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CHANGES IN VEGETATION AND COASTAL MORPHOLOGY ON SAN SALVADOR, BAHAMAS FOLLOWING HURRICANE FRANCES IN 2004

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ABSTRACT

On 2 September 2004 Hurricane Frances hit the island of San Salvador, the Bahamas with sustained wind speed of 120 mph (~190 kph) and pressure drops down to 948.1 mb when the leading edge of the eyewall passed directly over the island. The high winds accompanied with a >5 m storm surge had drastic effects on the coastal morphology and vegetation of the island. We conducted a remote sensing analysis using Landsat 7 Enhanced Thematic Mapper imagery from 30 August 2004 and comparing it to images that were acquired on 1 October 2004. We evaluated various vegetation indices, as well as band combinations with respect to changes in the island's vegetation and the shoreline.

A change detection analysis conducted in ERDAS Imagine software suggests that the southern half of the island's vegetation was under stress prior to the hurricane with biomass production in the coppice of the Blacklands well below the northern portion and areas populated by mangroves. Most of the beaches along the southeast portion of the island experienced substantial destruction of the backshore vegetation in addition to sediment deposition. Our preliminary analysis further indicates that only four weeks after the hurricane and accompanying heavy rainfall, large parts of the vegetation were recovering at a fast pace. The normalized difference vegetation index (NDVI), the normalized difference moisture content index (NDMI), as well as the soil adjusted vegetation index (SAVI) show an increase in chlorophyll production on the order of ten percent in the southern portion of the island's coppice vegetation. We hypothesize that the hurricane had a rejuvenating effect on the island's flora, as much of the debilitated or stricken vegetation did not survive the hurricane making room for new plants. At the same time a classification of the vegetation also suggests that vegetation close to the shore and coastline, i.e. coastal thicket and *Coccothrinax* shrub were permanently damaged from Hurricane Frances. This suggests that the islands' biodiversity has been negatively impacted in these zones.

INTRODUCTION

Six major hurricanes severely damaged islands in the Caribbean including the islands of the Bahamas in 2004. This study focuses on the impact of Hurricane Frances that hit San Salvador, Bahamas as a Category 4 hurricane on September 2, 2004 (Figure 1). Of particular concern are events of massive plant mortality caused by rapid fluctuations in environmental conditions (Jiménez et al., 1985a), such as hurricanes, droughts, chronic flooding, and active geomorphologic processes. Coastal and wetland vegetation transience caused by hurricanes have been documented but in many cases the absence of historical records impedes the ability of researchers to evaluate the scope of the damage (Kovacs et al., 2002). In our study, we analyzed short-term temporal shifts associated with Hurricane Frances. The hurricane not only deposited sediments that were transported by significant storm-induced currents but also generated massive washovers in association with the storm surge. This caused destruction of vegetation in the backshore lacustrine and lagoonal environments, in particular in the southeastern portion of the island and other vegetated areas across the island.

We utilize two satellite images acquired by the Landsat 7 Enhanced Thematic Mapper from August 30, 2004 and October 1, 2004 to examine vegetation changes caused by washover sediment along the shoreline and to document substantial defoliation caused by the storm surge and storm winds. Our approach is similar to the work of Cablk et al. (1994) who used multiple Landsat Thematic Mapper (TM) images to assess the impact of a hurricane on coastal, forested wetlands in South Carolina.

IMAGE SELECTION AND PROCESSING

The spectral data from the satellite images were processed and analyzed using the ERDAS Imagine 9.0 software. We produced maps of our analyses with the ESRI's ArcGIS 9.2 program. To avoid problems associated different factors impacting the temporal comparison, we acquired three Landsat Enhanced Thematic Mapper (TM) images that covered approximately three months. The main problem with the satellite imagery from Fall 2004 was that they post-date an instrument failure of Landsat 7's scan line correction utility. Consequently, all images contain stripes with no values for the spectral data. After careful inspection of the sub-scenes for San Salvador, Bahamas, we extracted lines extending from 1399 by 2124 pixels in all the images. Furthermore, a geometric registration was necessary in order to compare data for the same location from each of the different image dates. Employing a nearest-neighbor algorithm, both the August 30, 2004

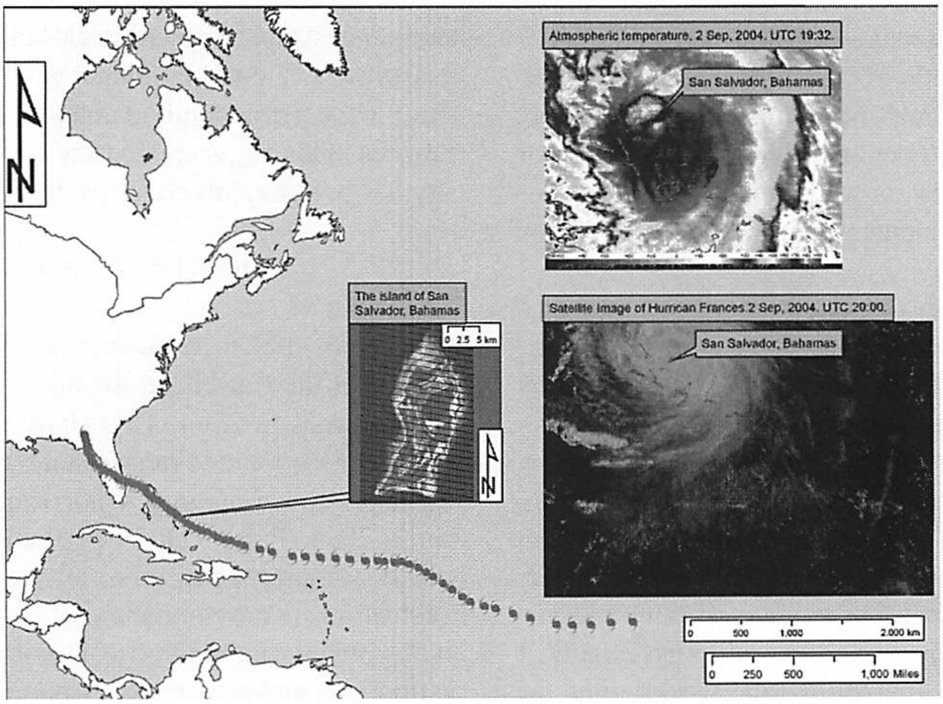

Figure 1. Hurricane Frances storm track from August 25 to September 9, 2004.

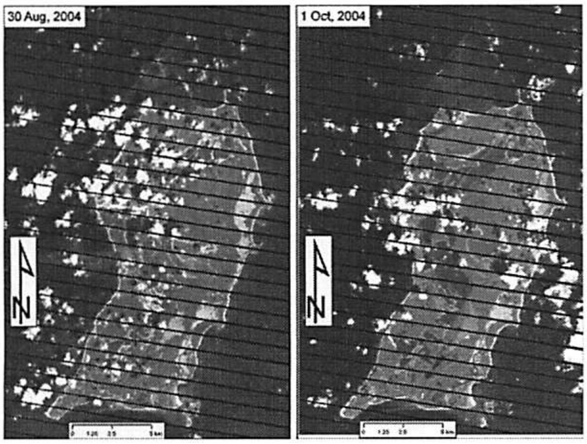

Figure 2. False color composite image of San Salvador Island showing Landsat Thematic Mapper bands 4, 3, 2. The image on the left is from August 30th before Hurricane Frances struck the island. The image on the right is about one month after the hurricane on October 1, 2004.

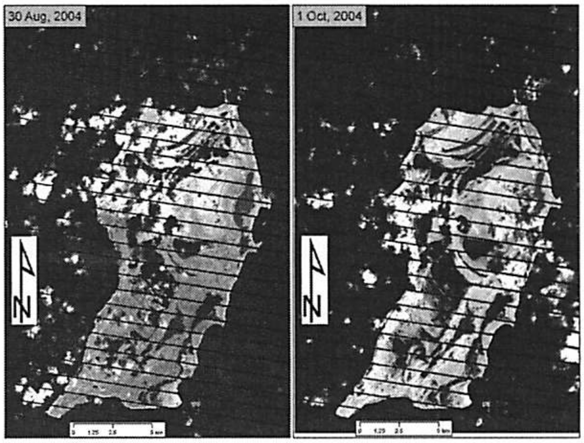

Figure 3. Landsat-7 satellite image of San Salvador Island, the Bahamas showing near-infrared bands (band 4). The image on the left is from August 30, 2004 before Hurricane Frances struck the island. The image on the right is from October 1, 2004, after the hurricane struck.

and October 1, 2004 scenes were rectified to a third scene acquired on 4 December, 2004 using 10 and 9 ground-control points, respectively. The root mean square (RMS) error for the October to December registration was 0.86(x)/1.28(y) with a total of 1.54 and for the August to December registration it was 1.05(x)/0.87(y) with a total of 1.36. For further analysis, we disregarded the December 4, 2004 image as it was obtained three months after the hurricane had struck, which may pose problems caused by seasonal differences. Another major limitation of image analyses was the obvious atmospheric disturbances, i.e. haze, clouds, and cloud shadows. A small-scale classification of vegetation was therefore not feasible and the focus is more directed towards an island-scale perspective of temporal changes.

IMAGE ANALYSES

The standard false color image comparison provides important information regarding the condition of the vegetation of the study region. Vegetation appears in shades of red, urban areas are cyan blue, and soils vary from dark to light browns and clouds are white or light cyan (Figure 2). This popular spectral band combination provides a quick assessment of the vegetative health prior to conducting further image processing and analysis. Generally, deep red hues indicate broad leaf and/or healthier vegetation while lighter reds signify grasslands or sparsely vegetated areas. We observed that prior to Hurricane Frances, large portions of the entire island appear darker red and brown compared to the image acquired in October of 2004. Only the vegetation in northeastern portion of the island appears to be in better shape in August compared to October.

To further investigate this phenomenon, we compared the near-infrared (NIR) bands of both images. Since high reflectance values in the near infrared characterizes healthy leaf tissue due to the plants chlorophyll content, a stress response (damage) in vegetation should be recognizable by decreases in the spectral value of band 4 (Landsat TM) over time (Kovacs et al., 2002; Hardisky et al., 1986). Figure 3 supports our initial inference that the vegetation prior to the hurricane is experiencing a state of stress. The spectral reflectance in the NIR is significantly increased in October compared to late August.

Conversely, if vegetation is damaged and chlorophyll content is decreased, plants can no longer absorb visible light for photosynthesis and would display an increase in the spectral values of band 3 (Kovacs et al., 2002). Our observation seems to support this relationship as well. Figure 4 shows Band 3 for the images from August and October of 2004. The spectral reflectance for the earlier scene is slightly higher than observed in the post-hurricane image.

Particularly popular in vegetation studies are band combination 4-5-1 and 4-5-3. The addition of the mid-IR band increases the sensitivity of detecting various stages of plant growth or stress because bands TM-4 and TM-5 show high reflectance in healthy vegetated areas. Often in color composite images, healthy vegetation appears in shades of reds, browns, oranges, and yellows while soils may be in greens and browns. Urban features tend to be white, cyan, and gray, while bright blue areas represent recently clear-cut areas. Reddish areas show new vegetation growth or potentially, sparse grasslands. Clear, deep water will be very dark in this spectral band combination, if the water is shallow or contains sediments it would appear as shades of lighter blue. Figure 5 is a band 4-5-1 false color composite that was evaluated with respect to vegetation. In agreement with previous images, we find that in August green colors dominate except for the northeastern portion of the island. Thirty-three days later, we find that most of the island is covered by reddish-brown shades indicating that the vegetation has recovered from the previous image.

Digital Change Detection in Vegetation Indices

To further refine our preliminary observations, we computed several vegetation indices in ERDAS Imagine software that provide the basis for our subsequent change detection analysis. Since an atmospheric correction was not performed as we found an overall loss in image qual-

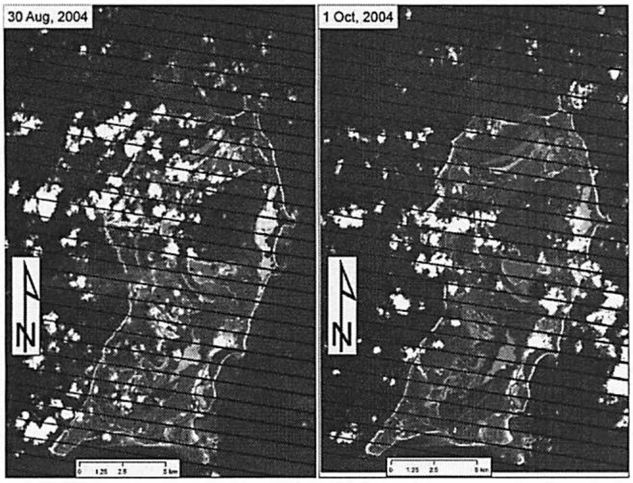

Figure 4. Landsat-7 satellite image of San Salvador Island showing the red TM band (band 3). The image on the left is from before Hurricane Frances struck the island; on the right is after the hurricane.

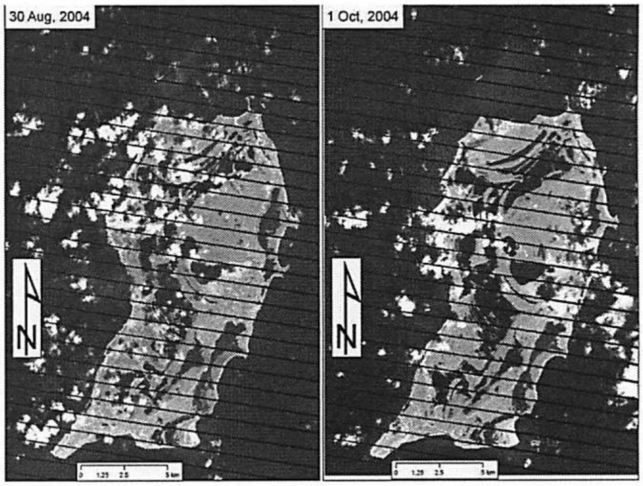

Figure 5. False color composite image combining Landsat-7 Thematic Mapper near-infrared band 4 and mid-infrared ban 5 and blue band 1. The image on the left is from August 30, 2004 before Hurricane Frances made landfall on the island. The image on the right is from October 1, 2004.

ity, we analyzed four different vegetation indices and compared the results to identify patterns in vegetation before and after Hurricane Frances.

Normalized Difference Vegetation Index

The Normalized Difference Vegetation Index (NDVI) can be used for monitoring biomass production for seasonal and inter-annual changes registering as vegetation growth or decline (Jensen, 2007). The index is useful because its computation reduces many forms of multiplicative noise in the form of atmospheric disturbances that are present in our images. Nonetheless there are a number of disadvantages in the reliability of the index that are discussed in detail in Jensen (2007). Figure 6 shows detected change that occurred between the acquisition of the image on August 30, 2004 and October 1, 2004. High spectral values (light) indicate vegetative gains, whereas low spectral values (dark) indicate vegetative losses. A second image in Figure 6 shows a thematic map of areas gaining or losing more than ten per cent in vegetation cover. The major contributing source of error is atmospheric moisture that occurs throughout the entire image. Although large parts of San Salvador Island are undisturbed by the atmosphere, some areas may still require careful evaluation as detected change may actually be a missing or added cloud cover. As indicated in our initial comparisons, we found that a biomass production increase predominates the southern half and along the northwest side of the island. Most areas where vegetation losses occur are found along the eastern shoreline and the northeast portion of the island, although some of these differences may be attributed to clouds and cloud shadows (compare to Figure 5). To overcome the disadvantages of the NDVI, we computed two further vegetation indices that eliminate many of the error sources impacting the NDVI (Jensen, 2007).

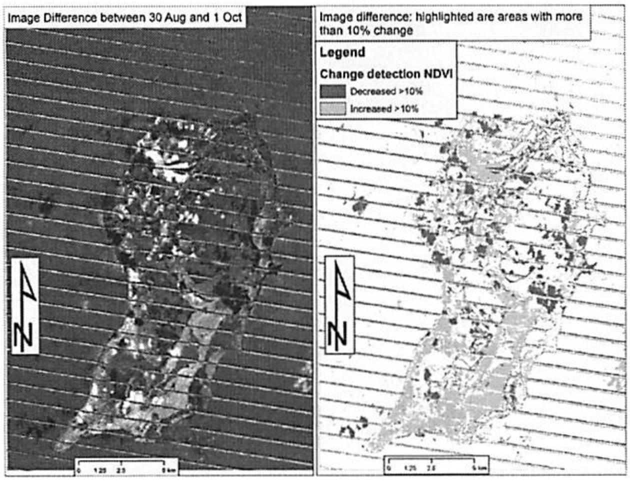

Figure 6. Change detection using the Normalized Difference Vegetation Index between two Landsat 7 images acquired August 30, 2004 and October 1, 2004. The image on the left shows high spectral values (light) that indicate vegetation gain whereas low spectral values (dark) indicate vegetation loss. The image on the right highlights areas with either greater than 10% or less than 10% change in vegetation.

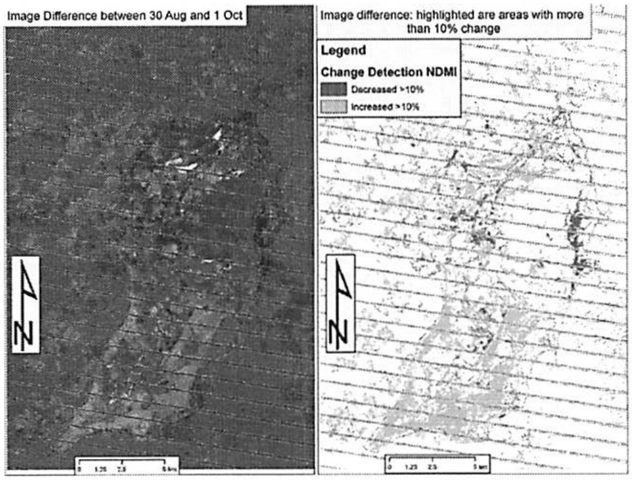

Figure 7. Change detection using the Normalized Difference Moisture Index on two Landsat 7 images acquired August 30, 2004 and October 1, 2004. The image on the left shows high spectral values (light) that indicate vegetation gain whereas low spectral values (dark) indicate vegetation loss. The image on the right highlights areas with either greater than 10% or less than 10% change in vegetation.

Normalized Difference Moisture Index

The Normalized Difference Moisture Index (NDMI) provides a measure for vegetation water content based on Landsat TM near and middle-infrared bands. The index is very sensitive to canopy water content and changes in plant biomass and water stress (Jensen, 2007). Mathematically, the NDMI is defined as Thematic Mapper band TM 4 minus TM-5 by divided by the sum of bands TM-4 and TM-5 (Jensen, 2007).

Figure 7 shows detected changes that occurred between the acquisition of the image on August 30 and October 1. Analogous to the NDVI, we observed that positive moisture differences are located mainly in the southern half of San Salvador Island showing an increase in biomass production. However, a comparison to the NDVI (Figure 6) shows that the NDMI method calculates fewer areas of vegetation loss.

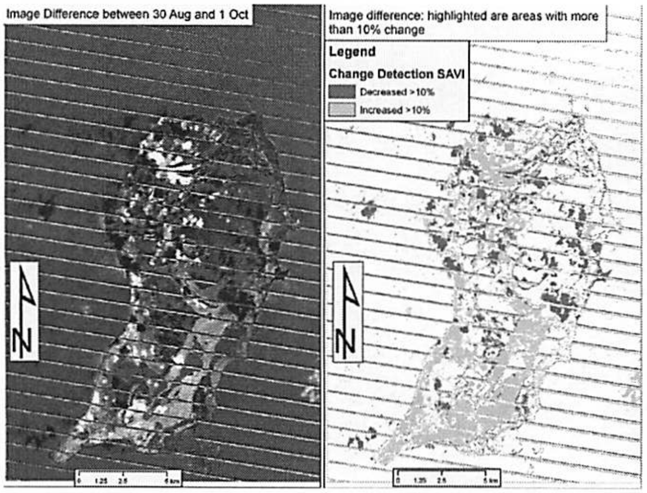

Figure 8. Change detection using the Soil Adjusted Vegetation Index on two Landsat 7 images acquired August 30, 2004 and October 1, 2004. The image on the left shows high spectral values (light) that indicate vegetation gain whereas low spectral values (dark) indicate vegetation loss. The image on the right highlights areas with either greater than 10% or less than 10% change in vegetation.

Soil Adjusted Vegetation Index

Another improved vegetation index that was utilized is the Soil Adjusted Vegetation Index (SAVI). This index is similar to the NDVI, although it contains an adjustment factor for canopy noise. SAVI is a further improvement because it minimizes the soil noise inherent in the NDVI, thereby increasing its dynamic range (Jensen, 2007).

Figure 8 shows detected change that occurred between the acquisition of the image on 30 August and 1 October. High spectral values (light) indicates vegetation gains whereas low spectral values (dark) indicate vegetation losses. A second image in Figure 8 shows a thematic map of areas gaining or losing more than ten per cent vegetation. Similar to the NDVI and the NDMI results, the southern half of San Salvador Island generally shows vegetation increases greater than 10%.

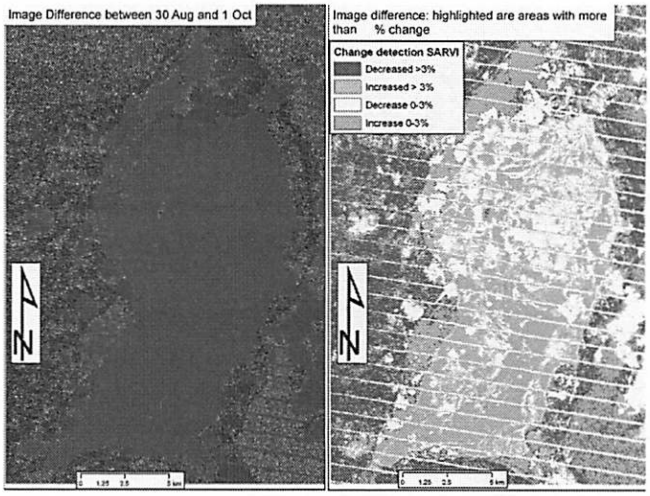

Figure 9. Change detection using the Soil and Atmospherically corrected Vegetation Index on two Landsat 7 images acquired August 30, 2004 and October 1, 2004. The image on the left shows high spectral values (light) that indicate vegetation gain whereas low spectral values (dark) indicate vegetation loss. The image on the right highlights areas with either greater than 3% or less than 3% change in vegetation.

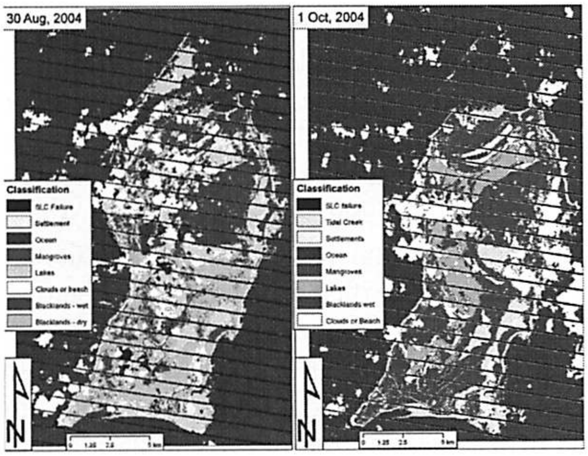

Figure 10. Land cover classification of the two Landsat 7 Thematic Mapper images. Classes follow vegetation types of Robinson and Davis (1999). The image on the left is from August 30th before Hurricane Frances and shows a distinct differentiation between stressed and healthy blacklands vegetation. The image on the right is about one month after the hurricane on October 1, 2004.

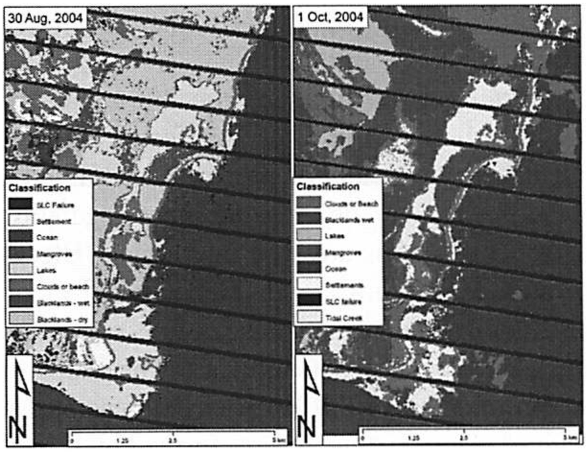

Figure 11. Land cover classification of the two Landsat 7 Thematic Mapper images of the southeast corner of San Salvador island. Notice the increase in areas classified as beach likely due to the defoliation of coastal vegetation and the deposition of washover fans from Hurricane Frances.

Soil and Atmospherically Corrected Vegetation Index

A different result is derived from the Soil and Atmospherically Corrected Vegetation Index (SARVI). Jensen (2007) proposes that the SARVI may deliver the best results where no atmospheric corrections were performed. Both noise values, soil and atmospheric disturbances, are best eliminated using SARVI. Figure 9 shows detected change that occurred between the acquisition of the image on August 30, 2004 and October 1, 2004. The high noise levels over the Atlantic are easy to detect. Clouds on the other hand only appear to have insignificant impact on the detected change. Overall, the island appears to be almost unchanged. A second image in Figure 9 shows a thematic map of areas gaining or losing more than three per cent vegetation. The lower half of San Salvador appears to have gained vegetation by 3% while in the central and northern portion of the island vegetation decrease seems to prevail. Further, along the eastern shoreline we found that vegetation decrease by a small margin, although this should be better quantified. The implications from the SARVI are significant. Following Jensen's (2007) suggestion of a high reliability in atmospherically uncorrected images, the results from the SARVI propose only marginal changes compared to the previous indices. Moreover, we can infer that the image from August 30, 2004 contains severe atmospheric disturbances that may introduce a considerable bias, for example if only the southern half of the island is impacted by atmospheric noise.

Vegetation Classification

In order to further investigate the areas that experienced vegetation changes, we classified both Landsat scenes used in the change detection analyses. Robinson and Davis (1999) compiled vegetation cover of San Salvador into a GIS database that we utilized for accuracy assessment along with the original Landsat images (Figure 10).

From our analyses of the 2004 Landsat TM images before and after Hurricane Frances, we identified the southern part of San Salvador Island as the region showing the most vegetation changes. This area is covered in coppice (Blackland) and agricultural land. Because of cloud cover, shadows, and other noise, a fine-scale vegetation classification that duplicates the maps of Robinson and Davis (1999) was not feasible. A supervised classification was performed by selecting easy-to-distinguish land cover types in both Landsat scenes. We mainly grouped the vegetation into mangroves and Blacklands. In the pre-hurricane images, the Blacklands class was divided into healthy and stressed Blacklands vegetation. These areas where expected to show the most drastic changes. In both cases, the areas classified as Blacklands will also contain coastal thicket and agricultural land, but since we are mostly interested in the overall change, a simplified classification seems beneficial. Other classified features that did not differentiate vegetation and areas impacted by the failure the Landsat 7 SLC utility are shown in Table 1.

Due to the various disturbances in the image, the accuracies are relatively low. Table 2 contains the groups or classes for the classification of the image from October 1, 2004 that mostly coincide with the former classification efforts by Robinson and Davis (1999). As distinct from August 30, the classification for October 1 additionally contains areas classified as tidal creek. Figure 11 shows a classification of the islands vegetation for August 30 and October 1 of 2004. We grouped the classes "Lakes" and "Tidal Creek" to enhance the value of the presentation of the results in Figure 11.

Concurring with the previously calculated vegetation indices, we find that in the pre-hurricane image San Salvador is divided into a northeast segment that shows healthy vegetation with high moisture content and a southern portion that is dominated by stressed vegetation. The post-hurricane image appears homogeneous and covered with mostly coppice-like vegetation. Further, the classification fails to identify mangroves as accurately as in the pre-hurricane example.

Furthermore, we utilized the classification to highlight changes in the coastline between the two image acquisitions. Field investigations have

Table 1. Accuracy Assessment for Classification of August 30, 2004 Landsat 7 image

Class Name	Reference Totals	Classified Totals	Number Correct	Producers Accuracy	Users Accurcay
Ocean	27	15	15	55.56%	100.00%
SLC Failure	13	15	8	61.54%	53.33%
Clouds or Beach	21	15	11	52.38%	73.33%
Blacklands - healthy	20	15	13	65.00%	86.67%
Mangroves	13	15	4	30.77%	26.67%
Blacklands - stressed	10	15	7	70.00%	46.67%
Settlement	4	15	3	75.00%	20.00%
Lakes	12	15	8	66.67%	53.33%
Totals	120	120	69		

Overall Classification Accuracy = 57.50%

found that storm surge, high winds, and saltwater overwash caused devastating damages to the coastal vegetation (Niemi et al., 2008; McCabe and Niemi, 2008). Figure 11 shows the southeastern extent of San Salvador, Bahamas. Due to the similar spectral reflectance, clouds and beaches are classified as the same class. Both images show the class in a red color. For this segment of the island, we can easily detect how the shoreline has widened, although the later image has atmospheric noise in the form of clouds in the northeast segment. Vegetation that was previously detected on the small islands in the far south has been classified as beach in the post-hurricane scene. Much of the increase in beach area is attributable to the removal of coastal thicket and Coccothrinax shrub that occupied much of the eastern margin of San Salvador (Compare to Figure 10).

DISCUSSION AND CONCLUSION

We compared Landsat 7 Enhanced Thematic Mapper images acquired before and after Hurricane Frances made landfall on the island of San Salvador, Bahamas on 2 September 2004. The evaluation of different color composites of both images suggests that much of the vegetation was under stress prior to the hurricane. This is particularly true for the southern and western parts of the island. Similar results were derived from the computation of different vegetation indexes and subsequent digital change detection based on the indices. The NDVI, NDMI, and SAVI indicate that biomass over most of the island improved as shown by an increase in chlorophyll content after the hurricane, rather than decline as might be expected by foliage damage following a major storm. The southern half of San Salvador appears to have revitalized its Blacklands coppice as indicated by increases in the spectral reflectance of the vegetation by more than ten per cent.

However, the analysis of the SARVI index yields a different interpretation. Although plant life increases or declines coinciding with previous patterns that were distinguished throughout the island, the magnitude of these changes is significantly smaller. SARVI is particularly useful for its capability to reduce atmospheric and soil disturbances. On the other hand, it seems to weaken the signals for obvious large changes. An example would be the scan line correction failure that leaves inaccurate values in the scene. These values were replaced by black striped by the satellite data provider. Along with clouds and cloud

Table 2. Accuracy Assessment for Classification of August 30, 2004 Landsat 7 image

Class Name	Reference Totals	Classified Totals	Number Correct	Producers Accuracy	Users Accuracy
Clouds or Beach	15	15	12	80.00%	80.00%
Mangroves	8	15	8	100.00%	53.33%
Settlements	10	15	10	100.00%	66.67%
Blacklands healthy	22	15	15	68.18%	100.00%
SLC failure	14	15	14	100.00%	93.33%
Ocean	29	15	15	51.72%	100.00%
Lakes	21	15	15	71.43%	100.00%
Tidal Creek	1	15	1	100.00%	6.67%
Totals	120	120	90		

Overall Classification Accuracy = 75.00%

shadows these black areas shift slightly between pre-and-post hurricane images. A change detection can highlight these alterations but it appears that the changes are quantified as rather small using the SARVI index as basis. It appears that these changes are quantified as rather small by the SARVI. On the other hand, if the results calculated using SARVI are overall more robust then this has major implications for all other applied methods using a change detection (NDVI, NDMI, SAVI). We would have to conclude that most of the satellite image acquired on August 30, 2004 is disturbed by atmospheric noise which in turn creates a bias in all other vegetation indices. This may even suggest that the northeastern portion of the island represents the true vegetative state on August 30, 2004 and that Blacklands vegetation was indeed destroyed by Hurricane Frances. To clarify whether this is the case, we would need to analyze another scene that predates August 30, 2004. A satellite image prior to August 30, 2004 was not available for this study. If a vegetation stress signal is detected in an earlier image, then the changes detected by NDVI, NDMI and SAVI could be verified.

If we consider the indicated vegetation improvements detected by means of NDVI, NDMI and SAVI as valid we can readily identify the impacted flora by means of a classification. The high noise levels in both images prevent us from distinguishing many different land cover classes. It seems most conducive to mainly select areas covered by coppice and agricultural plants, as these areas cover large parts of San Salvador. We find that prior to Hurricane Frances the vegetation can be grouped into stressed and healthy Blacklands vegetation, and following the hurricane the vegetation has a very homogenous, healthy signature based on the calculation of vegetation indices.

Lastly, we determined the extent of change in the coastal morphology. Through image classification, as well as change detection between Landsat ETM images acquired in August and October of 2004, we distinguished areas where vegetation was drastically reduced in favor of the growth in areas classified as beaches after Hurricane Frances had struck. From previous classification (Robinson and Davis, 1999), we found that the impacted areas are located along the eastern shore of San Salvador and mainly accommodate coastal thicket and *Coccothrinax* shrub. This vegetation appears to be severely or permanently damaged, but this conclusion needs to be verified by field investigations.

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