena and M. Schuller, 47-68. Lanham, New York: AltaMira Press.

Sutton, D. S. (2015). Structural and geophysical interpretation of Roatán Island, Honduras, Western Caribbean (unpublished M.A. Thesis). University of Louisiana at Lafayette; 10002482

Tomczyk, T (2010, February 1). Nature's Refuage at Port Royal: A 31-year effort of creating land protected area on the East Side of Roatán, begins to bear fruit. Bay Island Voice. Retrieved from http://www.bayislandvoice.com

Tuholske, C., López-Carr D., and D. Roberts. 2016 (*accepted*). Anthropogenic impacts on Roatán, Honduras: 30 Years of Land-Cover and Land-Use Change. *Plurimondi. An International Forum for Research and Debate on Human Settlements.*

Turner, R. (2015). Travel & Tourism, Economic Impact 2015, Caribbean (Report). World Travel and Tourism Council. p. 1. Retrieved 2016-05-23.

United States Geological Survey (2016). Landsat Surface Reflectance High Level Data Products. Retrieved from: http://landsat.usgs.gov/CDR_LSR.php

United Nations, Department of Economic and Social Affairs, Population Division, World Population Prospects: The 2014 Revision, New York, 2015.

Webster, P. J., Holland, G. J., Curry, J. A., & Chang, H. R. (2005). Changes in tropical cyclone number, duration, and intensity in a warming environment. *Science* **309**: 1844-1846.

Zhong, L., Gong, P., & Biging, G. S. (2014). Efficient corn and soybean mapping with temporal extendability: A multi-year experiment using Landsat imagery. *Remote Sensing of Environment* **140**: 1-13.