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Identifying factors in differential hurricane damage to the forests in the Southern Yucatan Peninsula using MODIS imagery

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Dr. John Rogan, Chief Instructor

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Abstract

Hurricane damage to tropical forests has immediate impacts such as branch and trunk damage or tree uprooting, and long-term impacts including mortality, and changes in species composition. Satellite imagery can provide regional-scale, continuous coverage of hurricane damage to locate areas of high impact and track forest recovery. This study identifies immediate disturbance to forest types from Hurricane Dean, category 5 on the Saffir-Simpson scale, in 2007 in the southern Yucatán Peninsula. Spectral mixture analysis applied to 500 m 8-day surface reflectance imagery from the Moderate Resolution Imaging Spectroradiometer (MODIS) is used to map changes in fractions of green vegetation (GV) and non-photosynthetic vegetation (NPV) throughout the hurricane impacted area. GV loss and NPV gain varied by wind speed and forest type. Tall and medium forests covered the largest area that experienced coincident high GV loss and NPV gain. Throughout all forest types, the highest mean GV loss occurred in modeled wind speeds of 60-62 m/s. The highest mean NPV gain throughout all forests occurred in wind speeds of 75-77 m/s. Forests experienced a higher mean GV loss north of the track at a distance of up to 10 km from the track and 25-80 km from the track. At 25-80 km from the hurricane track, forests experienced a higher mean NPV gain north of the track as opposed to south of the track. The results of the study indicate that locating hurricane damage using satellite imagery might benefit from using multiple indicators that are sensitive to both the decrease in green vegetation and the increase in woody debris.

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Introduction

Hurricanes are a recurrent disturbance in Caribbean tropical forests and can cause extensive damage to trees (Boose et al., 1994; Foster and Boose, 1995; Boose et al., 2003; Van Bloem et al., 2006; Vandecar et al., 2011). The severity of hurricane damage is driven by interacting factors such as hurricane wind speed, topographic exposure, soil conditions, and the structural characteristics of trees (Wang and Xu, 2009; Vandecar et al., 2011; McGroddy et al., 2013). The combined effects of hurricane-caused defoliation, branch loss, stem damage, and tree uprooting result in canopy openings and increased downed woody debris on the forest floor (Cooper-Ellis et al., 1999; Richardson et al., 2010; Shiels et al., 2015). Hurricane damage facilitates a number of changes to the microclimate, understory vegetation, wildlife habitats, nutrient cycling, albedo, and carbon flux (Whigham et al., 1991; Chambers et al., 2007; Negron-Juarez et al., 2008; Johnson and Winker, 2010; Fisk et al., 2013; Klawinski et al., 2014; Lodge et al., 2014; Shiels et al., 2015).

Satellite remote sensing can potentially provide a regional-scale assessment of hurricane damage to locate areas of high impact, estimate biomass loss, understand the role of the landscape and hurricane wind fields, and track vegetation recovery (Ramsey et al., 2001; Chambers et al., 2007; Wang and Xu, 2009; Negron-Juarez et al., 2014; Hoque et al., 2015; Li et al., 2016). In the DeSoto National Forest in southern Mississippi, a change in remotely sensed biophysical parameters such as Leaf Area Index (LAI) and Fraction of photosynthetically absorbed radiation (Fpar) from the Moderate Resolution Imaging Spectroradiometer (MODIS) was reported as less sensitive to hurricane damage than MODIS derived vegetation indices such as the Normalized Difference Vegetation Index (NDVI), the Enhanced Vegetation Index (EVI), and the Normalized Difference Infrared Index (NDII) (Wang et al., 2010). A 2000-2014 temporal trajectory of changes in NDVI in the region affected by Hurricane Katrina (2005) revealed that certain areas near Katrina's landfall experienced a mean absolute deviation in NDVI from its annual mean of about 0.16 in 2005 (Li et al., 2016). This was the highest mean absolute deviation during a time period of 2000-2014 (Li et al., 2016). Furthermore, the region experienced a decrease in mean NDVI of 0.027 in 2005 compared to the mean NDVI from 2000-2004 (Li et al., 2016). From 2000-2014, certain areas near landfall experienced the lowest mean NDVI of about 0.5 in 2006 (Li et al., 2016).

A decrease in the Enhanced Vegetation Index (EVI), a MODIS surface reflectance based measure of vegetation which corrects for the reflectance of canopy background and the influence of aerosols, was reported as achieving damage detection of up to 95% when compared to hurricane damage recorded in the field in tropical forests in the southern Yucatán Peninsula and Nicaragua (Rogan et al., 2011; Rossi et al., 2013). Detecting hurricane damage using EVI has been found to vary by timing of pre-hurricane and post hurricane imagery, wind speed, damage severity, and forest type (Rogan et al., 2011; Rossi et al., 2013). In the southern Yucatán Peninsula, the highest hurricane damage occurred in Saffir-Simpson wind speed category 5 and 4 and the least hurricane damage occurred in category 3 (Rogan et al., 2001). Using hurricane damage recorded in 93 field plots, change in EVI achieved higher damage detection rates among medium stature forests and mangroves (91-100%) than pasture and agriculture land covers (66.7% in wind speed category 3) (Rogan et al., 2011). Damage detection using changes in EVI also differed by wind speed (Rogan et al., 2011). Areas in wind speed category 5 were in highest correspondence with the field data with 95% damage detection (Rogan et al., 2011). Damage detection was 92.9% in wind speed category 4 and 87.1% in category 3 (Rogan et al., 2011). Dense broadleaf forests experienced the highest damage (ΔEVI -9 to -26) and pine forests experienced low hurricane damage (ΔEVI -4 to -8) from hurricane Felix (2007) in Nicaragua (Rossi et al., 2013).

Along with changes in vegetation indices which can provide a continuous measure of vegetation change, land-cover classification has been applied to pre-cyclone and post cyclone moderate spatial resolution imagery to detect transitions in discrete classes. Hoque et al. (2015) classified pre- and post-cyclone imagery into ten categories using object-based segmentation with an overall accuracy of 94% for the pre-cyclone map and an overall accuracy of 93% for the post cyclone map (Hoque et al., 2007). A conversion of the dense vegetation class to the sparse vegetation class was determined as cyclone damage from Cyclone Sidr (2007) in Bangladesh (Hoque et al., 2015). Significant decreases in mean canopy height from waveform Light Detection and Ranging (LIDAR) after hurricane Katrina have provided further insights into the use of active remote sensing to detect post hurricane structural changes in forests (Dolan et al., 2011). LIDAR derived mean canopy height loss was found to increase with hurricane wind speed (Dolan et al., 2011).

Estimates of increases in non-photosynthetic vegetation (NPV) from spectral mixture analysis (SMA) have shown significant correlations with field measured hurricane damage and mortality (r^2 = 0.6-0.88), and changes in LIDAR derived mean canopy height (Chambers et al., 2007; Dolan et al., 2011; Negron-Juarez et al., 2014). A number of studies have used an increase in NPV as inputs for modeling regional scale biomass loss and carbon flux resulting from hurricanes (Chambers et al., 2007; Negron-Juarez et al., 2008; Fisk et al., 2013). The increase in NPV as an indicator of hurricane damage has also been used to understand changes in regional climate resulting from hurricane disturbance (Negron-Juarez et al., 2008). While NPV has been widely used to study hurricane disturbance, few studies have simultaneously considered changes in NPV along with changes in green vegetation as indicators of hurricane damage. By disregarding GV loss, immediate hurricane damage might be underestimated. This study applies spectral mixture analysis (SMA) to moderate resolution imagery to isolate two constituents of post-hurricane forest change that reflect the direct consequences of hurricane damage to forests: the loss of green vegetation (GV loss) and gain in non-photosynthetic vegetation (NPV gain). GV loss and NPV gain is further analyzed in relation to modeled wind speeds, forest type, and aspect.

Study area

The study area consists of approximately 35,000 km^2 of the southern Yucatán Peninsula, Mexico covering multiple Saffir-Simpson wind speed categories and large areas of the Sian Ka'an Biosphere Reserve and the Calakmul Biosphere Reserve (Figure 1). The biosphere reserves are part of the Mesoamerican Biological Corridor and are recognized as biodiversity hotspots that protect mangrove communities and serve as habitat for endemic and threatened species (UNESCO). The vegetation in the area consists of mangroves, low statured forests (selva baja), shrubs that grow in seasonally inundated depressions (bajos), and medium statured forests (selva mediana) (Vandecar et al., 2011). The historical hurricane disturbance regime in the southern Yucatán Peninsula exhibits large spatial and temporal variation in both frequency and intensity (Boose et al., 2003). From 1851-2000, the eastern and northeastern areas experienced the most severe hurricane damage (Boose et al., 2003). During this time period, return intervals for hurricanes that can cause large blowdowns and gaps ranged from 20-30 years (Boose et al., 2003). Five major hurricanes have made landfall from 1998-2007 in the region (Rogan et al., 2011). Hurricane Dean made landfall on August 21, 2007 with maximum sustained winds of 172 mph making Dean a category 5 hurricane on the Saffir-Simpson hurricane wind scale (Franklin, 2008).

Data

The imagery used in this study consists of two 8-day (500 m) composite products (MYD09A1) from the Moderate Resolution Imaging Spectroradiometer (MODIS) on the Aqua platform. The pre-hurricane image (Julian date 217) is a composite of images captured August 5 – 12, 2007. The post hurricane image (Julian date 257) is a composite of images captured September 14 - 21, 2007. Another post hurricane MODIS daily surface reflectance image (MYD09GA) from September 13th, 2007 was used to fill surface reflectance values in a large patch of cloudy area near Chetumal in image 257 (Figure 1). Forest cover data were provided by the 2010, 30 m Environmental Disturbances in the Greater Yucatan (EDGY) land-cover map. The overall accuracy of the map is 90% (Rogan et al., 2011).

Hurricane Dean's gridded (1 km) estimated sustained wind speeds (m/s) were generated by the HURRECON model as part of the EDGY project, and were used in this study to characterize the forest damage in relation to modeled wind speed (Figure 7). HURRECON is a meteorological model based on empirical studies of hurricane structure (Boose et al., 1994). The model estimates the hurricane's surface wind speed as a function of storm position, storm speed and direction, eye diameter, maximum wind speed, and a wind profile constant (Boose et al. 1994). A 30 m Shuttle Radar Topography Mission (SRTM) Digital Elevation Model (DEM) was used to assess forest damage by aspect.

Hurricane damage was recorded in 92 (5 x 100 m) field plots between May and August 2008 (Vandecar et al. 2011). Damage plots were stratified by Saffir-Simpson wind speed zones and established throughout a range of damage conditions determined by differenced MODIS NDVI (MOD13Q1) (Vandecar et al. 2011). The species, diameter at breast height (dbh), and damage assessment was recorded for all trees with a dbh $\geq$ 5 cm within 2.5 m of a 100 m transect (Vandecar et al. 2011). The damage assessment consisted of seven categories: none apparent (O), small branch damage (SB), major branch damage (MB), bent (B), snapped (S), tree uprooted (TU), and dead (D) (Vandecar et al. 2011). SB consists of stems with broken branches <5 cm in diameter (Vandecar et al. 2011). MB consists of stems with broken branches >5 cm in diameter (Vandecar et al. 2011).

Methods

Linear spectral unmixing (LSU), an SMA methodology that is based on the linear mixing model, was used to extract fractions of green vegetation (GV), non-photosynthetic vegetation (NPV), and shade from the MODIS imagery. LSU estimates the per-pixel fraction of each endmember through inversion of the linear mixing model (Adams et al., 1995). The linear mixing model assumes the surface reflectance of a pixel is a weighted linear combination of pure endmember spectra within the pixel, plus an error term:

$$\rho_k = \sum_{i=1}^{M} \alpha_i \rho_{i,k} + \epsilon$$

subject to:

$$\sum_{i=1}^{M} \alpha_i = 1$$

where ρ_k is the surface reflectance of a given pixel in band k. For M endmembers, α_i is the fraction of endmember i and $\rho_{i,k}$ is the surface reflectance of endmember i for band k. The output of LSU includes a residual which is calculated as the square root of the sum of squared differences between the surface reflectance for a given band and the surface reflectance constructed by the LSU fractions and endmember surface reflectance (Eastman, 2016). The per-pixel residuals of the LSU were used to create a cloud mask for both scenes.

Endmembers were chosen from representative locations in the image. The GV endmember for both scenes were chosen from a forest location. The NPV endmember for the pre-hurricane scene was chosen from pasture land covers farther inland with drier properties. For the post hurricane scene, the NPV endmember was chosen from a coastal area near hurricane Dean's landfall within the mangrove land cover. The endmember for shade was chosen from deep water with very low reflectance past the red band (620–670 nm). The change in GV and NPV fractions between MODIS image 217 and 257 was calculated as:

$$\Delta GV = GV257 - GV217$$

$$\Delta NPV = NPV257 - NPV217$$

Determining change relative to pre-hurricane conditions resulted in the loss of change values for locations where pre-hurricane NPV was 0. Therefore, a simple difference was used to calculate damage. To characterize both the loss of live foliage and increased woody debris, GV loss, defined as the absolute value of decrease in the GV fraction, and NPV gain, defined as the increase in the NPV fraction, were used as indicators of hurricane damage. A boolean forest mask consisting of mangrove vegetation, secondary forest (<15 years), selva baja (short stature forest), bajos (short stature forest in depressions), selva mediana (medium stature forest), and selva alta (tall forest) was created from the 30 m EDGY land-cover map. Hurricane damage that had occurred in all other land-cover types was excluded from further analysis.

The HURRECON wind speed model values (m/s) were grouped into 12 intervals (42-44, 45-47, 48-50, 51-53, 54-56, 57-59, 60-62, 63-65, 66-68, 69-71, 72-74, 75 - 77 m/s). Mean GV loss and mean NPV gain were calculated for each forest type occurring within each wind speed zone. The two large protected areas (Calakmul Biosphere Reserve and Sian Ka'an Biosphere Reserve) were also used to assess GV loss and NPV gain by wind speed that had occurred in protected areas versus surrounding unprotected areas.

To understand the spatial pattern of forest damage by regional storm characteristics, sixteen 5 km buffers were created from the storm track up to 80 km from the track and the mean GV loss and NPV gain values were calculated for each buffer north and south of the track. To assess hurricane damage by exposure to wind, aspect was calculated from the 30 m SRTM DEM and mean GV loss and NPV gain were calculated for each aspect value. To compare the MODIS GV loss and NPV gain values with damage recorded in field plots, the percentage of damaged basal area per plot was calculated. For a given plot, the basal area of all stems for which the maximum damage was recorded as stem snapped, tree uprooted, and dead were summed and divided by the sum of basal area for all stems in the plot.

Results

The mean LSU residual for image 217 is 2048 (SD: 2077) with a range of 0 – 44345 (Figure 2). The mean LSU residual for image 257 is 2185 (SD: 20126.52) with a range of 15.86 – 18699 (Figure 3). For both images, the higher residuals (>5000) are at the location of cloudy pixels and were used to create a cloud mask. The study area experienced a mean decrease of 0.38 (range = 0.009 - 1) in the GV fraction, and a mean increase of 0.18 (range =0.009 - 1) in the NPV fraction. High GV loss occurred throughout Saffir-Simpson wind speed categories 5 and 4, with isolated patches in category 3 (Figure 4). High NPV gain occurred in isolated patches and is more restricted geographically to near-coastal locations in wind speed category 5 and 4. The largest contiguous patch of high NPV gain is located along the coast, slightly south of the hurricane track (Figure 5). A color composite image of GV loss in green, and NPV gain in red revealed that there are areas that experienced a higher magnitude of NPV gain than GV loss and vice versa (Figure 6).

Mangroves and selva baja occupy the largest areas in the highest wind speeds of 66-77 m/s (Figure 8). Secondary forests, selva alta, and selva mediana occupy larger areas in lower wind speeds with the largest area of selva mediana present in wind speeds of 48-50 m/s (1,657 km^2) (Figure 8). The highest mean GV loss throughout selva alta (0.61) and secondary forests (0.55) occurred in wind speeds of 66-68 m/s (Figure 9). The highest mean GV loss throughout bajos (0.53), selva baja (0.51), and selva mediana (0.55) occurred in wind speeds of 69-71 m/s (Figure 9). The highest mean GV loss throughout mangroves (0.31) occurred in wind speeds of 72-74 m/s (Figure 9). The highest mean NPV gain throughout mangroves (0.26), bajos (0.29), selva baja (0.27), and selva mediana (0.26) occurred in wind speeds of 75-77 m/s (Figure 10). The highest mean NPV gain throughout selva alta (0.25) occurred in wind speeds of 63-65 m/s (Figure 10). The highest mean NPV gain throughout secondary forests (0.24) occurred in wind speeds of 66-68 m/s (Figure 10).

At wind speeds of 45-47 m/s and 51-53 m/s, the Calakmul Biosphere Reserve experienced higher GV loss compared to the surrounding unprotected area (Figure 11). The Sian Ka'an Biosphere Reserve experienced lower GV loss compared to the surrounding unprotected area at all wind speeds (Figure 11). At the highest wind speeds, both the Calakmul and the Sian Ka'an Biosphere Reserve experienced slightly higher NPV gain compared to the surrounding unprotected area (Figure 12). The highest mean GV loss occurred on slopes facing northwest (Figure 13) and the highest mean NPV gain occurred on slopes facing northeast (Figure 14). The highest mean GV loss occurred north of the track at about 80 km from the track (Figure 15). The highest mean NPV gain occurred at a close range to the hurricane track (5-20 km north and 5- 20 km south) (Figure 16).

Eight plots were removed due to overlap with the cloud/noise mask for extracting GV change at locations of field plots. Ten plots were removed due to overlap with the cloud/noise mask for extracting NPV change at locations of field plots. GV loss with a range of 0.01 – 0.89 occurred at 66.3% of field plot locations. NPV gain with a range of 0.01 – 0.54 occurred at 85.2% of field plot locations. A scatter plot of GV change and percent severely damaged basal area per plot reveals a weak, negative, linear trend with a slope of -0.005 ($p < .01$, $r^2 = 0.08$) (Figure 17). A scatter plot of NPV change and percent severely damaged basal area in a plot reveals a weak, positive, linear trend with a slope of 0.002 ($p < .01$, $r^2 = 0.1$) (Figure 18).

Discussion and Conclusion

The GV loss and NPV gain maps reveal that these two indicators of hurricane damage carry unique information about the pattern and severity of hurricane damage. Coincident high GV loss and high NPV gain occurred throughout a very small area (172 km^2). Throughout these patches, the mean GV loss was 0.75 and the mean NPV gain was 0.77. The largest amount of area for patches of coincident high GV loss and NPV gain were located in wind speeds of 63-68 m/s, 10-15 km south of the track, and 15-20 km north of the track. When considering the same distances from the storm track, higher mean GV loss and NPV gain occurred north of the track at greater distances from the track. The higher surface wind speeds that occur to the right side of the hurricane track (Boose et al., 2001) likely contributed to higher GV loss and NPV gain north of the track.

Both GV loss and NPV gain vary by forest stature and regional hurricane wind characteristics that vary by distance from coast and distance from the hurricane track. This indicates that a heterogeneous hurricane wind field likely interacted with a landscape of heterogeneous forest canopy structure to create patchy disturbance severity throughout the region. Throughout the forest types, the highest GV loss occurred among selva alta forests in wind speeds of 66 - 68 m/s and the highest mean NPV gain occurred throughout bajos in wind speeds of 75 - 77 m/s. Regionally, the highest mean GV loss occurred in wind speeds of 60 - 62 m/s, throughout unprotected areas, on northwest facing slopes, and 75 - 80 km north of the hurricane track. The highest mean NPV gain occurred in wind speeds of 75 - 77 m/s, throughout unprotected areas, on northeast facing slopes, and 5 - 10 km south of the hurricane track. The lowest mean GV loss occurred in wind speeds of 45 - 47 m/s, throughout unprotected areas, on slopes facing east, and 40 - 45 km south of the track. The lowest mean NPV gain occurred in wind speeds of 42 - 44 m/s, throughout protected areas, on slopes facing east, and 75 - 80 km south of the hurricane track. As indicators of hurricane damage, GV loss and NPV gain offer different information regarding the location of the highest damage in relation to forest type, aspect, wind speed, land management (protected vs. unprotected), and the location of the forest in relation to the hurricane track. The results of the study indicate that locating hurricane damage using satellite imagery might benefit from using multiple indicators that are sensitive to both the decrease in green vegetation and the increase in woody debris.

References

Adams, J. B., D. E. Sabol, V. Kapos, R. A. Filho, D. A. Roberts, M. O. Smith, and A. R. Gillespie. (1995). Classification of multispectral images based on fractions of endmembers: Application to land-cover change in the Brazilian Amazon. Remote Sensing of Environment, 52, 137 - 154.

Boose, E. R., Chamberlin, K. E., Foster, D. R. (2001). Landscape and regionals impacts of hurricanes in New England. Ecological Monographs, 71(1), 27-48

Boose, E. R., Foster, D. R., Barker Plotkin, A., Hall, B. (2003). Geographical and historical variation in hurricanes across the Yucatan Peninsula. In: Gómez-Pompa, A., Allen, M. F., Fedick, S. L., Jiménez, J. J., Lowland Maya Area: Three Millennia at the Human-Wildland Interface, Haworth Press, New York.

Boose, E. R., Foster, D. R., Fluet, M. (1994). Hurricane impacts to tropical and temperate forest landscapes. Ecological Monographs, 64(4), 369-400.

Chambers, J. Q., Fisher, J. I., Zeng, H., Chapman, E. L., baker, D. B. Hurtt, G. C. (2007). Hurricane Katrina's Carbon Footprint on U.S. Gulf Coast Forests. Science, 318, 1107.

Cooper-Ellis, S., Foster, D. R., Carlton, G., Lezberg, A., (1999). Forest response to catastrophic wind: Results from an experimental hurricane. Ecology, 80 (8), 2683-2696.

Dolan, K. A., Hurtt, G. C., Chambers, J. Q., Dubayah, R. O., Frolking, S., Masek, J. G. (2011). Using ICESat's Geoscience Laser Altimeter System (GLAS) to assess large-scale forest disturbance cause by hurricane Katrina. Remote Sensing of Environment, 115, 86-96.

Eastman, R. (2016). TerrSet Manual. Clark Labs.

Fisk, J. P., Hurtt, G. C., Chambers, J. Q., Zeng, H., Dolan, A. K., Negron-Juarez, R. I. (2013). The impacts of tropical cyclones on the net carbon balance of eastern US forests (1851–2000). Environmental Research and Letters, 8.

Foster, D. R. and Boose, E. R. (1995). Hurricane disturbance regimes in temperate and tropical forest ecosystems. In: Coutts, M. P. and Grace, J. Wind and Trees. Cambridge University Press, Great Britain. Franklin, J. L. 2008. Tropical cyclone report Hurricane Dean. National Hurricane Center.

Hoque, M. A., Phinn, S., Roelfsema, C., Childs, I. 2015. Assessing tropical cyclone damage using moderate spatial resolution satellite imagery: Cyclone Sidr, Bangladesh 2007. Proceedings of the 36th Asian Conference on Remote Sensing 2015

Johnson, A. B. and Winker, K. (2010). Short-term hurricane impacts on a neotropical community of marked birds and implications for early-stage community resilience. PLoS ONE, 5(11), e15109

Klawinski, P. D., Dalton, B., Shiels, A. B. (2014). Coqui frog populations are negatively affected by canopy opening but not detritus deposition following an experimental hurricane in a tropical rainforest. Forest Ecology and Management, 332, 118-123.

Li, X. Yu, L., Xu, Y., Yang, J., Gong, P. (2016). Ten years after Hurricane Katrina: monitoring recovery in New Orleans and the surrounding areas using remote sensing. Science Bulletin, 61(18), 1460-1470.

Lodge, D. J., Cantrell, S. A., Gonzalez, G. (2014). Effects of canopy opening and debris deposition on fungal connectivity, phosphorus movement between litter cohorts and mass loss. Forest Ecology and Management, 332, 11-21

McGroddy, M., Lawrence D., Schneider, L., Rogan J., Zager, I., Schmook, B. 2013. Damage patterns after Hurricane Dean in the southern Yucatan: Has human activity resulted in more resilient forests?. Forest Ecology and Management, 310, 812-820

Negron-Juarez, R. I., Chambers, J. Q., Zeng, H., Baker, D. B. (2008). Hurricane driven changes in land cover create biogeophysical climate feedbacks. Geophysical Research Letters, 35.

Negron-Juarez, R. I., Baker, D.B., Chanbers, J.Q., Hurtt, G. H., Goosem, S. (2014).Multi-scale sensitivity of Landsat and MODIS to forest disturbance associated with tropical cyclones. Remote Sensing, 6, 5633-5649

Ramsey, E. W., Hodgson, M. E., Sapkota, S. K., Nelson, G. A. (2001). Forest impact estimate with NOAA AVHRR and Landsat TM data related to an empirical hurricane wind-field distribution. Remote Sensing of Environment, 77, 279-292

Richardson, B. A., Richardson, M. J., Gonzalez, G., Shiels, A. B., Srivastava, D. S. (2010). A canopy trimming experiment in Puerto Rico: The response of litter invertebrate communities to canopy loss and debris deposition in a tropical forest subject to hurricanes. Ecosystems, 13, 286-301

Rogan, J., Schneider, L., Christman, Z., Millones, M., Lawrence, D., Schmook, B. (2011). Hurricane disturbance mapping using MODIS EVI data in the southeastern Yucatán, Mexico, Remote Sensing Letters, 2(3), 259-267

Rossi, E., Rogan, J., Schneider, L. (2013). Mapping forest damage in northern Nicaragua after Hurricane Felix (2007) using MODIS enhanced vegetation index data. GIScience & Remote Sensing.

Shiels, A. B., Gonzalez, G., Willig, M. R. (2014). Responses to canopy loss and debris deposition in a tropical forest ecosystem: Synthesis from an experimental manipulation simulating effects of hurricane disturbance. Forest Ecology and Management, 332, 124-133.

Van Bloem, S. J., Lugo, A. E., Murphy, P. G. (2006). Structural response of Caribbean dry forests to hurricane winds: a case study from Guanica Forest, Puerto Rico. Journal of Biogeography, 33, 517-523

Vandecar, K. L., Lawrence, D., Richards, D., Schneider, L., Rogan, J., Schmook, B., Wilbur, H. (2011). High mortality for rare species following hurricane disturbance in the Southern Yucatan. Biotropica, 43, 676–684.

Wang, F., Xu, Y. J. (2008). Hurricane Katrina-induced forest damage in relation to ecological factors at landscape scale. Environmental Monitoring and Assessment, 156, 491-507.

Wang, W., Qu, J. J., Hao, X., Liu, Y., Stanturf, J. A. (2010). Post-hurricane forest damage assessment using satellite remote sensing. Agricultural and Forest Meteorology, 150, 122-132.

Whigham, D. F., Olmstead, I., Cano, E. C., Harmon, M. E. (1991). The impact of Hurricane Gilbert on trees, litterfall, and woody debris in a dry tropical forest in the Northeastern Yucatan Peninsula. Biotropica, 23 (4a), 434-441.

Figures

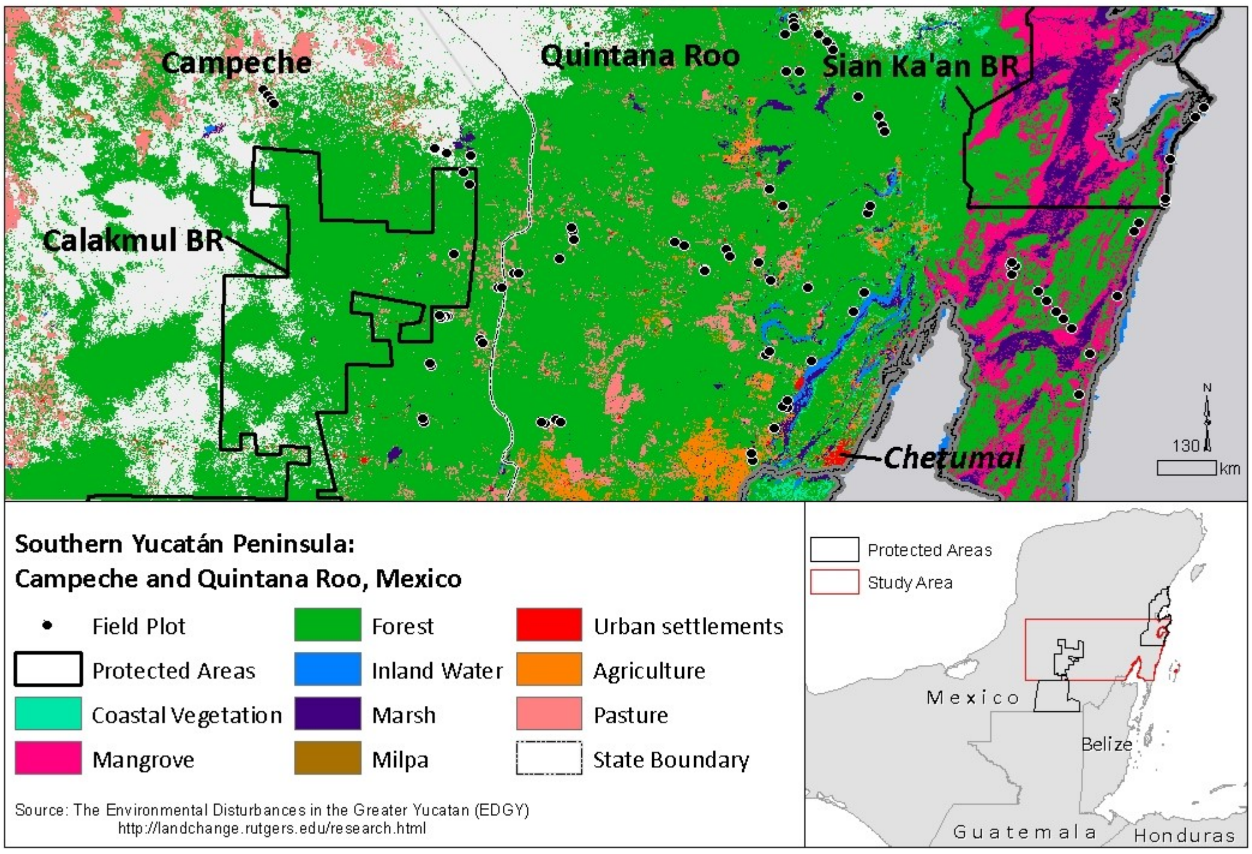

Figure 1: Map of the study area in the southern Yucatán Peninsula, Mexico, including the Calakmul and Sian Ka'an Biosphere Reserves

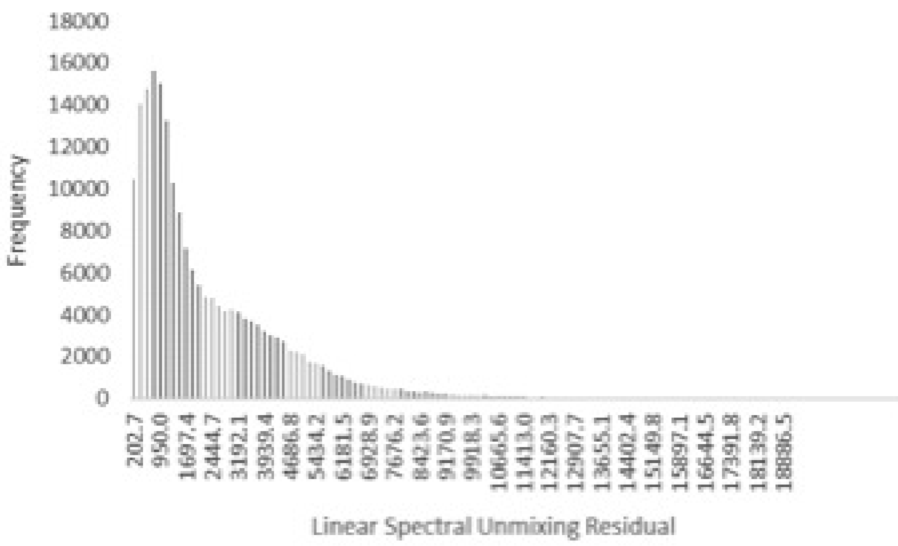

Figure 2: Linear Spectral Unmixing residuals for pre-hurricane MODIS image 217. Residuals >5000 were used to create the cloud/noise mask

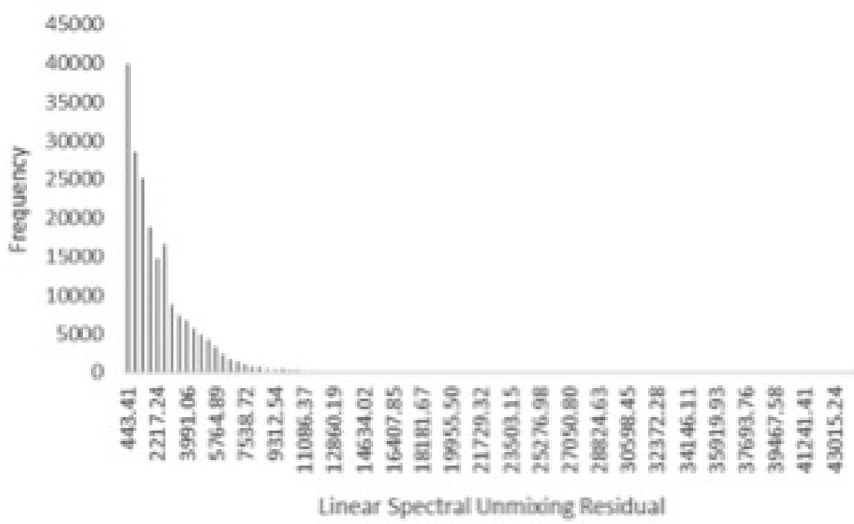

Figure 3: Linear Spectral Unmixing residuals for post hurricane MODIS image 257. Residuals >5000 were used to create the cloud/noise mask

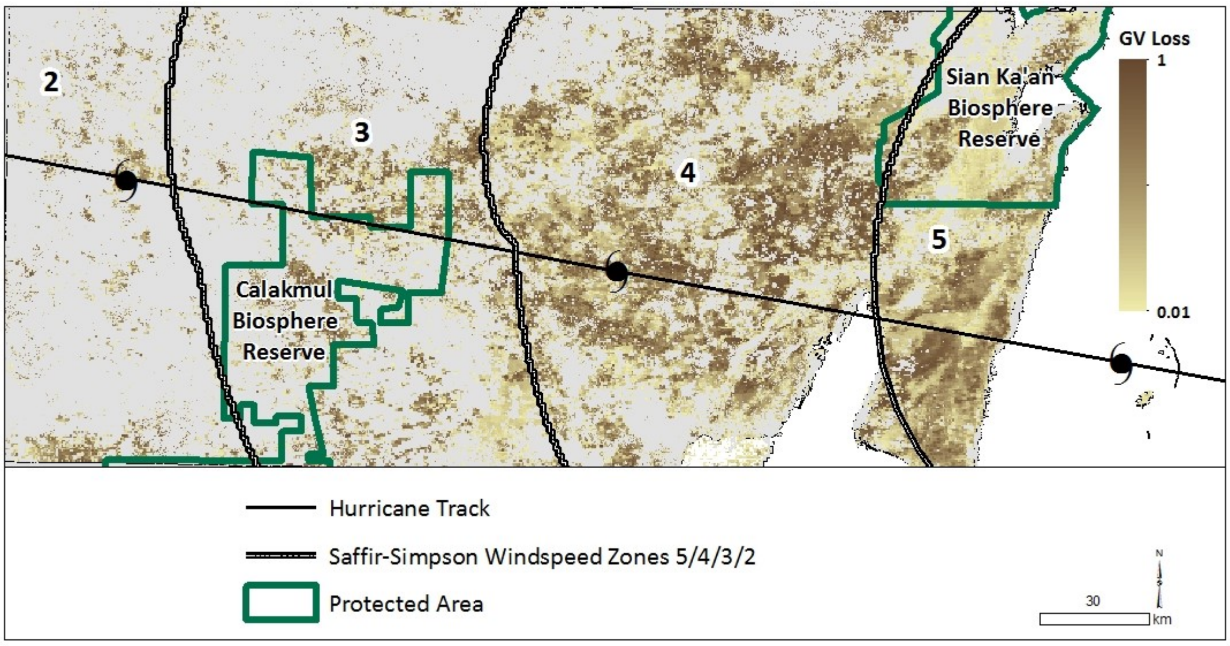

Figure 4: Absolute decrease in Moderate Resolution Imaging Spectroradiometer (MODIS) green vegetation fraction (GV Loss) between pre-hurricane (Aug 5 – Aug 12, 2007) and post hurricane (Sept 14-21, 2007) surface reflectance imagery* (500 m). *MOD09A1 MODIS Surface Reflectance 8-Day L3 Global 500 m

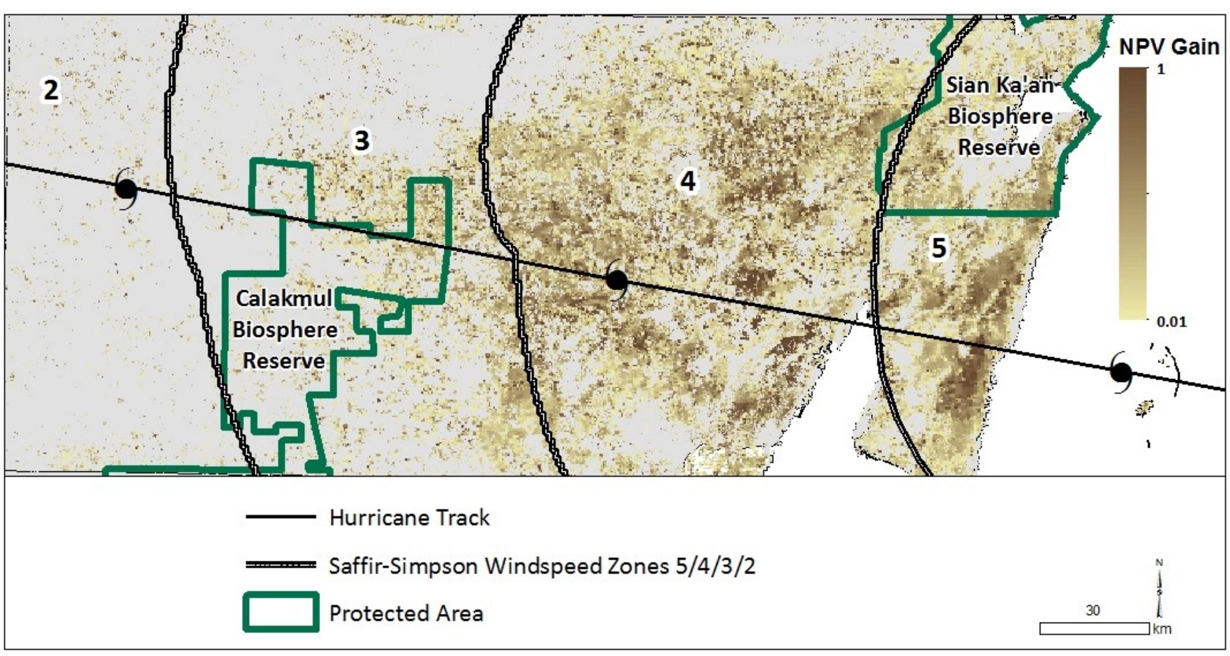

Figure 5: Increase in Moderate Resolution Imaging Spectroradiometer (MODIS) non-photosynthetic vegetation fraction (NPV Gain) between pre-hurricane (Aug 5 – Aug 12, 2007) and post hurricane (Sept 14-21, 2007) surface reflectance imagery* (500 m). *MOD09A1 MODIS Surface Reflectance 8-Day L3 Global 500 m

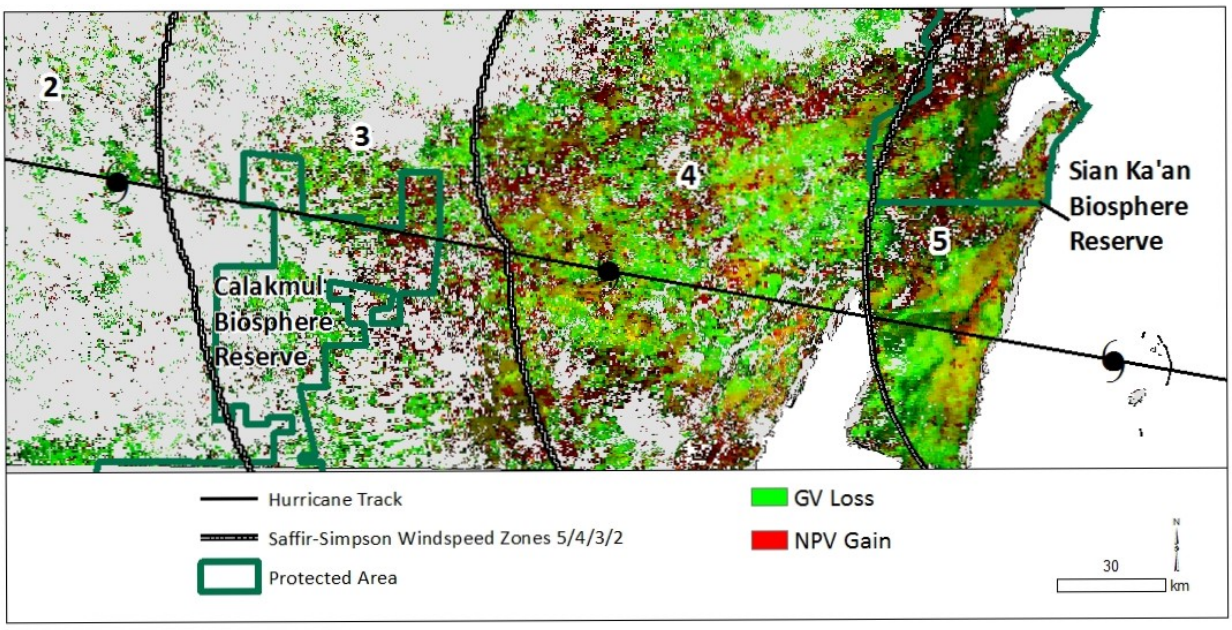

Figure 6: Hurricane Dean forest damage color composite map with absolute decrease in green vegetation fraction (GV Loss) between pre-hurricane (Aug 5 – Aug 12, 2007) and post-hurricane (Sept 14-21, 2007) imagery* is displayed in green. Increase in non-photosynthetic vegetation fraction (NPV Gain) between pre-hurricane (Aug 5 – Aug 12, 2007) and post hurricane (Sept 14-21, 2007) imagery* is displayed in red. *MOD09A1 MODIS Surface Reflectance 8-Day L3 Global 500 m

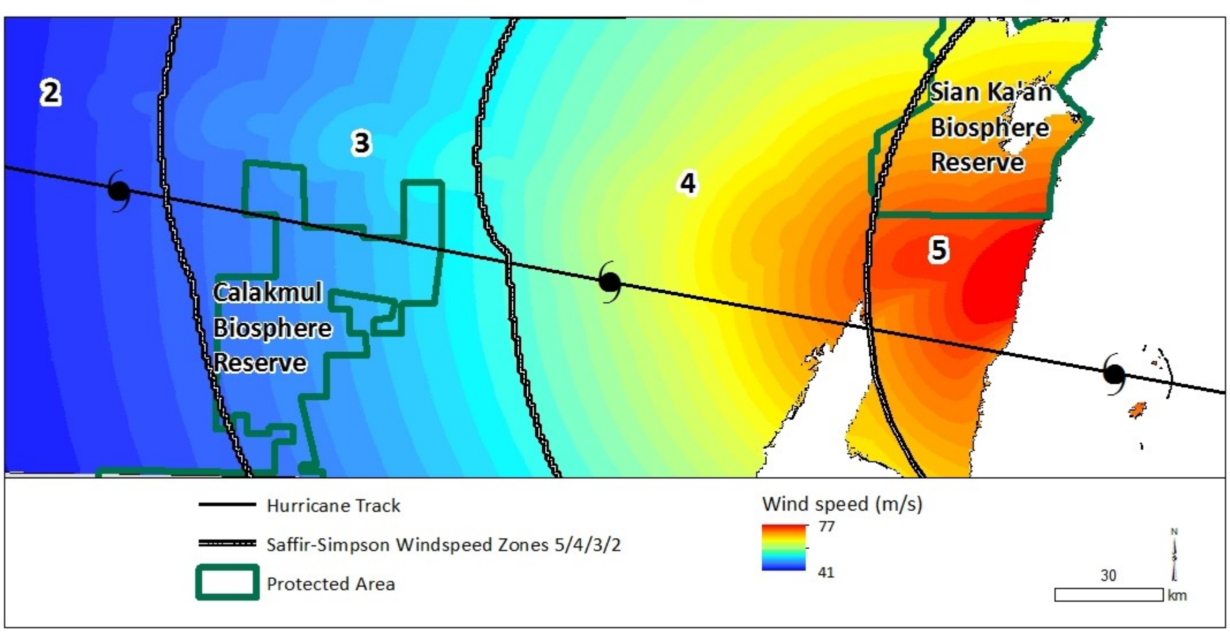

Figure 7: HURRECON modeled wind speeds (1 km)

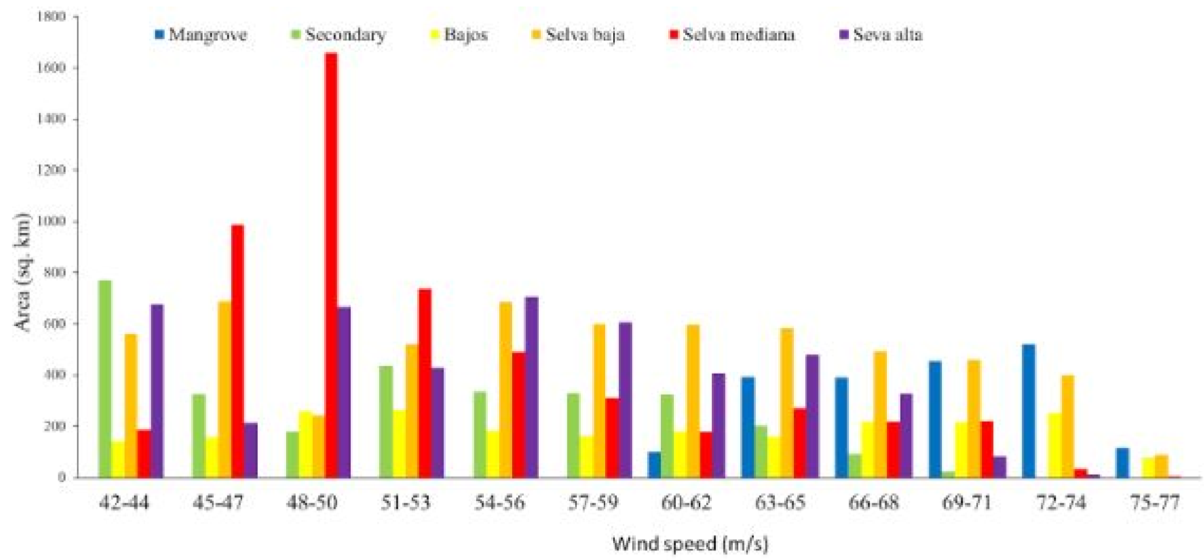

Figure 8: Area of forest type by HURRECON modeled wind speeds

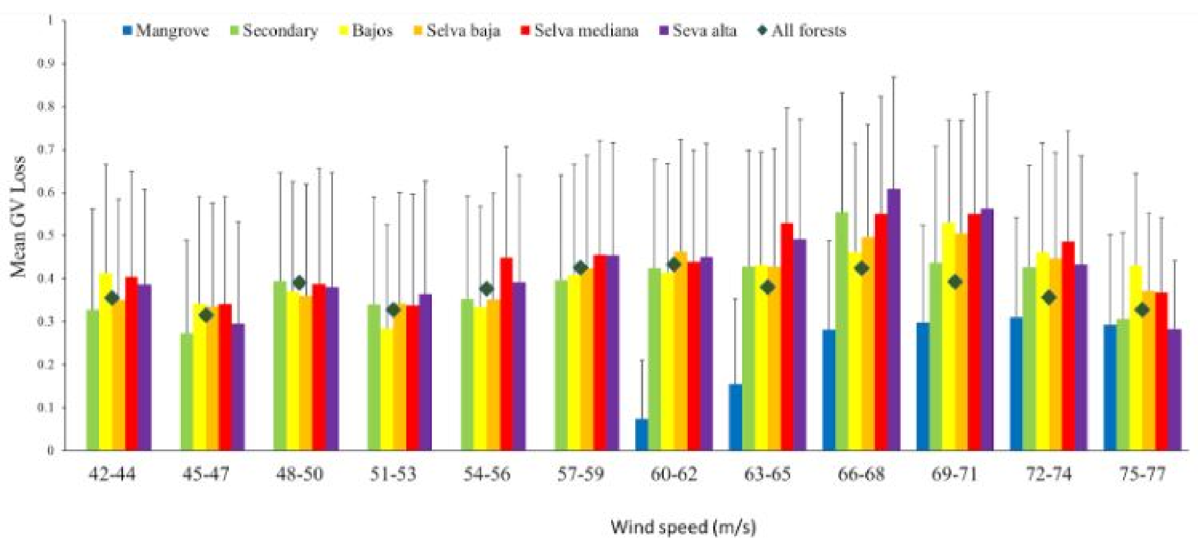

Figure 9: Mean absolute decrease in green vegetation fraction (GV Loss) by HURRECON modeled wind speeds (+SD). GV loss was calculated between pre-hurricane (Aug 5 – Aug 12, 2007) and post hurricane (Sept 14-21, 2007) imagery*.
*MOD09A1 MODIS Surface Reflectance 8-Day L3 Global 500 m

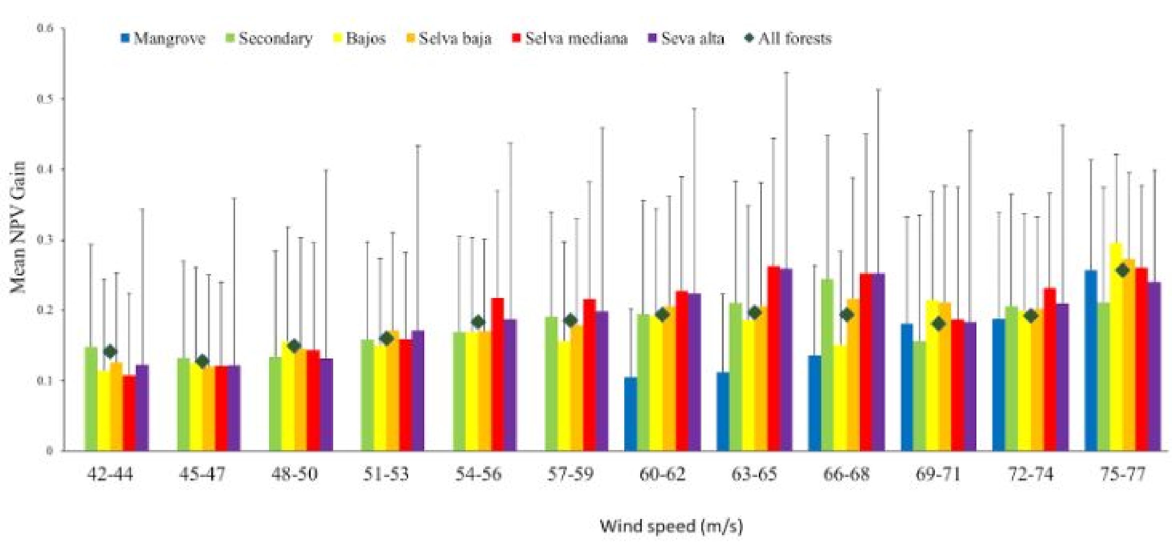

Figure 10: Mean increase in non-photosynthetic vegetation fraction (NPV Gain) by HURRECON modeled wind speeds (+SD). NPV gain was calculated between pre-hurricane (Aug 5 – Aug 12, 2007) and post hurricane (Sept 14-21, 2007) imagery*.
*MOD09A1 MODIS Surface Reflectance 8-Day L3 Global 500 m

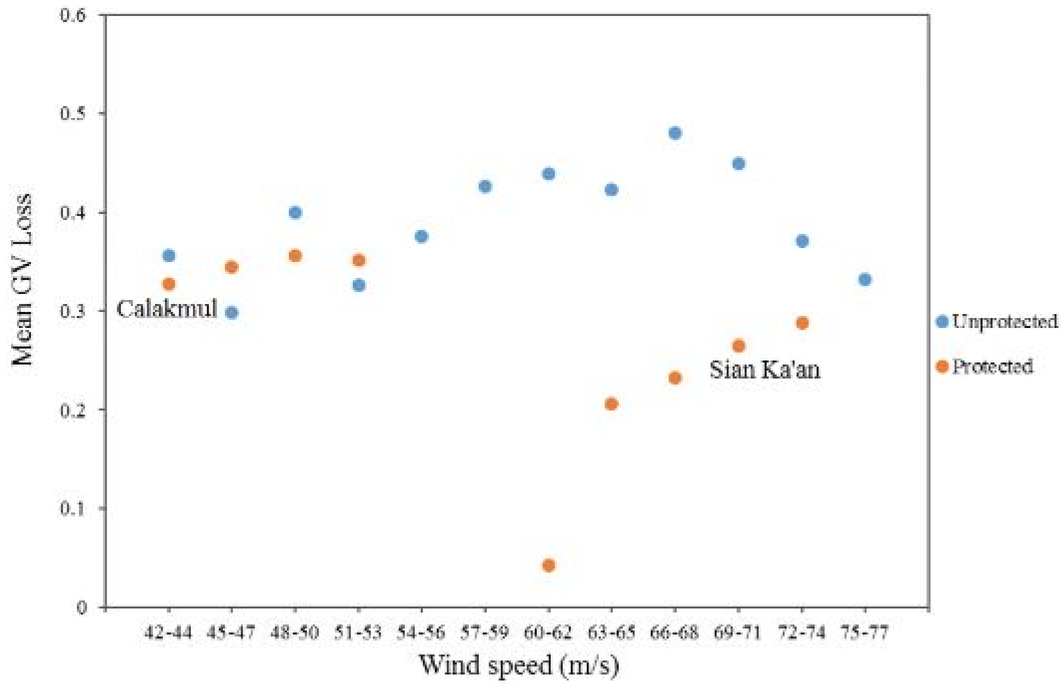

Figure 11: Mean absolute decrease in green vegetation fraction (GV Loss) by HURRECON modeled wind speeds in protected and unprotected areas. GV loss was calculated between pre-hurricane (Aug 5 – Aug 12, 2007) and post hurricane (Sept 14-21, 2007) imagery*.
*MOD09A1 MODIS Surface Reflectance 8-Day L3 Global 500 m

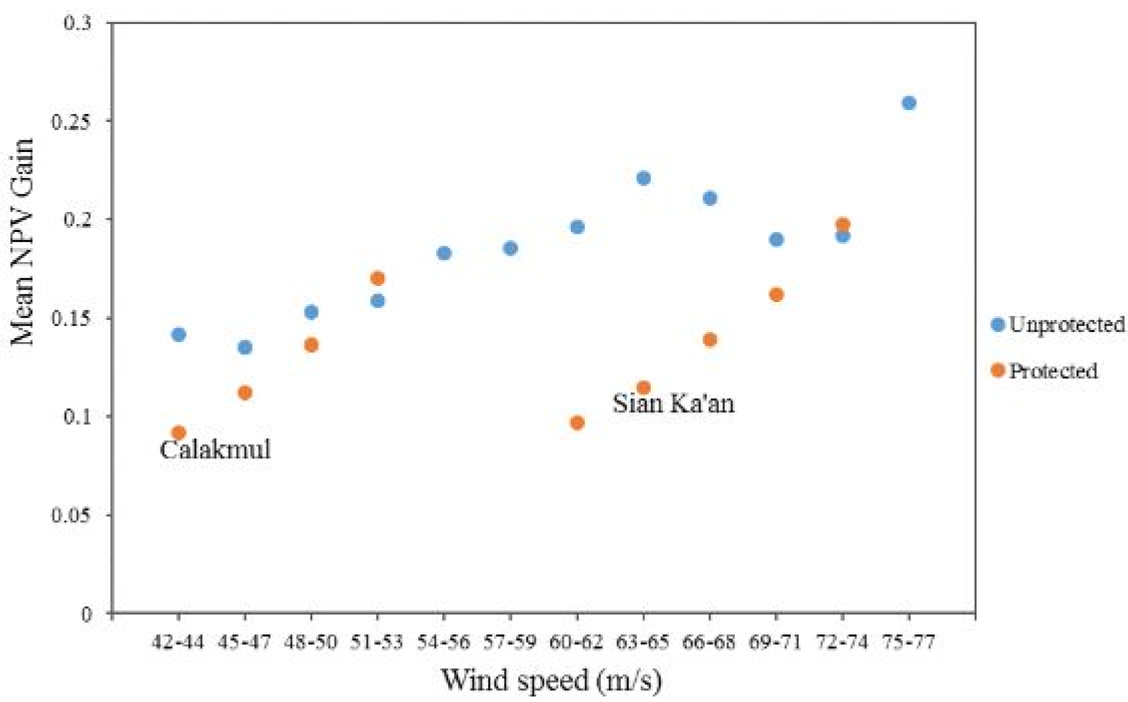

Figure 12: Mean increase in non-photosynthetic vegetation fraction (NPV Gain) by HURRECON modeled wind speeds in protected and unprotected areas. NPV gain was calculated between pre-hurricane (Aug 5 – Aug 12, 2007) and post hurricane (Sept 14-21, 2007) imagery*.
*MOD09A1 MODIS Surface Reflectance 8-Day L3 Global 500 m

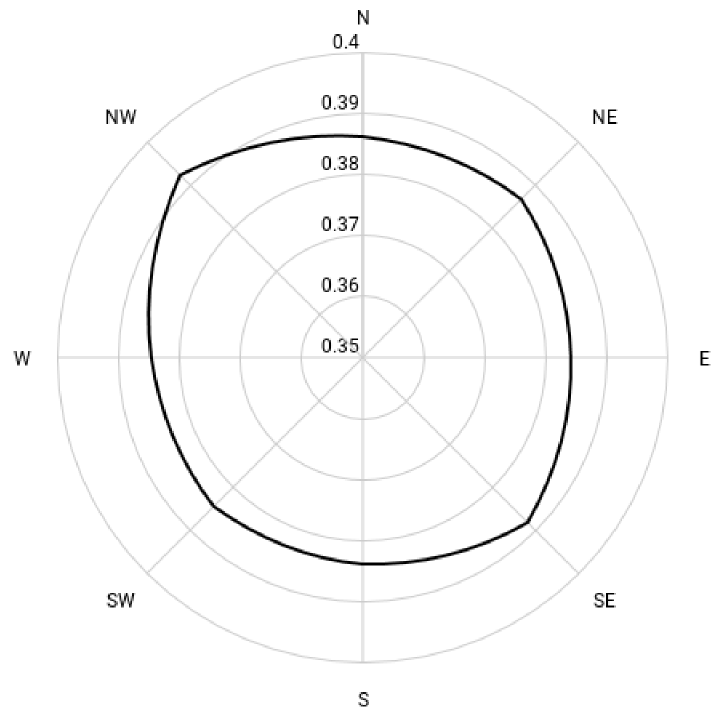

Figure 13: Mean absolute decrease in green vegetation fraction (GV Loss) by aspect. GV loss was calculated between pre-hurricane (Aug 5 – Aug 12, 2007) and post hurricane (Sept 14-21, 2007) imagery*.
*MOD09A1 MODIS Surface Reflectance 8-Day L3 Global 500 m

Figure 14: Mean increase in non-photosynthetic vegetation fraction (NPV Gain) by aspect. NPV gain was calculated between pre-hurricane (Aug 5 – Aug 12, 2007) and post hurricane (Sept 14-21, 2007) imagery*.
*MOD09A1 MODIS Surface Reflectance 8-Day L3 Global 500 m

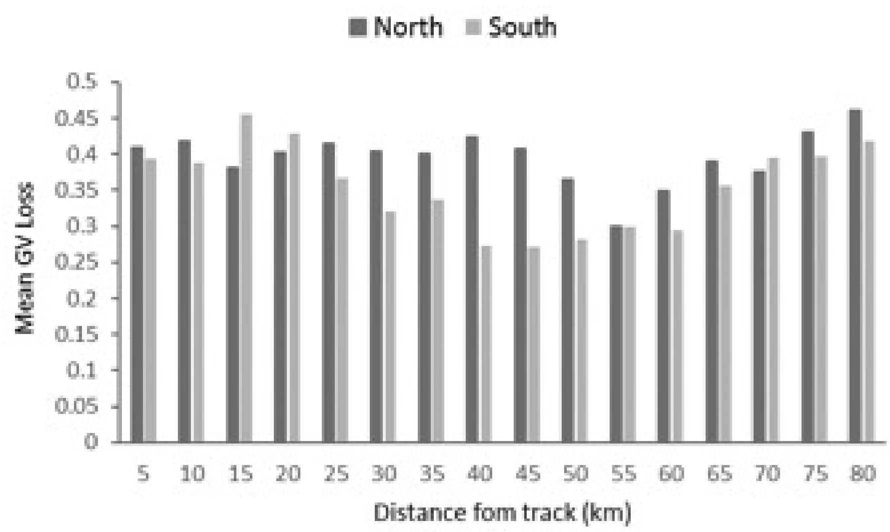

Figure 15: Mean absolute decrease in green vegetation fraction (GV Loss) by distance from track and forest position in relation to hurricane track. GV loss was calculated between pre-hurricane (Aug 5 – Aug 12, 2007) and post hurricane (Sept 14-21, 2007) imagery*.
*MOD09A1 MODIS Surface Reflectance 8-Day L3 Global 500 m

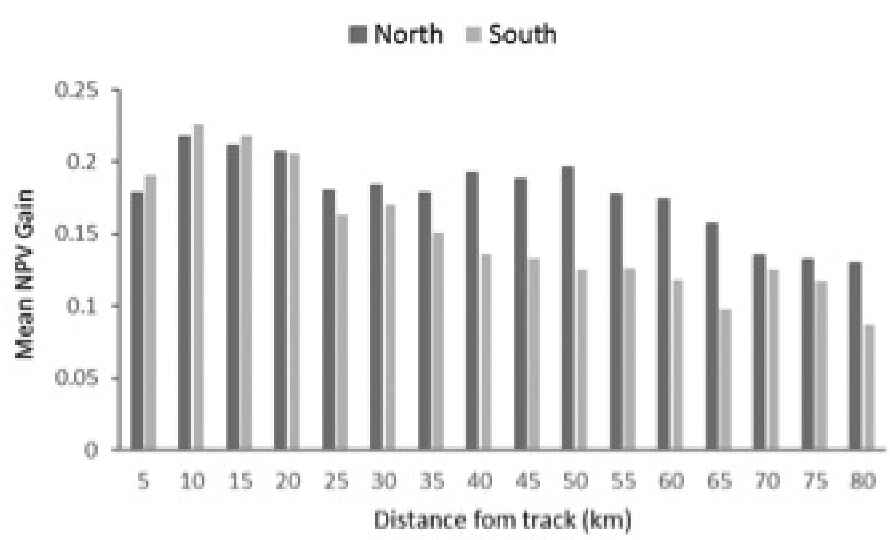

Figure 16: Mean increase in non-photosynthetic vegetation fraction (NPV Gain) by distance from track and forest position in relation to hurricane track. NPV gain was calculated between pre-hurricane (Aug 5 – Aug 12, 2007) and post hurricane (Sept 14-21, 2007) imagery*.
*MOD09A1 MODIS Surface Reflectance 8-Day L3 Global 500 m

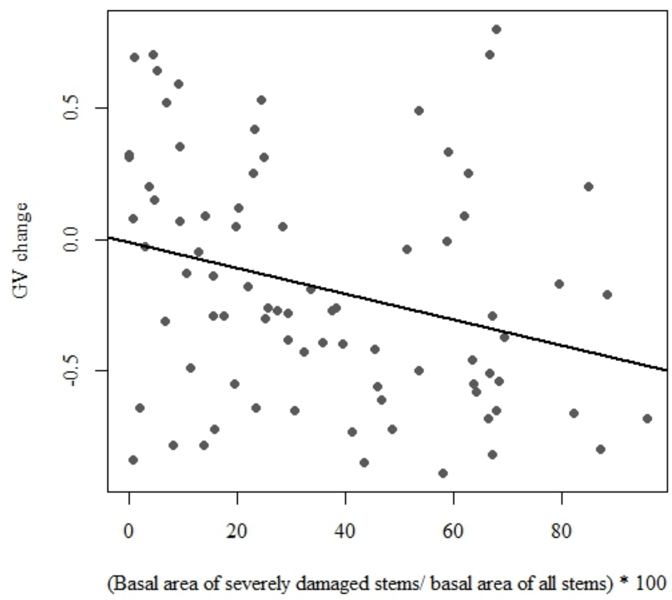

Figure 17: Scatter plot of change in green vegetation fraction (GV) and percent of severely damaged basal area in field plots. Severely damaged stems have the maximum damage recorded as stem snapped, tree uprooted, or dead. GV loss was calculated between pre-hurricane (Aug 5 – Aug 12, 2007) and post hurricane (Sept 14-21, 2007) imagery*.
*MOD09A1 MODIS Surface Reflectance 8-Day L3 Global 500 m

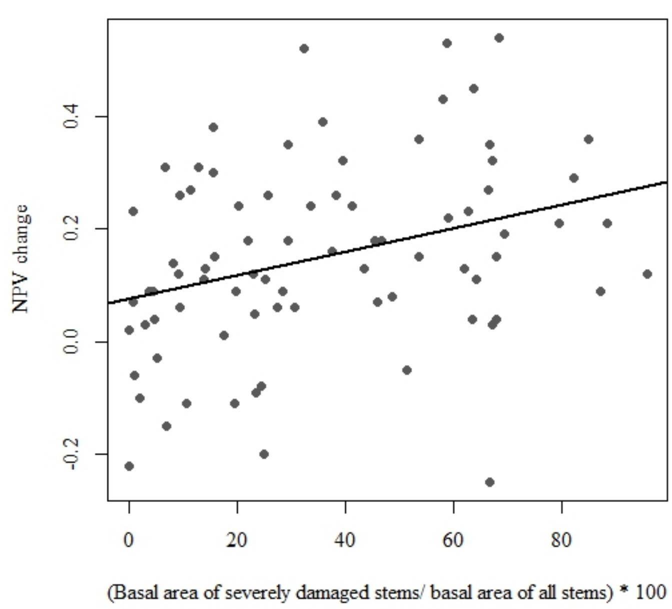

Figure 18: Scatter plot of change in non-photosynthetic vegetation fraction (NPV Gain) and percent of severely damaged basal area in field plots. Severely damaged stems have the maximum damage recorded as stem snapped, tree uprooted, or dead. NPV gain was calculated between pre-hurricane (Aug 5 – Aug 12, 2007) and post hurricane (Sept 14-21, 2007) imagery*.
*MOD09A1 MODIS Surface Reflectance 8-Day L3 Global 500 m