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Using ICESAT's geoscience laser altimeter system to assess large scale forest disturbance caused by Hurricane Katrina

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USING ICESAT'S GEOSCIENCE LASER ALTIMETER SYSTEM TO ASSESS LARGE SCALE FOREST DISTURBANCE CAUSED BY HURRICANE KATRINA

BY

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ABSTRACT

USING ICESAT'S GEOSCIENCE LASER ALTIMETER SYSTEM TO ASSESS LARGE SCALE FOREST DISTURBANCE CAUSED BY HURRICANE KATRINA

by

Katelyn Anne Dolan

University of New Hampshire, September, 2009

We assessed the use of GLAS data as a tool to quantify large-scale forest damage. GLAS data for the year prior to and following Hurricane Katrina were compared to wind speed, forest cover, and MODIS NPV maps to analyze senor sampling, and changes in mean canopy height. We detected significant losses in mean canopy height post-Katrina that increased with wind intensity, from ~.5m in forests hit by tropical storm winds to ~4m in forests experiencing category two force winds. Season of data acquisition was shown to influence calculations of mean canopy height. There was insufficient sampling to adequately detect changes at one degree resolution and less. We observed a strong relationship between delta NPV and post storm mean canopy heights. Changes in structure were converted into loss of standing carbon estimates using a height structured ecosystem model, yielding above ground carbon storage losses of ~30Tg over the domain.

CHAPTER I

INTRODUCTION

The biodiversity, structure, and functioning of forest systems in most areas are strongly influenced by disturbances (Dale et al., 2001, Oliver and Larson, 1996). Forest disturbance and recovery are critical mechanisms for transferring carbon between the land surface and the atmosphere, but only recently have these events been largely accounted for (Masek et al. 2008, Oliver and Larson, 1996). Forested ecosystems are a large stock of carbon within the terrestrial biosphere, and knowing the state of forests as a carbon sink or source of atmospheric carbon dioxide is important to understanding the larger carbon cycle. Disturbance events can emit carbon to the atmosphere through oxidation during events like fire (Page et al., 2002) and/or during decomposition of wood after disturbance such as blowdowns (Chambers et al., 2007). Recovery from past disturbance can sequester carbon from the atmosphere since young forests can be highly productive and have lower levels of heterotrophic respiration (Bradford, 2002). Determining whether a forest will be a carbon sink or source after disturbance depends on whether respiration from decomposition is greater than or less than photosynthetic uptake from regrowing vegetation.

Following a hurricane, forest biomass is converted from living to dead carbon. Unlike disturbances such as fire, there is little immediate change in the state of carbon from solid to gaseous phase after hurricane related damage. McNulty (2002) noted that many estimates of carbon sequestration do not include the influence of hurricanes on forest carbon storage. After studying the impacts of the four largest storms to hit the US during the 20th century, McNulty estimated a single hurricane could convert 10% of the total annual carbon sequestered by US forests into dead and downed forest biomass, assuming US forests sequester 200Tg of carbon a year. McNulty concluded his study stating that hurricanes were a significant factor in reducing short-term carbon storage in US forests.

The types and severity of damage caused by hurricanes vary over impacted landscapes. Types of damage range from leaf abrasion and stripping of small branches and crowns, to large branch loss, bole breakage, and/or uprooting (Stanturf, 2007). Direct hurricane damage can be caused from strong winds, water inundation, storm surge or a combination of these events (Lugo, 2008). The strongest winds occur in a semicircle to the right of the storm's path a short distance from the center, but tornadoes can often occur embedded within the rain bands that spiral out from the eye of the hurricane causing severe damage far from the storms center. Though wind is a significant factor in damage, saturating rains with only moderate winds may also cause windthrow far from the hurricane center adding to the spatial variability of damage (Stanturf, 2007). Hurricanes can also cause indirect damage by increasing trees susceptibility to pest outbreak, fire or future wind throw (Oliver and Larson, 1996).

Hurricane Katrina made an intense landfall over a wide expanse of forestland in August 2005. Several papers have since been published looking at the extent and patterns of forest damage from Katrina (Chapman et al 2008; Kupfer et al, 2007; Oswalt, 2008; Chambers et al, 2007; Stanturf 2007). Purpose, scale and methods of the studies have varied and therefore results of damage have also been reported differently (i.e board feet versus tons of carbon). Immediately after the storm the Forest Service estimated a potential 4.2 billion cubic feet in timber losses over 5 million acres of timberland in Alabama, Louisiana and Mississippi (FIA 2005). These estimates of damage were made by comparing historic Forest Inventory Analysis (FIA) surveys with Katrina's storm track and using models based on historic hurricane damage to extrapolate potential damage. The Forest Service estimates were published in a 2007 paper by Stanturf et al. (2007) that looked at the effects of disturbance on coastal forests using Katrina as a case study to develop a strategic approach to managing forests in hurricane impact zones. Oswalt (2008) compared and contrasted these initial Forest Service damage assessments with two years of hurricane related damage records from FIA field plots across Mississippi, confirming the acceptability of initial damage estimates. Kupfer et al (2007) tried to determine patterns of forest damage caused by the storm based on well sampled field data in DeSeto National Park, Al (450 plots over 153,000ha). This study focused on a relatively small effected area with the overarching goal of developing a predictive damage model that could be used to predict damage over broader regions. Tree age and stand condition proved to be the most important predictor variables in their study. No large scale volumetric damage estimates for Hurricane Katrina were made. Chambers et al (2007) used field investigations, remote sensing image analyses, and empirically based models to study damage and was the only study to estimate the carbon footprint of the storm. The study approximated a total live biomass loss of ~105 Tg C, an amount equivalent to 50-140% of the net annual US forested carbon sink and five times higher than the largest hurricane impact in the 20th century as estimated by McNulty 2001.

New Active remote sensing technologies such as Light Detection and Ranging (LiDAR) systems can provide more direct measurements of forest structure that may aid in disturbance and recovery assessments. Large footprint Lidar systems have been shown to accurately estimate important forest structural characteristics such as canopy heights, stand volume, basal area and above ground biomass (Dubayah, 2000, Drake et al. 2002, Hurtt 2004 et al., Anderson et al. 2006, Lefsky et al. 2005 & 2007, Pflugmacher et al. 2008, Sun 2008). The synergistic use of optical remote sensing and active remote sensing can improve estimates of forest metrics (Anderson et al 2008, Lefsky et al. 2005, Nelson et al 2009). Studies have also demonstrated improvement of mechanistic model predictions by incorporating data on vegetation structure into model initialization and parameterization (Hurtt et al. 2004, Thomas et al. 2008, Hurtt et al., in review). Airborne Lidar data used to initialize and test a height structured ecosystem model, the ecosystem demography model (ED), in La Selva, Costa Rica, improved regional estimates of carbon fluxes by resolving spatial and temporal heterogeneity in carbon stocks and fluxes (Hurtt et al. 2004). Thomas et al. (2008) used Lidar canopy height data to more accurately predict carbon stocks and fluxes within the Hubbard Brook Experimental Forest (HBEF) in the mountains of New Hampshire using ED.

Our research explored the capabilities of using the structural information derived from the Geoscience Laser Altimeter System (GLAS) aboard the Ice Cloud and Elevation Satellite (ICESat) to aid in damage assessment of Hurricane Katrina. Launched on January 12th, 2003 as part of NASA's Earth Observing System (EOS), the main objective of the GLAS instrument was to measure ice sheet elevations and changes through time. Measurement of vegetation cover was one of the mission's secondary objectives, thus sensor specifications are not the most ideal for vegetation studies (Harding et al., 2005). However as the first satellite Lidar system to measure forest structure globally, GLAS can give insight to areas where few auxiliary forest data exists. Flying at a near polar orbit approximately 600 km above the earth's surface, GLAS provides global coverage between 86° N and 86° S. The Instrument transmits short pulses (4 nsec) of infrared light at 1064 nm and visible green light at 532 nm 40 times per second or approximately a shot every 172 m on the ground along its orbital track. The area that is illuminated on the ground is called the lasers footprint (Figure 1). GLAS footprint sizes have varied over time between 50-150m (NSIDC). There are three lasers aboard GLAS; as of the fall of 2004 the sensor was on its third and final laser. The laser is turned on for three 33-day campaigns each year, each campaign is assigned a letter alphabetically (i.e. third laser (L3) first campaign (A) = L3A) (Schutz et al. 2005).

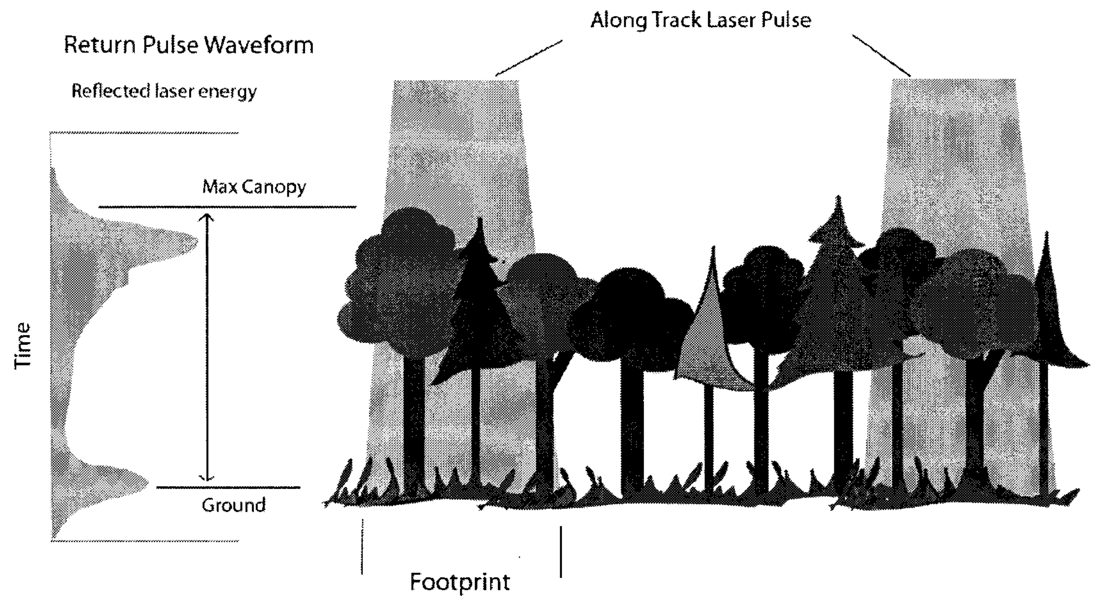

Figure 1- Explanation of GLAS laser pulse and waveform

The GLAS Lidar system works by recoding the time and amount of returned laser energy from each shot with a vertical sampling resolution of 15cm (Sun et al., 2008). For forests on level ground, discrete peaks in a waveform separate the height distribution of reflecting canopy surfaces from that of the underlying ground (Harding 2005) (see Figure 1). GLAS data have been both tested and used to characterize forest structure in a range of forested regions (Sun et al. 2008, Carajabl et al. 2005, Ranson 2004, Lefsky et al. 2005a&b, Rossette et al. 2008, Simard et al. 2008, Neuenshwander et al. 2008, Dolan et al. in review, Nelson et al. 2009, Pflumacher et al. 2008). Lefsky et al (2005b) combined GLAS waveforms and auxiliary data to estimate maximum forest height in three ecosystems: tropical broadleaf forests in Brazil, temperate broadleaf forests in Tennessee and temperate needle leaf forests in Oregon. Rosette et al. (2008) used GLAS derived vegetation height estimates in a mixed temperate forest in England to test modeled height predictions. Forest canopy heights derived from GLAS data have been combined with Landsat-based disturbance history maps in order to assess forest regeneration rates in three regions of the eastern United States (Maine, Virginia, Mississippi) (Dolan et al., in review). Recently GLAS data has aided in the mapping of mangrove forests, with the aim that subsequent Lidar will aid in the assessment of mangrove regeneration rates, and response to increasing sea levels (Simard et al. 2008).

The key question of this study was to what extent GLAS data can be used to detect and quantify forest structure change from large-scale disturbance events such as Hurricane Katrina. To investigate this key question, inquiry into the sampling and accuracy of the sensor as well as the ability to convert resulting structural information into disturbance estimates such as loss of standing carbon were made. The three main objectives in this study were to 1) assess the GLAS sampling regime over the footprint of Hurricane Katrina to determine whether the coverage was adequate, representative, and unbiased 2) determine the vegetation structure pre- and post-Katrina using a GLAS derived mean canopy height equation, and 3) produce estimates of forest structure change that account for uncertainty and input these estimates into a height structured ecosystem model to make preliminary estimates of standing carbon loss resultant from Hurricane Katrina. Throughout the research process attention was placed on ways in which methods could help with future disturbance assessments and on ways in which this case study could help inform future missions studying vegetation structure from space such as DESDynI.

CHAPTER II

DATA AND METHODOLOGY

Study Site

The southeastern landscape is a heterogeneous mix of natural and planned forests, wetlands, urban development and cropland. The land area hit by Katrina's tropical storm winds and greater included the majority of the state of Mississippi, Southwestern Alabama and Southeastern Louisiana. The landscape can be characterized as rather flat terrain, with elevation ranging from sea level to approximately 500ft. Most of the forests in the effected region can be described as coastal plain forests, which are largely pine in the uplands and hardwoods in the bottomlands or lowlands. Dominant softwood species include loblolly pine (*Pinus taeda*), slash pine (*P. elliottii*) and long leaf pine (*P. plaustris*). Dominant hardwood species in the bottomland hardwood forests and swamp forests include bald cypress (*Taxicodium distichum*) water tupelo (*Nyssa sylvatica*) swamp tupelo (*Nyssa biflora*), sweetbay (*Magnolia virginiana*), water oak (*Quercus nigra*) red maple (*Acer rubrum*) and sweetgum (*Liquidambar styraciflua*) (Stanturf et al 2007).

Defining GLAS Sample

To determine the extent of tropical storm winds, Hurricane Katrina's maximum sustained winds as derived from NOAA's H*WIND model outputs were mapped in ArcGIS geographic information systems (GIS) software (Powell 1998). Subsets of GLAS data covering all forested area hit by tropical storm winds and greater were obtained from the Colorado Ecological Applications of Lidar (CEAL) lab at the University of Colorado. GLAS data was processed using the ICESat Vegetation Product Utility (IVPU) to obtain footprint locations of all GLAS shots along with processed waveform parameters as described in Lefsky et al. 2005. GLAS footprint center locations were uploaded into ArcGIS. Only those GLAS shots falling on land within the area with wind data coverage were used for further analysis. Three ICESat Lidar campaigns, representing fall, winter and spring were chosen for both the year preceding Katrina's land fall (PRE) and the year following (POST) (Table 1). Maximum sustained winds were extracted and recorded for each GLAS center point location. GLAS shots were then stratified into different storm intensity classes as determined by the Saffire-Simpson Scale; Low winds (<40mph), Tropical storm (40-74mph), Category 1 (74-96), and Category 2 (96-111) (Figure 2).

Table 1 – GLAS data description adapted from the Attributes for ICESat Laser Operations Periods.

Storm Year	Laser Campaign	Year	Season	Start Date	End Date	Footprint Major Axis (m)
PRE	L3A	2004	FALL	3-OCT	8-NOV	55
	L3B	2005	WINTER	17-NOV	24-MAR	55
	L3C	2005	SPRING	20-MAY	23-JUN	55
POST	L3D	2005	FALL	21-OCT	24-NOV	52
	L3E	2006	WINTER	22-FEB	28-MAR	52
	L3F	2006	SPRING	24-MAY	26-JUN	51

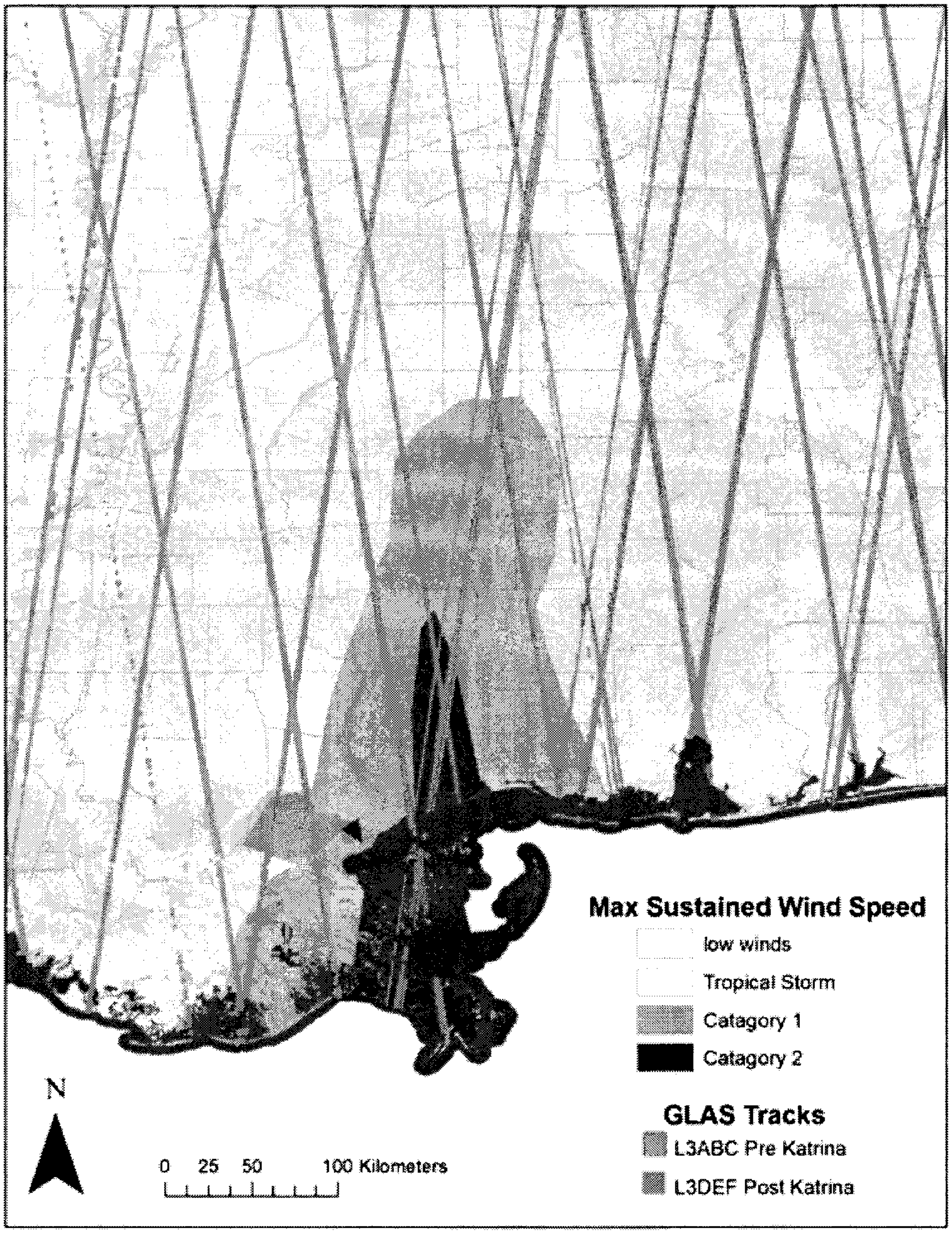

Figure 2- ICESat's orbital tracks for the year proceeding and following Hurricane Katrina overlaying Max sustained winds and forest.

A subset of the 2001 30m gridded National Land Cover Data (NLCD '01) was downloaded from the USGS seamless data server covering all areas experiencing tropical storm winds and greater. Land cover type was recorded for the center point of each GLAS shot. The NLCD was then reclassified into forested (41-Decidous, 42-Evergreen, 43-mixed, 44- forested wetlands) and non-forested pixels to create a forest mask for the region that was used to pick a forested subset of GLAS data shots. GLAS center point locations were buffered by 40m in ArcGIS to account for the ~50m GLAS footprint diameter and to address potential geo-location errors of the GLAS and Landsat sensors. GLAS polygons were overlaid over the forest layer and a new field was added to our GLAS database stating whether or not there was complete forest coverage for each shot. Only those shots that were defined as fully forested and that fell within tropical storm winds or greater were used to assess forest structure.

GLAS Derived Mean Canopy Height

We used mean canopy height as a measure of forest structure for each GLAS footprint. Mean canopy height is defined as the average canopy height of all dominant and co-dominant trees in a plot. Mean canopy height, unlike maximum canopy height, considers the spatial heterogeneity of forest structure. Due to complications of uneven terrain and non-uniform tree heights Lefsky (2005 & 2007) created an algorithm capable of retrieving information about terrain slope, stand uniformity and vertical distribution of visible ground surfaces from the waveform itself. The algorithm was designed to eliminate the need for Digital Elevation models (DEMs) and estimates canopy height with an RMSE of 5 m. Pflugmacher et al (2008) compared the accuracy and regional variability of GLAS derived mean canopy height with data from the US Forest Service Inventory and Analysis (FIA) data from Appalachia and the Cascades and found that current GLAS algorithms described in Lefsky (2007) provided accurate estimates of height, validating the regional applicability of height algorithms for the GLAS sensor.

Mean canopy height as derived through waveform parameters (Extent, Trail, Edge) outputted in version2 of the IVPU was calculated for each fully forested waveform using an equation slightly modified from Lefsky (2007) (Eq1) (Lefsky pers. com.) (Figure 3). Because this equation was not ideal for smaller stands (<10 m), we modified the equation so that if the *extent* was less then derived *ht*, mean canopy height would be recorded as *extent* (Eq2).

Eq 1. Ht=3.65728+(.599102*(Extent+(-.346713*(Trail + Lead)))

Eq 2. If Extent < Ht than Ht=Extent else Ht = Eq 1

Only waveforms whose mean canopy heights were less than 30 m were used in analysis of height distributions to avoid noisy or saturated waveforms.

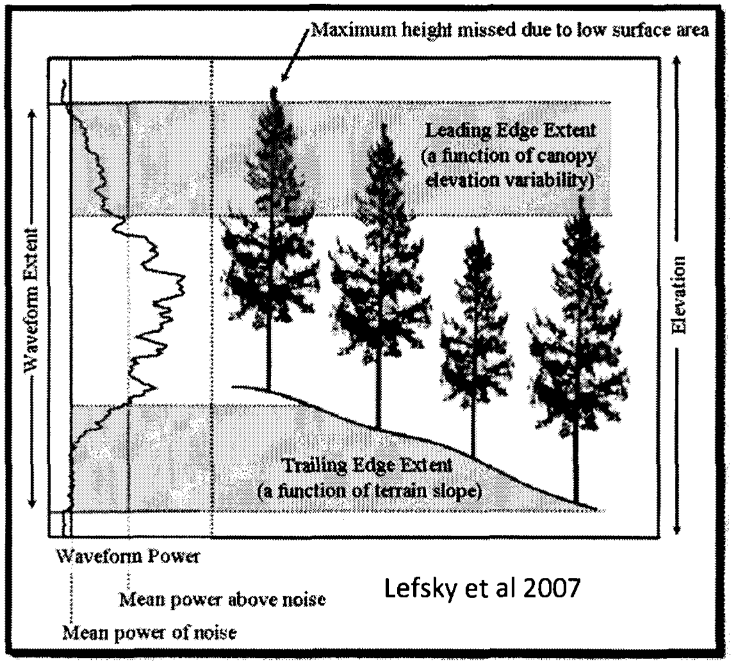

Figure 3 - Lefsky et al 2007 showing waveform over sloped terrain in a heterogeneous stand and resultant waveform parameters (Extent, Trail, Lead).

JMP statistical software was used to statistically analyze distributions of mean canopy heights for all GLAS derived shots that fell within forest areas struck by tropical storm winds or greater pre and post Katrina. GLAS footprints were non-coincident and therefore non-repeat sample statistics were used. The statistical tests used within this study to begin to explore differences in mean canopy height, assumed normality of data. Students T-tests were used to test whether there were significant differences in pre vs. post storm mean canopy heights (alpha= 0.05). Tukey-Kramer HSD, which protects the significance tests of all combinationsof pairs, was then used to test the influence of laser, season, and wind intensity on changes in mean canopy heights pre and post Katrina. Differences in mean canopy heights pre vs. post-Katrina were determined with 95% confidence bounds, for each season and wind zone.

Sampling Assessment

A series of comparative analysis looking at how well GLAS detected landscape characteristics such as forest cover type, wind intensity, and MODIS derived change in Non Photosynthetic Vegetation (NPV) were preformed to assess how well GLAS sampling represented the impacted landscape. To compare how well GLAS captured forest types across the hurricane impacted area, we first calculated the percent of the forested domain that fell into each of the NLCD01 forest types (Deciduous (41), Conifer (42) Mixed (43) and Forested Wetland (90)) in ArcGIS. The percentage of GLAS shots that fell within each of the defined forest classes was then calculated and compared. We also evaluated the differences in GLAS forest sampling by year, season and wind zone to see if there was any sampling bias of the landscape. Similar methods were employed to study GLAS representation of wind zones and Δ NPV.

Scale

The potential of making a gridded height change product was explored. A six by six degree grid covering all areas experiencing tropical storm winds and greater was assessed for sampling coverage at a one degree, ½ degree and $^1/_4$ degree resolution. Total number of samples by campaign was recorded for each grid cell. Sampling density was calculated by recording the number of samples per square kilometer of forest. Average change in mean canopy height was computed for each grid, both aggregated by year and by individual campaign, and significance of change was recorded.

Comparing GLAS to Δ NPV

We compared GLAS derived pre-storm and post-storm mean canopy heights to 500 m MODIS ΔNPV estimates described in chambers et al. 2007. Chambers found a strong correlation between the optically derived ΔNPV values and field measured tree mortality and damage resultant from Hurricane Katrina. MODIS derived ΔNPV fractions were recorded over all forested areas as defined by 30m NLCD pixels. ΔNPV values were extracted for each GLAS center point in ArcGIS. JMP statistical analysis and graphing software was used to find the best fit between post-storm mean canopy heights and positive changes in ΔNPV. The linear relationship was then used to extrapolate height change over the forested study domain where MODIS data were available. Forested areas having negative ΔNPV values were considered to have no change in height.

Relating Structure Change to Loss of Standing Carbon Storage

A height structured ecosystem model, The Ecosystem Demography model (ED), was used to estimate above ground carbon loss resulting from Hurricane Katrina. The ED model is a mechanistic model of forest ecosystem dynamics in which individual-based forest dynamics can be efficiently implemented over local, regional to global scales due to advanced scaling methods (Hurtt et al. 1998, Moorcroft et al. 2001, Albani et al. 2006). All plants in ED have explicit height and structure, properties that allow direct connection to data on vegetation structure (Thomas 2008, Hurtt 2004). ED was run for 300 years at one degree resolution over the study domain. An average height to biomass relationship was calculated for each degree cell using similar methods to Thomas et al. (2008) and Hurtt et al. (2004). Height to biomass relations were then averaged over the whole domain and used to estimate loss of above ground biomass by multiplying GLAS derived height loss over forested areas hit by tropical storm winds and greater.

CHAPTER III

RESULTS

Land areas experiencing tropical storm winds or greater from Hurricane Katrina totaled approximately 150,000km^2, of which more than half or 85,800km^2 was forested as defined by 01 National Land Cover Dataset (Appendix Table 10) little more than 1500km^2, or two percent of the forested domain, was hit by category two sustained winds, 15% of the forested domain was hit by Category one winds, and 70,800km^2 or 83% of the domain was hit by tropical storm winds. Within the land area hit by tropical storm winds or greater, approximately 168,000 GLAS shots were recorded during both the year preceding and proceeding Katrina. Of those shots slightly less than 25% or ~41,000 (~16,500 pre and ~24,500 post) meet the criteria to be used in the following forest structure analyses (i.e. were defined as fully forested, and fell within the acceptable range of heights) (Table 2).

GLAS Derived Forest Structure and Change

The inter-quartile range of mean canopy heights derived from all campaigns previous to Hurricane Katrina (PRE) were 11.7m to 18.2m with a mean canopy height of 14.8m. The inter-quartile range of mean canopy heights derived from all campaigns within a year after Hurricane Katrina (POST) were 10.8 to 17.3 with a mean canopy height of 14 m. A 0.76m +/- 0.1m loss in mean canopy height was detected post Katrina. We rejected the null hypothesis that there was no significant difference between the mean canopy heights pre vs. post Katrina over areas experiencing tropical storm winds and greater (alpha=.05) (Table 2) (Figure 4).

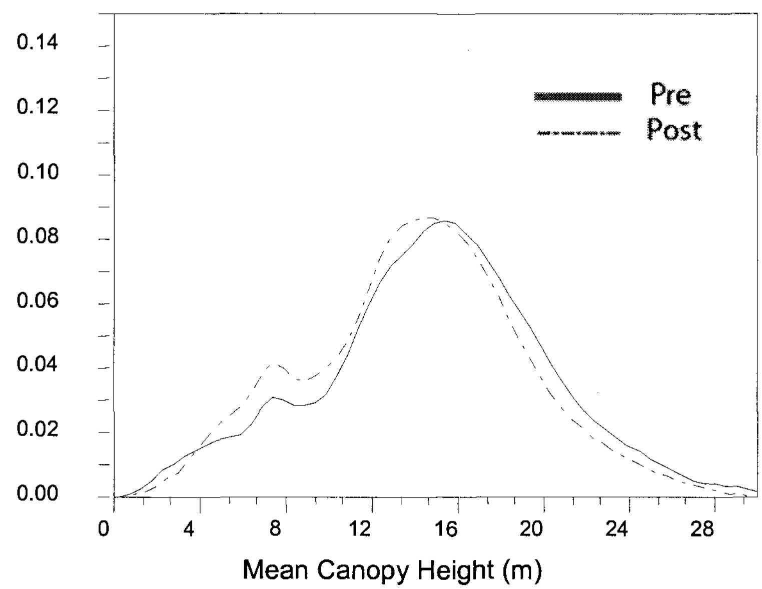

Figure 4 - Distribution of GLAS derived mean canopy heights pre and post Katrina for all areas hit by tropical storm winds and greater. Solid line Pre dotted line post.

Forest mean canopy height distributions pre and post Katrina were further compared to wind intensity (Figure 5). Pre-storm average mean canopy heights, ranged from 14.4m to 14.8m. Using a Tukey-Kramer test to compare the means, no significant difference was detected between wind zone and pre-storm heights (Table 2). A significant decrease between pre and post storm mean canopy heights was detected in all wind zones. This decrease in height significantly increased as wind speed increased from a 0.4m loss in forests hit by tropical storm winds (TS), to a 2.4m loss in areas experiencing category one winds (CAT1), and a 4.1m loss in average mean canopy height in forests hit by category two winds (CAT2) (Table 2).

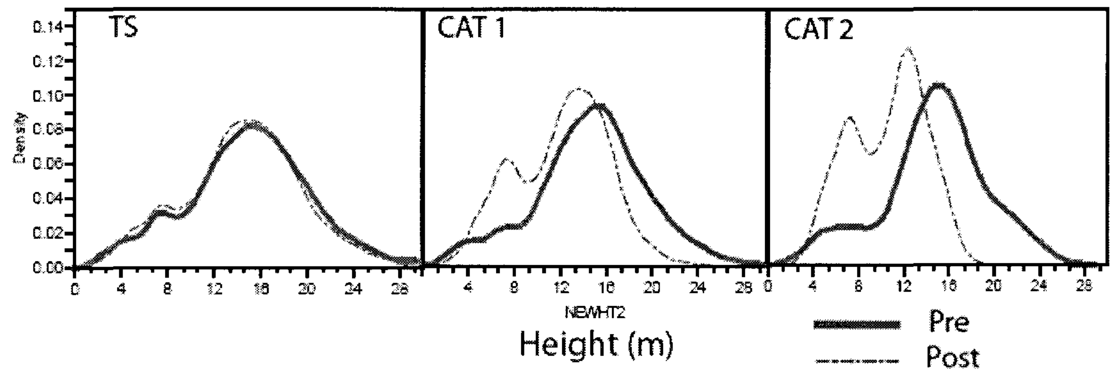

Figure 5- Distribution of mean canopy heights by wind zone for all campaigns for the year pre and post-Katrina. Solid blue show distribution of mean canopy heights pre Katrina dotted red line shows distribution of mean canopy heights post Katrina.

Table 2- Mean canopy heights for the year pre and post-Katrina for domain and by wind zone

Wind zone	Forested Area (km)	Year	n	mean ht (m)	Tukey*	Ht change(m)	sig (p)**
ALL	85,797	PRE	16539	14.80	-	**0.76**+/- .10	0.0001
		POST	24680	14.03			
TS	70,811	PRE	13305	14.84	A	**0.43** +/- .11	0.0001
		POST	21051	14.41	B		
CAT 1	13,400	PRE	2403	14.59	AB	**2.43** +/- .24	0.001
		POST	2884	12.15	C		
CAT 2	1,585	PRE	831	14.67	AB	**4.11** +/- .40	0.001
		POST	754	10.55	D		

*Means connected by the same letter are not significantly different (alpha= .05)
**Students t-test

To test the seasonal influence on height distributions, mean canopy height measurements were broken down into season (laser campaign) (Figure 6). No significant difference was detected in pre-storm mean canopy heights in the Fall or Spring for any of the wind zones, however, Winter mean canopy heights pre-storm were significantly lower than Fall or Spring across all wind zones (Table 3). Winter pre-storm mean canopy heights were significantly higher in the category two zone (13.3m) than in category one (11.8m) or TS (11.4m). Post-storm mean canopy heights were significantly lower than pre in all seasons and wind zones except in the tropical storm zone where Winter mean canopy heights showed a significant increase of 0.3m post-storm (Table 3).

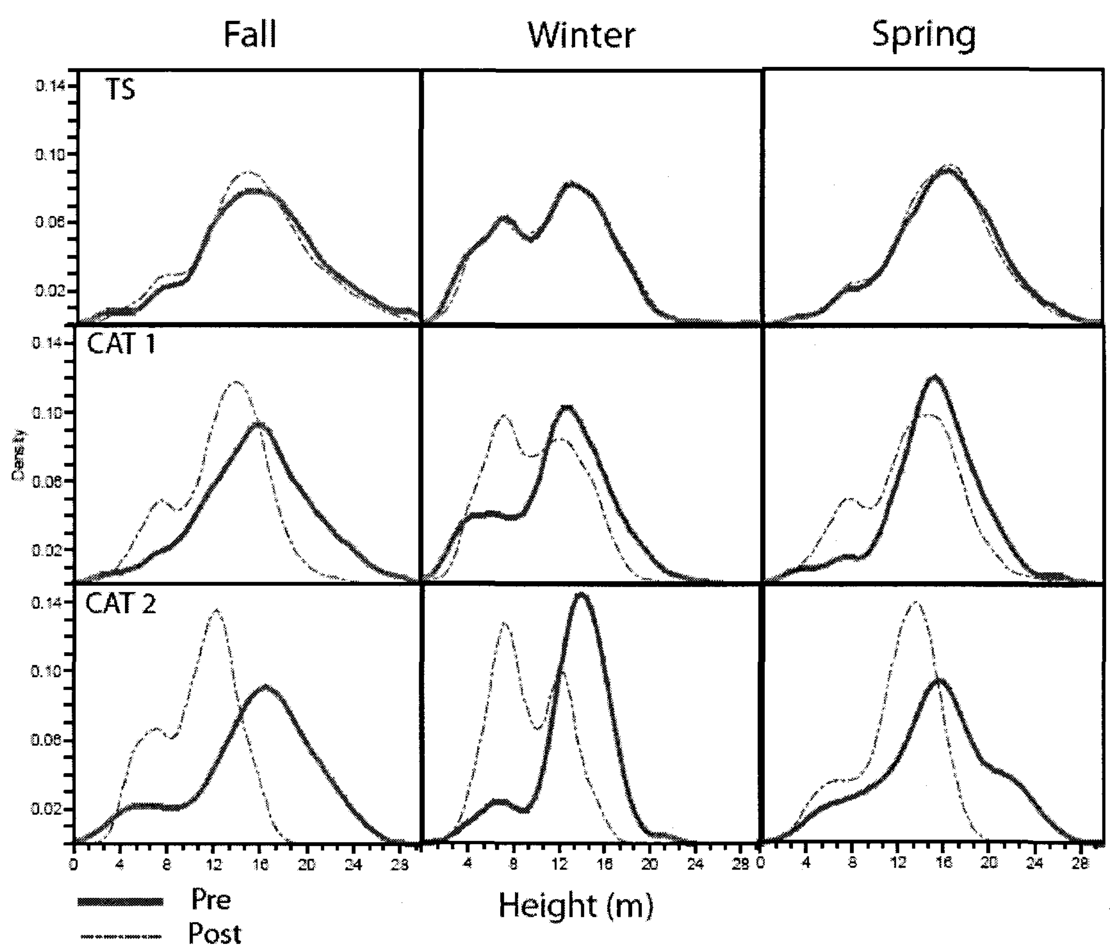

Figure 6 - GLAS derived height distributions pre and post-Katrina broken into season and wind zones

Table 3- Average mean canopy heights by wind zone and season

Wind zone	Season	Year	n	mean ht (m)	Tukeys*	Ht** change	(p)**
TS	Fall	PRE	4361	15.88	AB	**0.714**	0.0001
		POST	7885	15.26	C	+/-.181	
	Winter	PRE	3084	11.33	F	**-0.302**	0.0039
		POST	5606	11.64	F	+/-.215	
	Spring	PRE	5860	15.91	A	**0.349**	0.0001
		POST	7560	15.57	B	+/-.167	
CAT 1	Fall	PRE	1419	15.57	ABCD	**2.936**	0.0001
		POST	1542	12.69	E	+/-.311	
	Winter	PRE	539	11.69	F	**1.704**	0.0001
		POST	653	10.07	G	+/-.492	
	Spring	PRE	445	14.96	CD	**2.072**	0.0001
		POST	689	12.69	E	+/-.514	
CAT2	Fall	PRE	417	15.37	ABCD	**4.705**	0.0001
		POST	296	10.67	FG	+/-.592	
	Winter	PRE	271	13.29	E	**3.933**	0.0001
		POST	262	9.40	G	+/-.675	
	Spring	PRE	143	15.25	ABCD	**3.221**	0.0001
		POST	187	12.03	EF	+/-.865	

*Means connected by the same letter are not significantly different (alpha= .05)

**Students t

Sampling

Total number of samples used in our study varied by year, season and wind zone (Table 3). Using a Kia squared test, differences in proportion of samples falling into the three wind zones was detected between years (Appendix

Table 8). Differences were also found between the seasonal composition between years both at the domain level and wind zone level (Appendix Table 9). GLAS oversampled forestlands over the study domain (Appendix Table 10) GLAS shots used in the forest structured analysis of this study captured the breakdown of forest type very closely; each forest type sampled was within one percent of the actual fraction of the forested landscape (Table 4). Between years and campaigns there was a statistically significant difference in the fraction of each land cover class captured (Kia test) (Appendix Table 11). Actual forest cover varied by region with forests in the category two zone dominated by Evergreen Forests, 56%, and Forested Wetlands, 41%, whereas forests in the tropical storm zone showed a more equal mix of forest types with Deciduous trees comprising 22% of the forestland, Mixed Forests 16%, Forested Wetlands 27%, and Evergreen Forests 35% (Figure 7). GLAS capture of each forest type by region also differed significantly by year and season, there was no clear confounding trends pre vs. post Katrina (Figure 8).

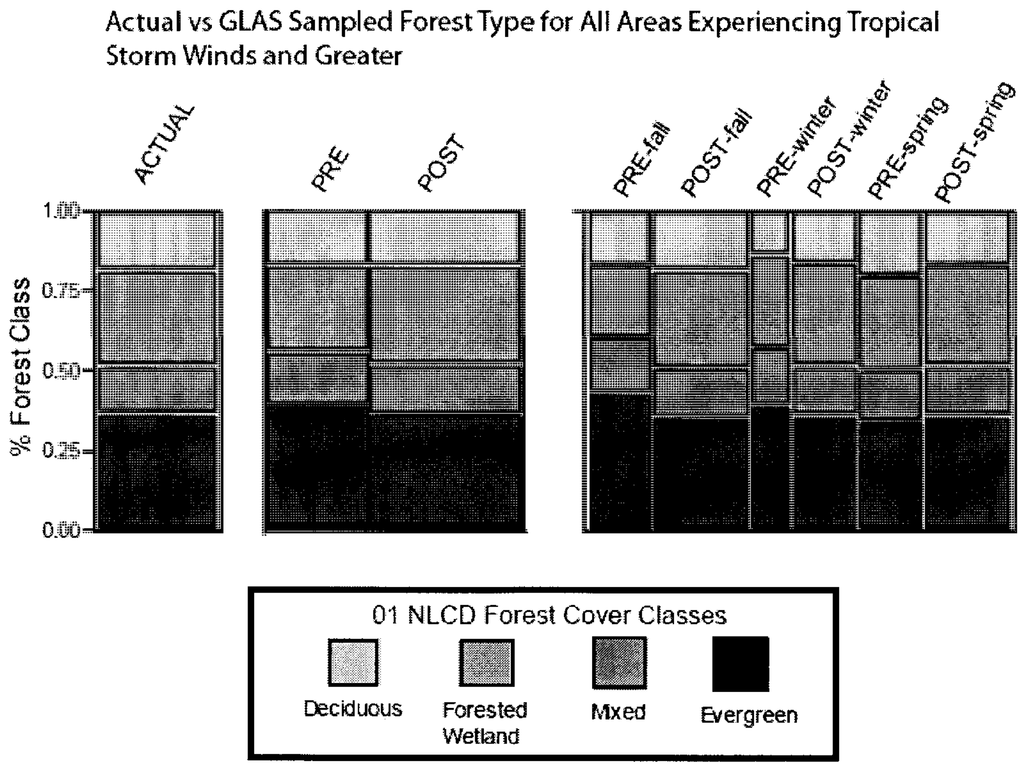

Figure 7- Actual forestland cover over all land areas experiencing tropical storm winds and greater as compared to percent sampled by GLAS pre and post Katrina as well as by campaign. Column widths within boxes are proportional to total sample.

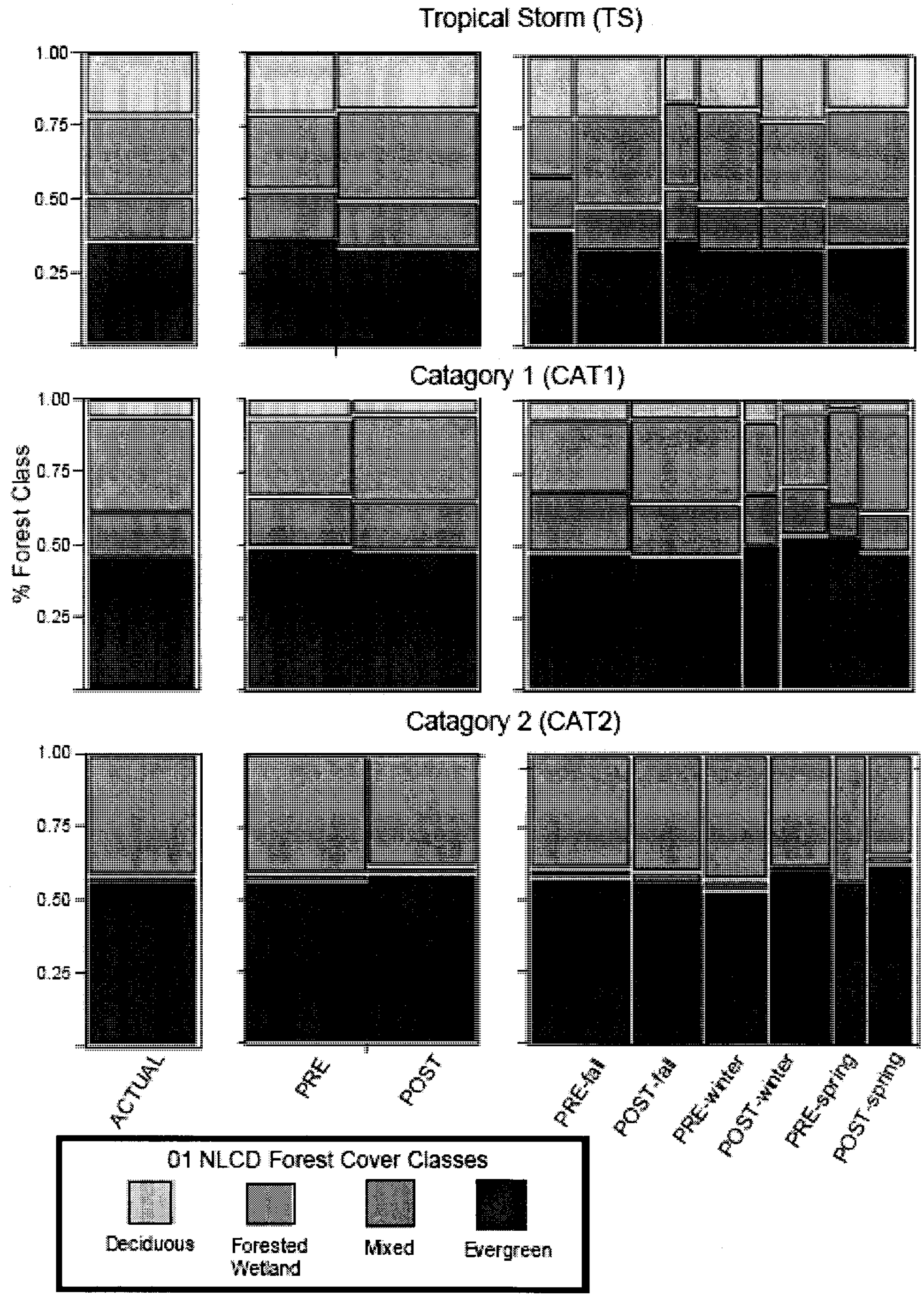

Figure 8- Actual forest land cover by wind zone as compared to percent sampled by GLAS pre and post Katrina as well as by campaign. Column widths within boxes are proportional to total sample.

Table 4- NLCD forest composition over landscape compared to GLAS captured compostion

Wind Zone	Forest Class	LANDSCAPE AREA (KM2)	LANDSCAPE % of forest	GLAS Forest Type By Season and Year (%/N) ALL GLAS	ALL PRE	ALL POST	FALL PRE L3A	FALL POST L3D	WINTER PRE L3B	WINTER POST L3E	SPRING PRE L3C	SPRING POST L3F
ALL	Evergreen	31228	**36.4**	36.8	38.6	35.6	43.0	35.3	39.0	35.6	34.2	36.0
	(42)			*15175*	6390	8785	*2666*	*3430*	*1518*	*2322*	*2206*	*3033*
	Mixed	12966	**15.1**	16.2	16.9	15.7	17.4	15.8	17.8	15.7	15.8	15.7
	(43)			*6671*	2792	3879	*1081*	*1534*	*693*	*1022*	*1018*	*1323*
	Forested Wetland	25763	**30.0**	29.5	27.0	31.3	*22.9*	*30.4*	*29.4*	*32.4*	*29.5*	*31.3*
	(90)			*12179*	4464	*7715*	*1416*	*2958*	*1143*	*2115*	*1905*	*2642*
	Deciduous	15838	**18.5**	17.5	17.5	17.4	16.7	18.5	13.9	16.3	20.5	17.1
	(41)			*7194*	2893	4301	*1034*	*1801*	*540*	*1062*	*1319*	*1438*

Gridded Analysis

Height structure, change, and sampling were explored at a one degree and quarter degree gridded resolution over a six by six degree domain covering all areas experiencing tropical storm winds or greater (Figure 9). At one-degree, the number of shots per grid cell pre storm ranged from 74-2200 with a mean of 840 shots. Sampling density ranged from 0.05 shots per km^2 of forestland per year to 0.6 shots per km^2 forestland per year. The median density for the year pre Katrina was 0.20 shots per km^2 and 0.28 shots per km^2 post Katrina. Density of shots showed a greater range at a quarter-degree resolution than one degree resolution, ranging from 0 to a maximum density of 4.5 shots per km^2 of forestland post Katrina. The median density pre Katrina was 0.14 shots per km^2 and mean density was 0.21 shots per km^2 post Katrina. Total number of shots per grid cell pre storm ranged from 0-445 with a mean of 88 shots. More than a quarter of all grids at a quarter degree resolution had no GLAS shots. When broken down by season, more than 75% of the grid cells did not have data for at least one season.

At one degree resolution, mean canopy pre-storm height ranged from 10.9-17.6m, with the middle 50% of mean heights falling between 13.1-15.9m and a mean of 14.6m. Mean post-storm heights ranged from 7.2-17.4m with the middle 50% of the mean heights falling between 12.6 and 15.4m and a mean of 13.8m. The median height change (pre minus post) detected was 0.7m and ranged from -2.2m - 5m, one third of which were not statistically significant (alpha= 0.05)(Figure 10).

At quarter degree resolution, the mean pre-storm canopy height was 14.8m, and ranged from 4.8-26.1m with the mid 50% falling between 13.0-16.6m. The mean post-storm height was 13.3m and ranged from 1.2-20.5m with the middle 50% of the mean heights falling between 11.6-15.4m. The median height change detected was 0.8m and ranged from -10.3-15.6m. Forty seven percent of the gridded height changes were not statistically significant (alpha= 0.05)(Figure 10).

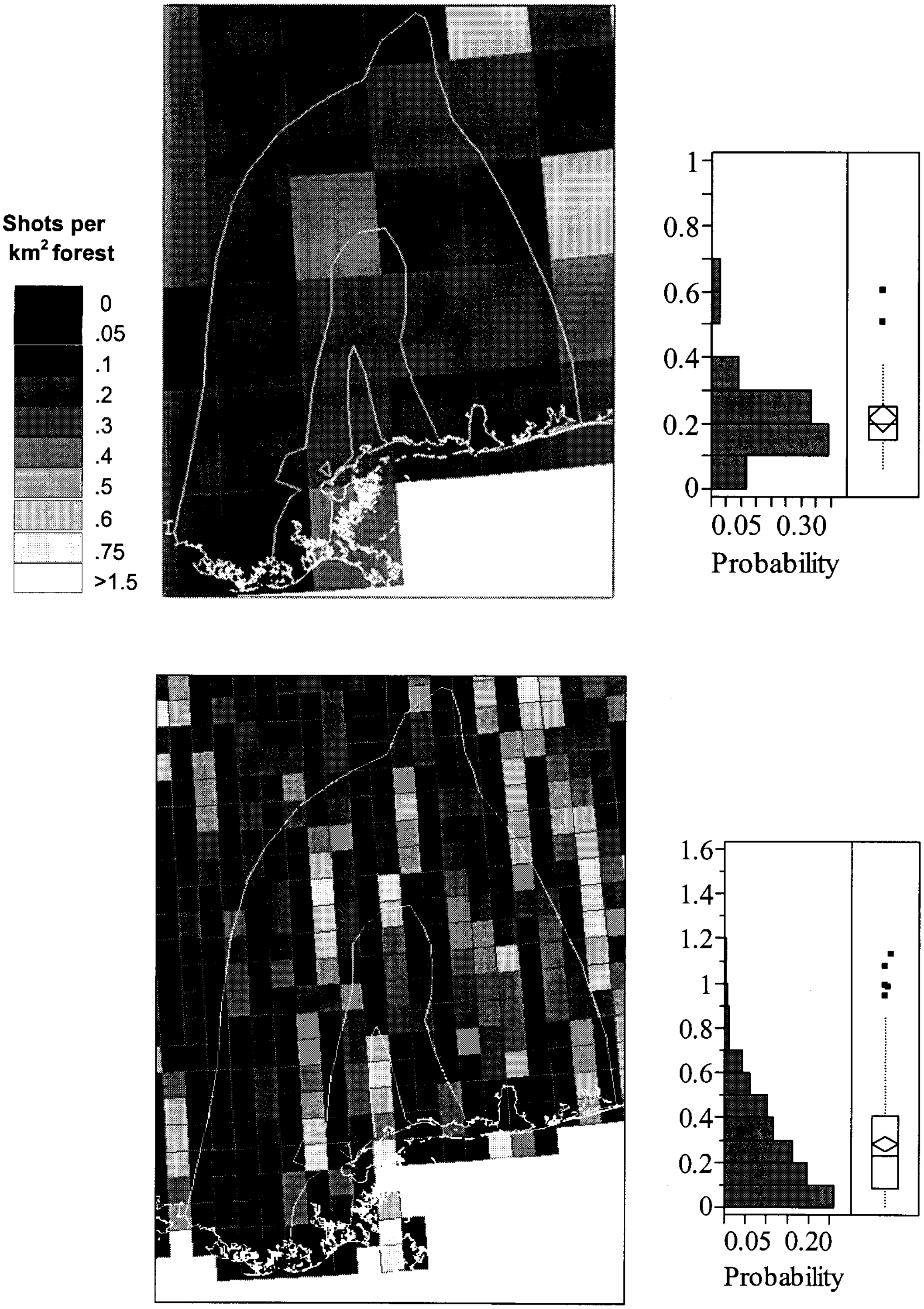

Figure 9 - Sampling density (GLAS shots/km^2 forest) over a 6X6 degree area at one-degree (Top) - and quarter degree (bottom) resolution for all campaigns pre Katrina. Right panels show frequency distributions of height changes (diamond shows 95% confidence in the mean, box shows middle 50% value with center line equal to median, dots show potential outliers).

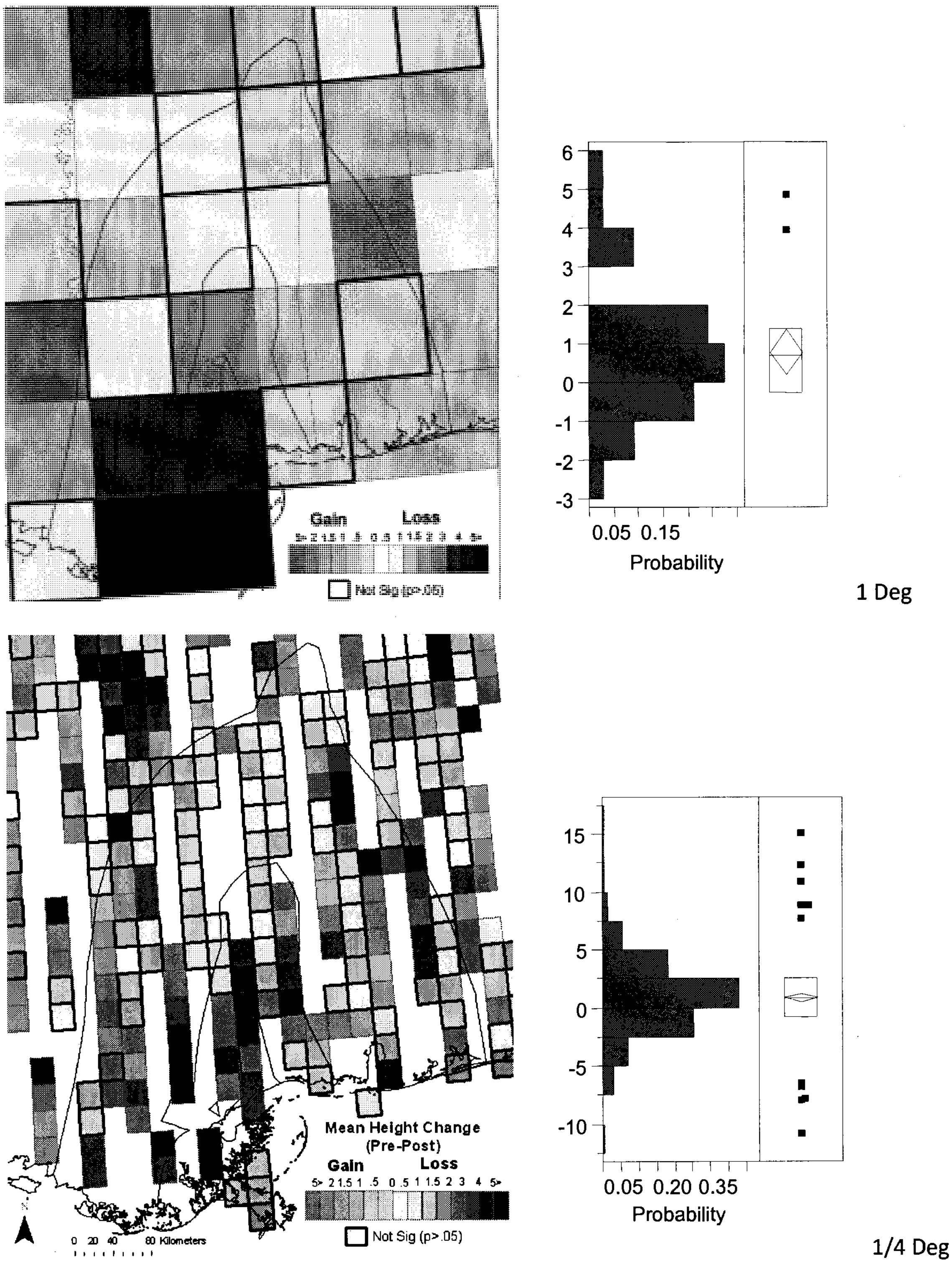

Figure 10- Gridded mean height change at 1 deg (top) and quarter degree (bottom) resolution. Maps show spatial variability of height change, changes that are not significant have dark boarder surrounding cell. Left panel shows frequency distributions of height changes, diamond shows 95% confidence in the mean, box shows middle 50% value with center line equal to median, dots show potential outliers.

Delta NPV

The extent of the ΔNPV product obtained from Chambers et al. (2007) spanned from ~89-92 degrees West and 28.5-33 degrees North; data did not cover the northern extent of tropical storm winds. The range of ΔNPV was from -0.8 - 1.25 with 99% of ΔNPV values falling between -0.165 and 0.467.The median fractional change of non photosynthetic vegetation was 0.088 with a mean of 0.098 (Std dev +/- 0.111) (Table 5). The median ΔNPV value sampled by all forested GLAS shots was 0.077 and the mean was 0.089. Ninety-nine percent of ΔNPV values sampled by GLAS fell between -0.184 and 0.519. PRE-storm GLAS shots had higher ΔNPV range (0.016-0.151), median (0.078) and mean (0.091) than post-storm range (0.015-0.146), median (0.077), and mean (0.087) (Figure 11).

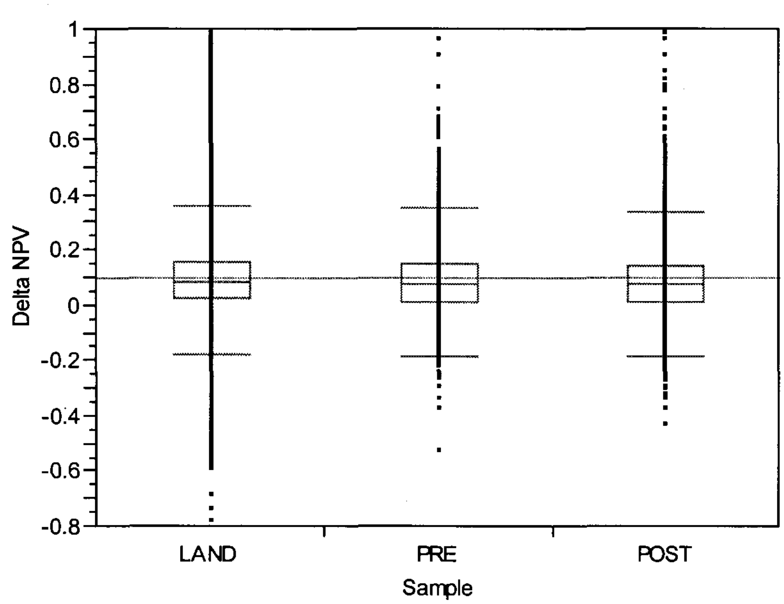

Figure 11- Distribution of ΔNPV across the forested domain (LAND) compared to range captured by pre and post-storm GLAS shots. Boxes represent the middle 50% of samples, center-line represents the median and the outer horizontal lines represent the bounds of the data.

Table 5- Summary stats of ΔNPV across the forested study domain and as sampled by GLAS pre and post-storm.

		Quantiles			Means and Std Dev			
Sample	**n**	**25%**	**Median**	**75%**	**Mean**	**Std Dev**	**Lower 95%**	**Upper 95%**
LAND	428504	0.025	0.088	0.160	0.098	0.111	0.098	0.099
All GLAS	33089	0.015	0.077	0.148	0.089	0.115	0.088	0.090
GLAS PRE	13431	0.016	0.078	0.151	0.091	0.116	0.089	0.093
GLAS POST	19658	0.015	0.077	0.146	0.087	0.114	0.086	0.089
L3A	4866	0.024	0.087	0.163	0.101	0.118	0.098	0.105
L3B	3128	0.014	0.078	0.151	0.091	0.117	0.087	0.096
L3C	5437	0.011	0.070	0.138	0.081	0.112	0.078	0.084
L3D	8022	0.012	0.073	0.144	0.084	0.115	0.082	0.087
L3E	4992	0.022	0.080	0.146	0.092	0.116	0.088	0.095
L3F	6644	0.014	0.078	0.148	0.088	0.112	0.085	0.091

No significant correlation was found between pre storm heights and +ΔNPV fraction (Figure 12-top). There was a significant negative correlation between post-storm GLAS derived mean canopy heights and ΔNPV (Figure 12-bottom). Based on this significant correlation, we calculated a mean height loss in forests experiencing an increase in ΔNPV to be 1.01 m for every 0.1 ΔNPV. Approximately 83% of forests over the domain showed an increase in NPV over which we calculated an average loss in mean canopy of 1.30 m, ranging from 0-12.6 m with the middle 50% falling between 0.6-1.8 m. In the tropical storm zone a 1.2 m average canopy height loss was calculated for the 80.4% of forests that showed positive ΔNPV. In the category one zone a 1.5m average canopy height loss was calculated for the 91.9% percent of forests showing positive ΔNPV. In the category two zone a 2.4m loss in mean canopy height was calculated for the 99.7% forest area having a positive ΔNPV.

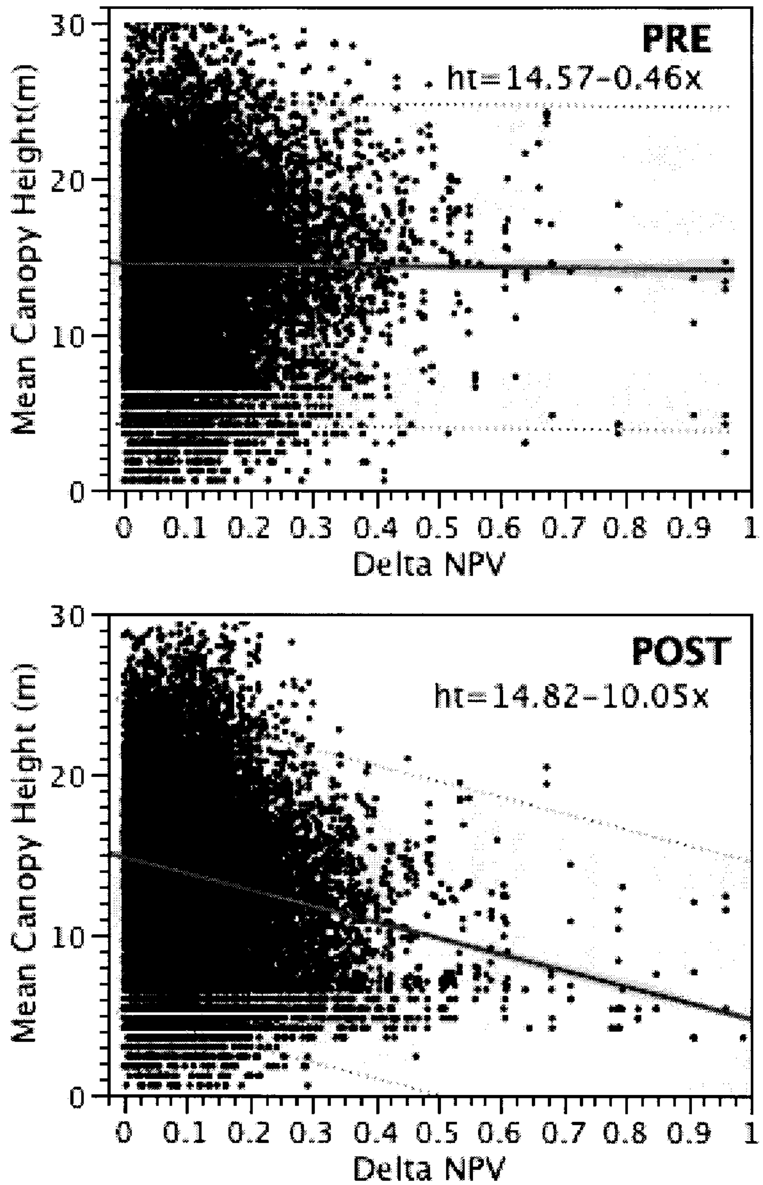

Figure 12- Relationship between change in Non-Photosynthetic Vegetation after Katrina andpre-storm (top) and post-storm (bottom) Mean Canopy Height (m). Light dotted lines show the upper and lower 95% confidence limits for an individual predicted value. The darker shaded area around the line of best fit shows the confidence of the fit.

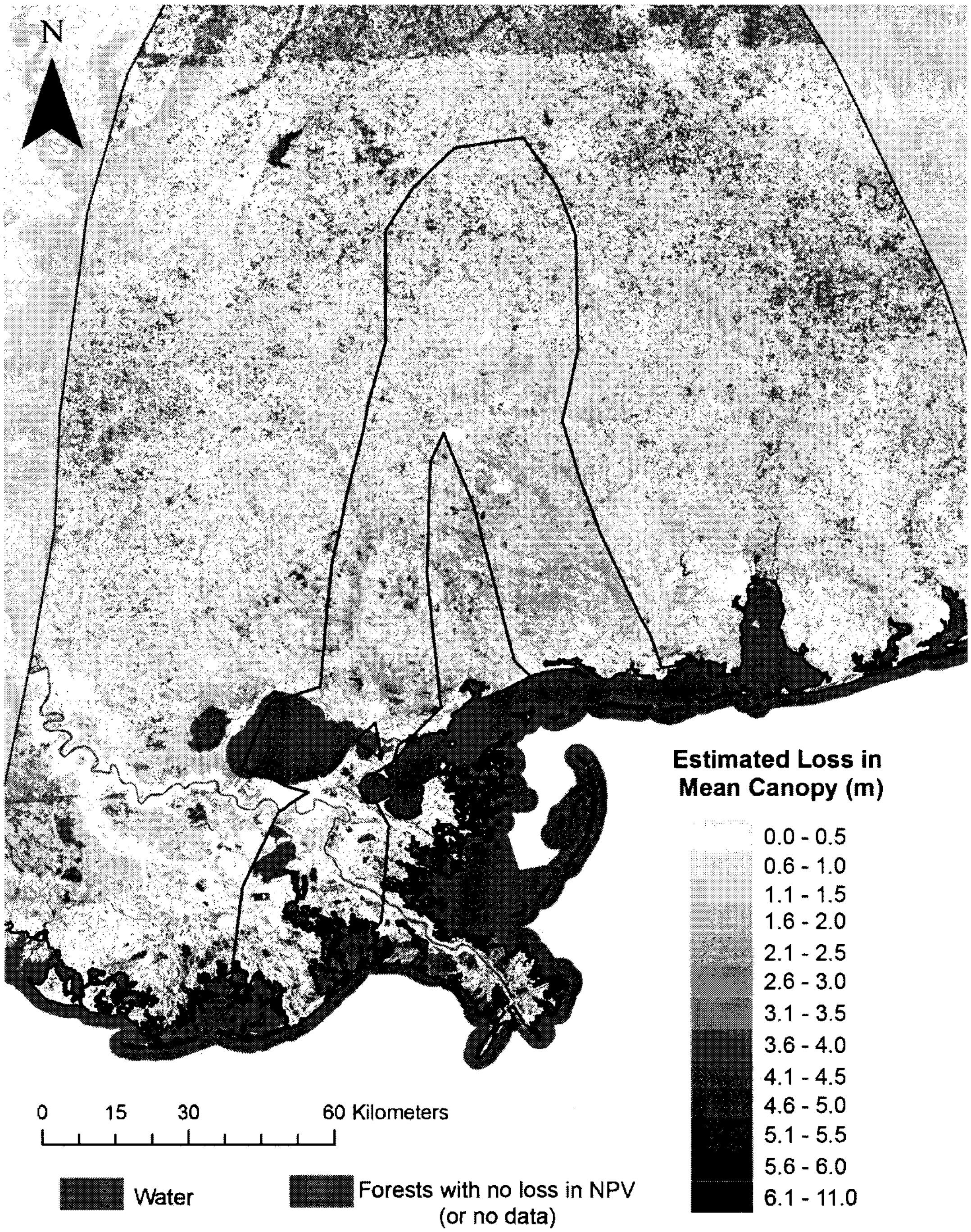

Figure 13 - Map of estimated loss in mean canopy height (m) based on ΔNPV to post storm height relationship

Carbon Conversion

We calculated an average above ground carbon to mean canopy height relationship of 0.43 kg C/m over the study domain with a range of 0.36-0.49 kg C/m (Table 6). Using this relationship we calculated the estimated carbon loss across the study domain, weighed equally by area and season, to be ~22Tg C(+/- 7Tg C). Estimates of loss in standing carbon over the domain varied greatly between seasons from over 38Tg C (+/- 7Tg C) in the Fall to 12Tg C (+/- 3Tg C) in the Winter, assuming no loss or gain in the tropical storm region (Figure 14). Assuming a pre storm biomass of ~7.8kgC/m2 (Hurtt et al. 2002) we estimated the percent loss in standing carbon to be between 18-26% in category two, 9-16% in category one and 0-3% in forests hit by tropical storm winds (Appendix Figure 15) .

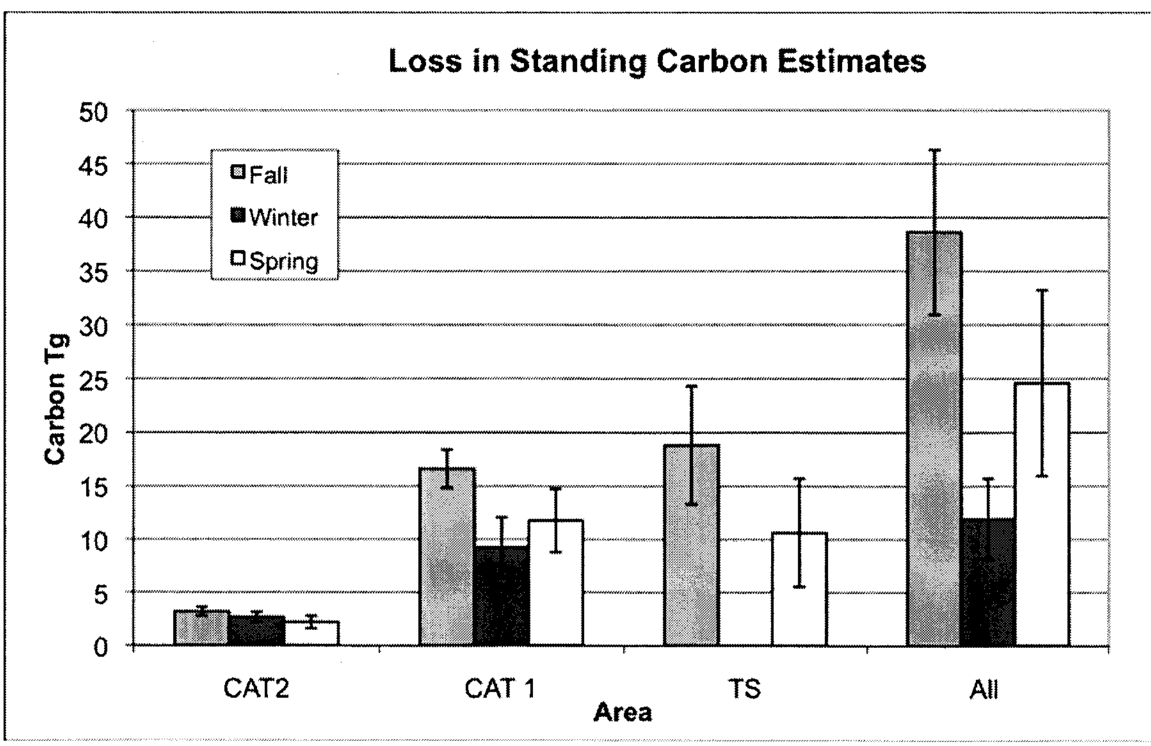

Figure 14- Best estimates of standing carbon loss

Table 6- Above ground standing carbon loss estimates using 0.43kgC/m relationship and percent of standing carbon loss estimates based on pre storm estimate of $7.8kgC/m^2$

Wind Zone	Season	Forested Area (km)	Height loss	Change in above-ground carbon (Tg)*	Lower CI	Upper UC	Percent loss above-ground C
ALL	All	85797	0.76	28.19	24.5	31.88	4.2
TS	All	70811	0.43	13.07	9.73	16.42	2.4
CAT1		13400	2.43	14.01	12.63	15.4	13.4
CAT2		1585	4.11	2.8	2.53	3.07	22.6
AVG		85797	2.32	29.89	24.88	34.89	4.5
All	Fall	85797	1.06	39.11	33.2	45.12	5.8
	Winter		0.12	4.24	-2.54	11.07	0.6
	Spring		0.56	20.55	14.9	26.19	3.1
	AVG		0.58	15.97	11.39	20.6	2.4
	Leaf ON			29.83	24.05	35.66	4.5
TS	Fall	70811	0.62	18.82	13.31	24.33	3.4
	Winter		-0.32	-9.65	-16.23	-5.34	-1.7
	Spring		0.35	10.63	5.36	15.53	1.9
	AVG		0.22	6.6	6.38	13.77	1.2
	Leaf ON		0.48	14.73	9.33	19.93	2.7
CAT 1	Fall	13400	2.88	16.61	14.81	18.38	15.9
	Winter		1.6	9.24	6.4	12.07	8.8
	Spring		2.04	11.76	8.8	14.72	11.3
	AVG		2.18	12.53	10	15.06	12
	Leaf ON		2.46	14.18	11.81	16.55	13.6
CAT2	Fall	1585	4.7	3.21	2.8	3.61	26
	Winter		3.93	2.68	2.19	3.11	21.7
	Spring		3.22	2.2	1.61	2.79	17.8
	AVG		3.95	2.69	2.2	3.17	21.8
	Leaf ON		3.96	2.7	2	3.02	21.8
All area weighted	**FALL**	**85797**	**1.05**	**38.63**	**30.92**	**46.32**	**5.8**
	WINTER*		**0.32**	**11.92**	**8.59**	**15.18**	**0.3**
	SPRING		**0.67**	**24.59**	**15.77**	**33.04**	**3.7**
	AVG		**0.60**	**21.83**	**18.58**	**32**	**3.3**
	Leaf on		**0.86**	**31.61**	**23.34**	**39.68**	**4.7**

Wind Zone	Season	Forested Area (km)	Height loss	Change in above-ground carbon (Tg)*	Lower CI	Upper UC	Percent loss above-ground C
NPV-ALL**	ALL		1.07	39.48			5.9
NPV-TS**			0.94	28.62			5.2
CAT 1			1.42	8.18			7.8
CAT 2			2.36	1.61			13

* Area weighted domain winter estimates assume zero loss in Tropical storm zone
** Extrapolates beyond sampled MODIS Region Highly Uncertain.

CHAPTER IV

DISCUSSION

Quantifying disturbance location, extent, severity, and fate of disturbed biomass are ways to improve carbon budget estimates and can lead to better initialization, parameterization, and testing of forest carbon cycle models (Frolking et al., in press). Space-born optical remote sensing has been used to map large-scale forest disturbance occurrence, location, and extent over the last 30 plus years (*wind*, Chambers et al., 2007, *logging*, Masek et al., 2008, *pests* Mukia et al., 1987, *fire*, Roy et al., 2008). Active remote sensing data such as Lidar can more directly indicate canopy structural properties and biomass than optical remote sensing data (Dubayah 2000, Frolking in press). Large footprint Lidar systems have been shown to accurately estimate important forest structural characteristics such as canopy heights, stand volume, basal area and above ground biomass (Dubayah, 2000, Hurtt 2004, Pflugmacher et al. 2008). Our study assessed the use of the large footprint space-born Geosicence Laser Altimeter System to sense forest structure change resulting from large scale forest disturbance using Hurricane Katrina as a case study. Results demonstrated the potential of using space-born Lidar systems to monitor changes in forest structure over large regions. Using GLAS data from a year previous and following Hurricane Katrina, we observed significant losses in mean canopy height that significantly increased with wind intensity. Domain wide carbon and damage estimates made using a height to biomass relationship developed for the Southeast using ED fell within the range of previous published studies. While results highlight the potential use of space-born Lidar in damage detection and quantification, they also emphases limitations on the scope and scale at which current data could quantify hurricane damage. Future improvements in sampling coverage and sensor specifications are expected in upcoming missions like DESDnyl that may improve our ability to detect and quantify forest structure changes from disturbance events.

Study Design

Our first step into the inquiry of whether GLAS could detect and quantify height loss resulting from Hurricane Katrina was to determine the domain over which to study. Our domain was defined by the estimated extent of maximum sustained winds for Hurricane Katrina provided by NOAAs H*Wind product (Powel et al 1998). Though the majority of damage has been reported to occur within these areas, damage associated with Hurricane Katrina has been noted outside these bounds as far north as Tennessee (Chambers et al. 2007, Oswalt 2008) and, as our results demonstrate, small to moderate damage over a large area can accumulate to make impacts larger than severe damage over smaller areas. As our study focused on changes in forest structure, defining forest was an important element of our study. The use of 2001 30m National Land Cover data allowed for a high-resolution forest map to select forested GLAS waveforms. Some land classified as forest could have been logged or converted post classification; we assume if sampling is unbiased this should not affect the results significantly. Other studies have used MODIS derived land cover products to stratify forest waveforms successfully (Nelson et al 2009, Pflugmacher et al. 2008); however, for a landscape as heterogeneous as the Southeast, a higher resolution product was sought.

An essential element of our study was selecting a GLAS derived metric to describe forest structure over the domain that would adequately detect damage as well as provide a means to estimate loss of standing carbon. A common measurement of forest structure derived from Lidar data has been maximum canopy height (Lefsky 1999, Harding 2001). Maximum tree height can be directly extracted from a waveform and has the advantage of being easily compared among field and Lidar datasets; however, when the upper canopy surface height is variable, it is possible that only a single tree will have the maximum height and may not return enough energy to be detected (Lefsky 2007). Furthermore, due to GLAS's large footprint, on the order of 50-100m in diameter, maximum canopy height is not a valid metric to quantify disturbance or biomass unless the forest and landscape within its sample area are completely homogenous. We chose to use mean canopy height as derived by outputs from the ICESat Vegetation Product Utility, as a descriptor of forest structure and a means to convert structure change into standing carbon loss. We chose this metric in part due to its ability to be directly linked into mean height to biomass relationships used within the height structured ecosystem model ED. Because coarse-scale studies often do not have the detailed information available as local studies, height equations need to be robust across a range of forest types and conditions

(Pflugmacher et al. 2008). The equation used in this study was developed to fit developed forest stands on varying terrain without the need of digital elevation models and has been tested against field estimates in different regions (Lefsky 2005, 2007, Pflugmacher 2008). The ability to use this equation in many different regions to study disturbance where high-resolution auxiliary data may not exist added to the benefit of using this equation. Pflugmacher et al. (2008) compared the accuracy and regional variability of GLAS height estimates with data from the US Forest Service Inventory and Analysis (FIA) program and found that current GLAS algorithms described in Lefsky (2007) provided accurate estimates of height, validating the regional applicability of height algorithms for the GLAS sensor. Additionally no biases between GLAS derived mean canopy height and median topographic slope, elevation, or forest type was found. The study also found that regional models based on height as a single predictor variable performed as well as models that accounted for variations in forest types and ecological subsections. This finding suggests that generalized, non-site and non-species specific allometric equations, like the one used in our study, can be useful for coarse-scale estimation of forest biomass (Pflugmacher et al. 2008). What we may have given up in plot level accuracy by using the mean canopy height equation based of Lefsky (2007) was outweighed by the gains in its regional applicability. One problem encountered in using the mean canopy height equation was the fact that since small trees did not compose a significant portion of equation training data, the best fit model for fitting waveforms to mean canopy height, derived by Lefsky (pers. comm.), resulted in a 4meter intercept and higher levels of uncertainty for trees less than ~8m. Since we were interested in identifying low canopy heights, we modified the equation so that if the extent, which should in most cases represent the maximum height of a stand, was less then the derived height, mean canopy height would be recorded as extent. Continued research into the applicability of Lefsky's equation for smaller stands and over varying disturbance conditions (i.e. high levels of debris/ dense undergrowth) is suggested. Future studies could investigate the use of other Lidar/GLAS derived variables that may be useful in predicting biomass, timber volume or other forest metrics of interest (See Nelson et al. 2009 for description of variables).

Detecting Changes in Mean Canopy Height

Methods for quantifying changes in mean canopy height progressed throughout our research. Initial estimates of changes in mean canopy height combined all data collected from the GLAS sensor for a year previous to Katrina and all data collected one year following. Each year consisted of data from three campaigns taken during the fall, winter and spring, and all campaigns were from GLAS's third laser and had relatively consistent footprint sizes (NSIDC). We did not compare data from earlier Lidar campaigns due to inconsistencies in laser energy return and footprint sizes (Harding, 2005). Because GLAS footprint locations are non-coincident we were not able to directly measure forest structure change, instead we used sample statistics to compare sample means between years. Using a student's t-test we detected a significant decrease in mean canopy height between years over the forested domain. To determine if we could attribute that change in height to storm damage, we explored the influence of several factors on mean canopy distributions pre and post Katrina, including breaking down mean canopy heights by wind category. We found no significant difference between mean canopy heights and wind zone before Katrina, yet we observed a significant decrease in height post-storm across all wind zones that significantly increased with increasing wind intensity. This finding increased our confidence that changes we were detected were related to Katrina. Stanturf (2007) and Kumpfur et al. (2007) also observed a significant correlation with hurricane related damage and wind speed.

To check for any biases that may have affected our original estimates of height loss we decided to disaggregate our data into campaigns to look at distributions and changes in measured mean canopy height by season of acquisition. A seasonal bias in both mean canopy height as well as amount of height loss between years was detected. Although there was no notable difference in mean canopy heights calculated in the spring or fall for the year before Katrina over the whole domain, mean Winter height measurements averaged lower than Spring or Fall over all wind zones both pre and post Katrina. One reason for the decrease in heights could be due to changes in leaf cover during Winter months. Duong et al. (2008) also observed differences between winter and Summer GLAS waveforms, acquired over broad-leaved, mixed wood and needle leaved forest in Europe. Their results showed that height of median energy (HOME) showed a 148% change from Winter to Summer and a 36% change in conifers over a six month study. Original height change estimates in our study were not weighted equally by campaign and therefore could have been influenced by change in proportion of shots acquired in leaf off versus leaf on seasons each year.

Differences between damage calculated by season lead us to disaggregate our original height estimates and report estimates of height and biomass change by season. Although we found a strong correlation between increased height loss and wind speed for all seasons, significant differences in the amount of change detected varied by season. Changes in height estimated in the fall were significantly higher than in spring or winter in every wind zone. In forests hit by the strongest winds data collected in the spring resulted in the smallest calculation of height change. The smallest changes in the lightest wind zones were calculated in the winter, for which a gain in height was detected in forested areas hit by tropical storm winds. Differences in height change detected may be attributed to type of disturbance being detected and subsequent recovery, for example the loss of leaves on some trees post Katrina that grew back in the spring may lead to larger estimates of change in the fall then in spring. Other possible influences could be bias in sampling of forest type and age, changes in Lidar intensity, or natural shifts in timing of leaf break. More research will need to be done to determine why differences are being detected between seasons and which season gives best estimates of infield changes. Our results showed that seasonal changes in detection of mean canopy height could be just as large as those detected due to storm intensity. However, wind intensity was a larger influencer in height change between years than seasonality. Future research could further investigate distribution shifts between years and seasons, as well as use more advanced statistical methods including bootstrap analyses to provide more comprehensive estimates of forest structure change.

Assessing Sample Representativeness

We were interested in whether our estimates of height change were representative of damage over the landscape hit by Hurricane Katrina. Although we did not have a data set to answer that question directly we compared how well GLAS sampled other metrics such as forest cover, distribution of winds and MODIS derived ΔNPV, which showed a strong correlation to field measured storm damage. The sampling design of GLAS is neither random nor stratified across the landscape, with high density of shots along track but large areas un-sampled between campaign tracks. We found that GLAS did a satisfactory job capturing the land cover composition over the domain as well as in each wind zone. In general, composition of the landscape was best captured when all GLAS samples were considered in analysis. We observed a larger landscape sampling bias as data was broken down by year and campaign total number of samples also decreased. Although changes were statistically significant, differences between GLAS sampled composition and landscape composition was most often less than 5% of one another and no confounding trends between years or campaigns were observed. We therefore felt that GLAS did a reasonable job sampling the forested landscape and biases were not large enough to warrant discounting earlier findings, although future work could try and quantify influences of bias on estimate. We also compared the forested distribution of ΔNPV, an index closely related to field measured damage and mortality, with the distribution as sampled by the center point of all forested GLAS footprints. Though slightly lower, GLAS captured a mean and mid-range of ΔNPV within a hundredth of a fraction of the landscape.

Scale

Although we presented broad damage estimates over the landscape, we were interested in exploring the spatial variability in change to more depth. We were particularly interested in inputting height changes into the Ecosystem Demography model to convert estimates of height loss into estimates of above ground biomass loss. Furthermore we were interested in the future possibility of using GLAS Lidar data both pre and post storm for model initialization that could lead to estimates of recovery and carbon flux.

We attempted to summarize sampling density and calculate mean canopy height at one degree and quarter degree scales, a scale at which many regional to global scale models operate. Our findings suggest that more sampling is required to adequately represent forest structure change at scales one degree and smaller. At a quarter-degree resolution, using all data pre and post Katrina, more than a quarter of grids had no pre storm or post storm data, additionally 50% of the changes in mean height could not be declared as significant. Due to low sample numbers and density of shots in some grids we could not confidently report changes in height less than a meter at both the degree and quarter degree scale. Influence of seasonal biases as described earlier increased as data was broken down to smaller resolutions, but separating data by season lead to even smaller sample sizes and more data cells without information. Mapping height change at the degree scale and smaller we observed significant gains in height post storm that are physically impossible. This may have been caused by bias in sampling by season, forest type or other factors (i.e. if a cell has a high percentage of pre-storm winter shots averaged in, but little to no winter shots post storm, one might expect to observe an increase in height). Another potential source of error was that GLAS samples may have been close enough along transects to cause spatial autocorrelation, which again would be exasperated at smaller scales. The occurrence of spatial autocorrelation would violate the assumption of independence among samples, which may underestimate the variance in forest height and biomass (Nelson, 2009). These issues and the ability to detect changes only grow as samples are limited to leaf-on or leaf-off seasons and/or constrained to smaller areas, therefore we chose to explore other methods of disaggregating the spatial patterning of disturbance.

The scale at which one can detect change in forest structure depends on both the sampling density, spatial heterogeneity of forest structure (i.e. Std dev) and amount of change one wants to detect. Requirements for both the vertical and horizontal scale at which disturbance impact must be measured will vary based on user need (i.e. forest stand manager, habitat and biodiversity mapping vs. regional carbon mapping). Pflugmacher et al 2008 notes that information on carbon flux is needed on a spatial scale small enough to be linked to individual landscape units as they undergo natural disturbances, succession, or land-use changes. Under ideal conditions, in a change analysis, we would have been using coincident waveforms that were randomly but systematically placed, at densities high enough to capture the range of forest and disturbance conditions. Ideally we would also evaluate the accuracy of height change and biomass estimates with field and GLAS co-located plots. However, a comprehensive field campaign was beyond the scope of this study. Future studies could incorporate FIA field measurements pre and post storm to more accurately assess waveforms predictability of forest structure and change. Power analysis could be an important tool in determining sampling requirements for future missions trying to characterize vegetation structure and change from space. Ideally this tool is used in sampling design, as its use post-hoc has been debated (Thomas 1997). As an example, we used the power analysis to determine that 1400 samples would have been needed to detect a significant (alpha = 0.05) change in height of 1m over a forest with a vertical height standard deviation of 5 meters with 95% confidence, assuming data normality. Similar analysis could be done when determining sampling requirements for future missions.

We compared differences in both sampling density and area between the Forest Inventory Analysis (FIA) and GLAS samples used in our forest structure change analysis (Table 12). The USDA Forest Service has set up systematically arranged permanent field plots at the scale of approximately 1 plot for every 24km^2 of forestland which consists of four 0.016ha plots (Oswalt, 2008). Legislation mandates that 20% of the plots in each state be measured each year (FIA 2005). Assuming each subplot is treated as a separate sample, this equates to 0.0005% of all forestland being sampled per year or .03 samples per squared kilometer, which would lead to a little less than 3000 samples over the study domain. GLAS sampling density varied both spatially and temporally. The average density per year over the whole study domain was 0.24shots/km or 7 times more samples than FIA. In forestlands hit by category 2 winds the density of GLAS shots was double the domain average. Assuming a footprint radius of .025km, GLAS on average sampled ~0.05% of the forested area per year. Despite the increased sampling and area coverage by GLAS, there are important differences in sampling methodologies and data collection that may make FIA data more desirable. One of the large differences is lack of coincident GLAS waveforms. Placement of FIA has a consistent, regular, spatial and temporal distribution of sampled locations across the US (FIA). More detailed information about canopy structure and health can be made on the ground from repeated human observations than can be inferred from non repeat Lidar waveforms. Data of this caliber is not available globally and gaps in data coverage still exist nationally.

Comparing GLAS to ΔNPV

We explored alternative ways to study estimates of damage at finer scales and to explore the spatial variability in damage. We compared GLAS derived mean canopy heights to ΔNPV for which a strong correlation with field measured tree mortality and damage was previously established (Chambers, 2007). Using optical remote sensing and active remote sensing synergistically has been shown to improve estimates of forest structure and dynamics (Anderson et al

2008, Lefsky et al 2005). We found a significant relationship between post-storm heights and increasing fraction of NPV. Height change estimates made using this relationship were slightly lower but within the range of seasonal estimates for category one and category two wind zones. We did not have full spatial coverage of ΔNPV for the tropical storm zone. Preliminary results warrant further research into the potential synergy of these products.

Damage and Carbon Estimates

In this study the Ecosystem Demography model was used to create above ground carbon to height relationships from which we could use to estimate loss of standing carbon based on GLAS derived height change estimates. ED differs from most other terrestrial models by formally scaling up physiological processes through individual based vegetation dynamics to ecosystem scales, while simultaneously modeling natural disturbances, land use, and the dynamics of recovering lands (Moorcroft 2001). These model characteristics present a unique ability to study how altering disturbance regimes may affect regional to global terrestrial carbon budgets as well as how they may affect future ecosystem structure and succession. Previous studies have integrated Lidar data into dynamic carbon ecosystem models successfully (Hurtt 2004, Thomas et al 2008). Future research could use Lidar data to initialize the Ecosystem Demography model to study how carbon fluxes may be affected and use information to make better projections of future impacts.

Using the domain averaged height to biomass relationship developed in ED, we estimated standing carbon losses on the order of those estimated by McNulty in 2001 (Largest storm accounting for 20Tg). Our estimates for Hurricane Katrina fell between estimates made by Chamber's (2007) and the Oswalts (2008). Chambers estimated a higher loss of carbon at ~105 Tg, whereas our highest estimates were slightly below half his estimate. It is important to note that our domains did not completely coincide. We also compared our results to those measured by Oswalt (2008). Oswalt measured 15% of all trees experienced blowdown and or stem breakage in areas described as heavily disturbed, an area that corresponds fairly well with land area hit by category two winds (Figure 15). Forests defined as moderately disturbed by the forest service experienced 7% blowdown and stem breakage and covered similar area to forests hit by category one winds. By assuming a pre-storm biomass of 7.8kgC/m2 across our domain we calculated estimates of damage about double that of forest extreme damage estimates (Figure 15). We may have been picking up on more than just wind throw and bole breakage. However, the FIA notes much higher damage rates for more minor disturbance damage such as branch breakage and tree lean. Information on stand density, and canopy cover may aid in the ability estimate biomass loss and determine types of disturbance being detected by GLAS (i.e. wind throw vs., crown damage) that play important roles in stand recovery trajectories. Our results highlighted that small disturbance spread over a large area can account for as much damage as intense disturbance over smaller areas. Therefore studies that only focus on the most intensively hit areas of a hurricane could be missing the bulk of damage. This has important implications for the need to be able to observe and detect damage across large areas after hurricane events and the importance of adequately chosing and reporting boundaries for damage assessment studies.

CHAPTER V

CONCLUSIONS

This study highlighted the potential to use structural data from space-born Lidar systems to detect and quantify changes in forest structure. GLAS was able to detect changes in mean canopy height post-Katrina across forests hit by tropical storm winds and greater that were strongly associated with wind intensity. Detection of height structure and change was heavily influenced by season. Variations in seasonal height change estimates may reflect sensitivity to different types of structural disturbance as well as recovery. Carbon estimates made using a height to biomass relationship developed for the Southeast in ED fell within the range of previous published estimates. While results highlight the potential use of space-born Lidar in damage detection and quantification, they also emphasis limitations on the scope and scale at which current data can quantify hurricane related changes. Limited sampling hindered our ability to make reliable height estimates of height change at one degree resolution and smaller across the domain. Future improvements are expected in sampling coverage and sensor specifications in upcoming missions, such as DESDnyl, that may improve our ability to detect and quantify forest structure changes from disturbance events. Combining GLAS data with other optical remote sensing products, such as MODIS NPV and Landsat forest cover, show promise for improving spatial representation and quantification of damage with data synergy in future studies.

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APPENDIX

Table 7- Leaf on estimates of height change

Wind zone	Season	Year	n	mean ht (m)	Ht change	(p)**
ALL	Leaf on	PRE	4329	15.8	0.829	0.0001
		POST	7877	14.97	+/- .11	
	Leaf off	PRE	3062	11.513	0.1152	0.22
		POST	5575	11.3978	+/- .18	
TS	Leaf on	PRE	10221	15.9	0.49	0.0001
		POST	15445	15.41	+/- .12	
CAT 1	Leaf on	PRE	1864	15.423	2.645	0.0001
		POST	2231	12.758	+/- .27	
CAT2	Leaf on	PRE	560	11.191	4.146	0.0001
		POST	483	15.337	+/- .18	

Table 8- Contingency analysis of Wind Zone by Year

Count Total % Col % **Row %**	**TS**	**CAT 1**	**CAT 2**	All wind zones
PRE	13305 32.28 38.73 **80.45**	2403 5.83 45.45 **14.53**	831 2.02 52.73 **5.02**	16539 40.12
POST	21051 51.07 61.27 **85.3**	2884 7 54.55 **11.69**	745 1.81 47.27 **3.02**	24680 59.88
PRE and POST	34356 **83.35**	5287 **12.83**	1576 **3.82**	41219
Landscape	70811km **82.53**	13400km **15.62**	1585km **18.48**	85797km

Table 9 Contingency analysis of season by year

Zone	Season		PRE	POST
Domain	Fall	%	37.5	39.4
		N	*6197*	*9723*
	Winter	%	23.5	26.4
		N	*3894*	*6521*
	Spring	%	39.0	34.2
		N	*6448*	*8436*
TS	Fall	%	32.8	37.5
		N	*4361*	*7885*
	Winter	%	23.2	26.6
		N	*3084*	*5606*
	Spring	%	44.0	35.9
		N	*5860*	*7560*
CAT 1	Fall	%	59.1	53.5
		N	*1419*	*1542*
	Winter	%	22.4	22.6
		N	*539*	*653*
	Spring	%	18.5	23.9
		N	*445*	*689*
CAT 2	Fall	%	50.2	39.7
		N	*417*	*296*
	Winter	%	32.6	35.2
		N	*271*	*262*
	Spring	%	17.2	25.1
		N	*143*	*187*

Table 10- Contingency analysis of GLAS sampled land cover by wind zone vs. actual land cover by wind zone. Bold numbers represent the percent forest by wind zone.

Count/km^2 Total % Col % Row %	GLAS Forest	GLAS Non-forest	GLAS Total	Actual Forest	Actual Non- forest	Actual Total
TS	96695 57.57 83.62 **71.80**	37984 22.61 72.57 28.20	134679 80.18	70811 46.43 82.5 **59.72**	49774 32.63 74.6 41.28	120585 79.07
CAT 1	14850 8.84 12.84 **59.55**	10086 6.00 19.27 40.45	24936 14.85	13399 8.77 15.62 **51.39**	12673 8.31 19.00 48.61	26072 17.10
CAT 2	4087 2.43 3.53 **48.91**	4269 2.54 8.16 51.09	8356 4.97	1585 1.04 1.85 **27.13**	4258 2.79 6.38 72.87	5843 3.83
All	115632 **68.84**	52339 31.16	167971	85795 **56.26**	66705 43.74	152500

Table 11-Comparison between actual and GLAS sampled forest cover by wind zone

Wind Zone	Forest Class	LANDSCAPE AREA (KM2)	LANDSCAPE % of forest	GLAS Forest Type By Season and Year (%/N): ALL GLAS	ALL PRE	ALL POST	FALL PRE L3A	FALL POST L3D	WINTER PRE L3B	WINTER POST L3E	SPRING PRE L3C	SPRING POST L3F
TS	Evergreen	24253.6	**35.1**	34.1	35.7	33.1	40.2	32.4	35.8	32.4	32.3	34.3
				11709	4750	6959	*1752*	*2553*	*1105*	*1817*	*1893*	*2589*
	Mixed	10823.3	**15.7**	16.6	17.5	16.0	17.7	15.7	19.1	16.2	16.5	16.2
				5702	2331	3371	*773*	*1239*	*589*	*909*	*969*	*1223*
	Forested *Wetland*	19069.0	**27.6**	29.3	26.2	31.2	20.6	30.3	28.9	32.9	28.9	31.0
				10057	*3482*	*6575*	*900*	*2390*	*890*	*1844*	*1692*	*2341*
	Deciduous	15011.7	**21.7**	20.1	20.6	19.7	21.5	21.6	16.2	18.5	22.3	18.6
				6888	*2742*	*4146*	*936*	*1703*	*500*	*1036*	*1306*	*1407*
CAT1	Evergreen	*6094.5*	**45.5**	48.6	49.0	48.2	47.5	46.2	49.9	53.5	52.6	47.6
				2567	1177	1390	*674*	*713*	*269*	*349*	*234*	*328*
	Mixed	2094.0	**15.6**	17.4	18.1	16.9	20.7	18.4	17.4	16.7	10.8	13.6
				922	436	486	*294*	*283*	*94*	*109*	*48*	*94*
	Forested *Wetland*	*4386.6*	**32.7**	28.2	26.6	29.6	24.9	29.1	25.2	25.9	33.7	34.4
				1493	*639*	*854*	*353*	*448*	*136*	*169*	*150*	*237*
	Deciduous	824.7	**6.2**	5.8	6.3	5.3	6.9	6.4	7.4	4.0	2.9	4.4
				305	*151*	*154*	*98*	*98*	*40*	*26*	*13*	*30*
CAT2	Evergreen	880.2	**55.5**	57.0	55.7	58.5	57.6	55.4	53.1	59.5	55.2	62.0
				899	*463*	*436*	*240*	*164*	*144*	*156*	*79*	*116*
	Mixed	49.5	**3.1**	2.98	4.28	2.95	3.36	4.05	3.69	1.53	0.7	3.21
				47	*25*	*22*	*14*	*12*	*10*	*4*	*1*	*6*
	Forested Wetland	653.4	**41.2**	39.9	41.3	38.4	39.1	40.5	43.2	38.9	44.1	34.2
				629	343	286	*163*	*120*	*117*	*102*	*63*	*64*
	Deciduous	2.2	**0.1**	0.1	0.0	0.1	0.0	0.0	0.0	0.0	0.0	0.5
				1	0	1	*0*	*0*	*0*	*0*	*0*	*1*

Table 12 - FIA vs. GLAS sampling intensity

		FIA yearly sampling*				Forested GLAS Samples used in study**				
Wind zone	Forested Area (km)	subplots/ km^2	estimated subplots sampled (n)	total area sampled (km^2)	% forest area sampled	Year	n	shots/ km^2 forest/ yr	total area sampled (km^2)	% forest area sampled
ALL	85797	0.03333	2860	0.4576	0.00053	PRE	16539	0.1928	32.4742	0.0379
						POST	24680	0.2877	48.4590	0.0565
TS	70811	0.03333	2360	0.3777	0.00053	PRE	13305	0.1879	26.1243	0.0369
						POST	21051	0.2973	41.3335	0.0584
CAT 1	13400	0.03333	447	0.0715	0.00053	PRE	2403	0.1793	4.7183	0.0352
						POST	2884	0.2152	5.6627	0.0423
CAT 2	1585	0.03333	53	0.0085	0.00053	PRE	831	0.5243	1.6317	0.1029
						POST	754	0.4757	1.4805	0.0934

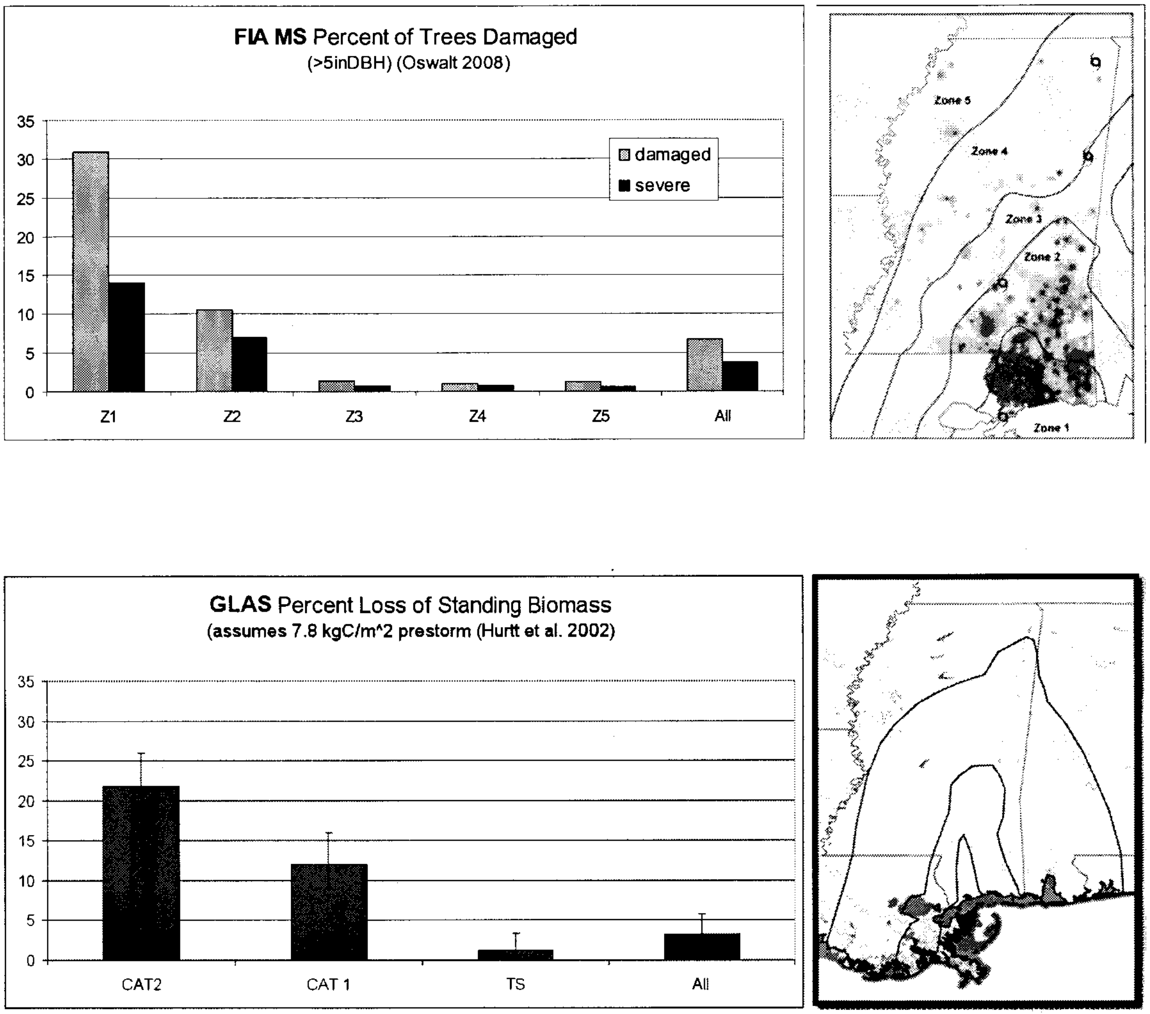

Figure 15- Comparison of percent of forest damaged as estimated in Oswalt 2008 with map of corresponding damage zones (above) to GLAS based estimates (bottom)