MODELING HURRICANE-CAUSED TREE DEBRIS IN HOUSTON, TEXAS

By

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To hurricane-affected communities and urban forest managers of the Southeastern United States

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Abstract of Thesis Presented to the Graduate School
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Local governments' estimations of post-storm vegetation debris in hurricane-affected areas of the Southeastern United States are limited by a lack of science-based hurricane planning and response tools. A stratified subset of permanent Urban Forest Effects (UFORE) research plots within the city of Houston, Texas, originally established in 2001 were selected for re-inventory and measurement of debris following Hurricane Ike which struck the Houston region on September 13th 2008. Three statistical models for estimating post-hurricane tree debris were developed. Model input parameters including variables characterizing urban forest structure, wind behavior and land cover were derived from the 2001 Houston UFORE dataset, the National Hurricane Center's H*Wind dataset, and the United States Geological Survey's National Land Cover Database, respectively. The statistical models estimate tree debris based on alignment of pre- and post-storm data in the region. Results of statistical modeling suggest that non-storm variables have greater influence over variation in debris estimates than storm-related variables. Land cover was tested as a proxy variable for pre-storm urban forest biomass and post-storm tree debris so that debris estimates stratified by land cover may be applied in cities without UFORE data. Estimates of pre-storm, urban

forest biomass were established to test the statistical relationship between pre-storm biomass and post-storm debris. Testing of both land cover as a proxy variable and the biomass-debris relationship were performed so that volumetric estimates of debris produced through statistical modeling may be simplified, spatially modeled to determine debris locations, and applied to other hurricane-affected cities in the Southeastern United States.

CHAPTER 1
INTRODUCTION

Literature Review

Hurricane impacts to forested landscapes consist of physical damages, socio-economic burdens, and ecological changes (Everham and Brokaw, 1996; Pielke and Landsea, 1998). Physical damages to forested landscapes include tree defoliation, breakage, and uprooting of individual trees (Foster and Boose, 1992; Francis and Gillespie, 1993; Duryea et al., 2007a; Duryea et al., 2007b). Damage to many trees across landscapes can result in stand-level or regional impacts (Foster and Boose, 1992; Stanturf et al., 2007; Oswalt and Oswalt, 2008) which result in both short and long term changes in ecological health, productivity, and structure of forested ecosystems (Foster and Boose, 1992; Everham and Brokaw, 1996; Stanturf et al., 2007). Landscape-scale disturbances obligate forest managers and communities with financial costs of damage mitigation and implementation of storm recovery efforts (Pielke and Landsea, 1998; Stanturf et al., 2007; Staudhammer et al., 2009).

Many studies of hurricane-forest interactions are based on a single event and are typically reviews of storm observations, post-storm assessments, evaluations of storm recovery processes, or a combination of these research approaches (Foster and Boose, 1992; Francis and Gillespie, 1993; Zimmerman et al., 1994; Everham and Brokaw, 1996; Pielke and Landsea, 1998; Batista and Platt, 2003; Tanner and Bellingham, 2006; Kupfer et al., 2008; Oswalt and Oswalt, 2008). Additionally, many studies focus on stand-level hurricane effects (Everham and Brokaw, 1996; Stanturf et al., 2007) and report impacts on forest ecosystem components (Francis and Gillespie, 1993; Everham and Brokaw, 1996; Kupfer et al., 2008; Oswalt and Oswalt, 2008). The extent and

severity of hurricane damages to forest ecosystems are affected by hurricane characteristics including size, speed, direction, maximum wind speeds and wind distribution patterns (Margoles and Umpierre, 2005; Stanturf et al., 2007; Kupfer et al., 2008; Escobedo et al., 2009). Complexities inherent to hurricane-generated winds result in variable patterns and scales of damages across landscapes (Tanner et al., 1991; Foster and Boose, 1992; Stanturf et al., 2007).

The literature offering insights into hurricane effects on forested landscapes may also be helpful for determining how urban trees respond to catastrophic winds (Duryea et al., 2007a; Duryea et al., 2007b). Few studies have investigated landscape-scale hurricane impacts to vegetation in urban landscapes (Everham and Brokaw, 1996; Duryea et al., 2007a; Duryea et al., 2007b; Burley et al., 2008; Escobedo et al., 2009; Staudhammer et al., 2009). Research has documented hurricane effects on specific trees and individual species within urban areas (Francis and Gillespie, 1993; Duryea et al., 2007a; Duryea et al., 2007b), yet it remains difficult to characterize urban landscapes with such data because variation in individual tree or species' specific hurricane responses at large spatial scales is unknown.

There is a growing scientific interest in the ecological functioning of urban ecosystems (Cadenasso et al., 2007) and that urban landscapes may be studied using similar methods to forested landscapes (Zipperer et al., 2000). Urban forest managers (e.g. planners or urban foresters) and researchers of urban forests have been successful in adapting forestry practices to the study and management of trees in urban areas (Nowak, 1993; Nowak et al., 1996; Nowak, 2002; Xiao et al., 2004; Myeong et al., 2006). An example of adapting forestry practices to urban landscapes comes from the

USDA Forest Service's Urban Forest Effects (UFORE) model (Nowak, 1993, 2006). The UFORE model's design and methods are based on those used by the USDA Forest Service's Forest Inventory Analysis (FIA) Program, which has been used to make landscape-scale assessments of forested ecosystems (Nowak, 1993; Kupfer et al., 2008; Oswalt and Oswalt, 2008). In addition, landscape-scale assessments of forested areas are often facilitated by Geographic Information Systems (GIS) (Nowak et al., 1996; Xiao et al., 2004; Myeong et al., 2006; Sales et al., 2007; Blackard et al., 2008; Hu and Wang, 2008; Oswalt and Oswalt, 2008). Methodologies such as extrapolations of ground-based data, statistical modeling, spatial interpolations, and modeling through combinations of related spatial datasets have been used by researchers to estimate biomass at large spatial scales (Sales et al., 2007; Zeng et al., 2007; Blackard et al., 2008; Hu and Wang, 2008). Emergency managers in Broward County, Florida, assert that spatial relationships between land cover and tree biomass can lend insights to locating areas of greater tree debris in the event of a hurricane (Margoles and Umpierre, 2005).

Studies suggest that classification of land cover is an effective way to represent the complexity and variability of urban landscapes (Anderson, 1977; Ridd, 1995; Cadenasso et al., 2007) and that degrees of vegetation cover in the landscape are important to development of land cover classifications that are ecologically relevant (Buyantuyev et al., 2007). Temporal and spatial distributions of trees and tree cover are influenced by land-use and land cover change throughout urban systems (Ridd, 1995; Nowak et al., 1996; Hu and Wang, 2008). Spatial distributions of trees as well as their

quantity, species composition, and dimensions are cited as principally important in describing urban forest structure (Xiao et al., 2004).

Urban forest structure is influenced by three main factors: complexities of urban landscapes' non-consecutive and variable land cover types; specific land uses within those cover types; and the natural environmental characteristics within and surrounding urban areas (Nowak et al., 1996; Xiao et al., 2004). Despite that many land cover and land-use classifications do not adequately convey the true ecological functioning of urban systems (Cadenasso et al., 2007), it remains important to quantify the complexities and heterogeneity of urban landscapes to accurately assess urban ecological functions (Cadenasso et al., 2007). Ecological integrity within and among land cover classes is of primary importance to the accuracy of ecological models applied to the landscape (Buyantuyev et al., 2007).

Positive correlations between tree damage and wind speed imply that hurricane damage to urban forests can be modeled (Duryea et al., 2007b). Kupfer et al. (2008) suggest that modeling of hurricane damage is possible in spite of an absence of fine-scale wind data. Others contend that any debris estimation method cannot easily, accurately, and consistently predict realistic results due to complexity and variation of damage-dependent variables (Stanturf et al., 2007). However, several models have been developed to estimate hurricane-caused tree debris (COES, 2005; Margoles and Umpierre, 2005; FEMA, 2006; Escobedo et al., 2009).

The Hazards U.S. Multiple Hazards (HAZUS-MH) model is disaster management and loss estimation software developed by the Federal Emergency Management Agency (FEMA). The hurricane module of the HAZUS model calculates estimates of

debris based on tree density and tree height data, and also incorporates spatial hurricane wind data from the National Hurricane Center's (NHC) H*wind Model. Based on a single study of wind-throw among Ponderosa Pine trees, the model assumes that all trees respond to wind uniformly (FEMA, 2006) and that only trees greater than 30 feet in height will generate debris (FEMA, 2006). In Virginia and North Carolina, this model over-estimated tree debris by roughly 90% and 41%, respectively (FEMA, 2006; Escobedo et al., 2009).

The United States Army Corps of Engineers developed a Hurricane Debris Estimating Model based on data collected from hurricanes Frederic[1], Hugo[2], and Andrew[3]. Model input values include the number of households within a given area, extents of vegetation cover, density of commercial development, precipitation, storm category according to the Saffir-Simpson scale, and wind speed (COES, 2005). Geographic Information Systems (GIS) are used to estimate wind speeds derived from meteorological data analyzed in 5-mile wide bands across hurricane-affected areas. This model has a reported accuracy of within +/- 30% (COES, 2005; FEMA, 2007).

The HurDET model was developed by emergency management staff in Broward County, FL in 2005 as a GIS-based decision support tool for managing hurricane debris. It estimates debris in three categories: building and construction, vegetation, and sediment from storm surge effects. The model incorporates spatial information from

[1] Hurricane Frederic made landfall near Mobile, Alabama on 12 September 1979 as a strong Category 3 hurricane on the Saffir-Simpson Scale and affected coastal areas of Alabama and Mississippi.

[2] Hurricane Hugo made landfall along the South Carolina coast on 21 September 1989 as a Category 4 storm on the Saffir-Simpson Scale.

[3] Hurricane Andrew made landfall on 24 August 1992 as a Category 5 Hurricane on the Saffir-Simpson Scale and caused widespread damage across Southern portions of Miami-Dade County, FL, before crossing over the Florida Peninsula to regain strength over the Gulf of Mexico and make a second landfall on the Louisiana coast on 26 August 1992 as a Category 3 hurricane on the Saffir-Simpson Scale.

seven different land cover classifications and organizes data at the level of county traffic analysis zones. This model categorizes debris according to assumed debris volumes per tree and assumed proportions of tree cover in hardwood trees versus palms. Results of this model vary based on assumed rates of impact on tree cover according to Saffir-Simpson storm categories (Margoles and Umpierre, 2005).

The Storm Damage Assessment Protocol—Florida Adaption (SDAP-FL) is a new extension of the Storm Damage Assessment Protocol (SDAP) included with the USDA Forest Service's tree inventory and management software package known as i-Tree Storms[4]. The Florida Adaptation is a Microsoft Excel-based tool completed in 2008 (Escobedo et al., 2009). It is based on a statistical analysis of tree debris data from project worksheets submitted to FEMA during the 2004-2005 Florida hurricane season (Escobedo et al., 2009). Due to its recent development this tool has not yet been tested with actual hurricane events.

Existing debris models, with the exception of the SDAP-FL, are empirical in nature and have not all been tested as predictive tools (COES, 2005; Margoles and Umpierre, 2005; FEMA, 2006; Escobedo et al., 2009). Additional scientific research at the landscape level is needed to guide management of trees and forests for hurricane effects at varying spatial scales (Stanturf et al., 2007). All existing models rely on spatial data (e.g. land cover or spatially-modeled wind data) to generate volumetric debris estimates, however none produce spatial estimates of debris (Margoles and Umpierre, 2005; FEMA, 2006; Escobedo et al., 2009).

[4] I-Tree is a software package developed by the USDA Forest Service which contains research-based tools used to analyze urban forests' structure and function and calculate monetary values for associated benefits.

Modeling of post-hurricane tree debris can improve efficiency of forest managers' response to hurricanes (Margoles and Umpierre, 2005; Stanturf et al., 2007). Improvements to storm response through debris prediction may include identification of equipment staging sites, location of debris collection centers, procurement of contractors, enlistment of additional human and labor resources, and estimation of costs associated with clean-up and disposal of hurricane debris (Margoles and Umpierre, 2005; Stanturf et al., 2007).

Resulting damages and associated costs of hurricanes can easily exceed US $1 million per community, per storm (Burban and Andresen, 1994; Pielke and Landsea, 1998). This includes damages to both private property and municipal infrastructure. Furthermore, clean up, mitigation, and recovery efforts require large investments in human resources, equipment rental, and contract work (Margoles and Umpierre, 2005). Estimated costs associated with Hurricane Katrina[5] totaled US $81 billion, making this event the most destructive natural disaster in the history of the United States (Oswalt and Oswalt, 2008).

Hurricanes generate hundreds of tons of vegetation debris that account for significant portions of total hurricane recovery costs (Margoles and Umpierre, 2005). Research on hurricane-affected Florida cities from the record-breaking 2004-2005 hurricane seasons showed that clean-up and disposal of vegetation debris cost communities between US $3,000 and $4 million. On average, the Florida communities

[5] Hurricane Katrina made landfall on 29 August 2005 as a Category 3 hurricane on the Saffir-Simpson Scale and affected coastal regions of the states of Texas, Louisiana, and Mississippi, only after skirting the Southeastern tip of Florida on 25 August 2005 as a weak Category 1 hurricane.

sampled as part of a study in 2008 spent US $704,045 per community, per storm for vegetation debris disposal (Staudhammer et al., 2009).

Local governments in the U.S. are responsible for assessing quantity of hurricane debris in units of cubic yards and debris disposal costs to meet requirements for reimbursement of Federal monies (FEMA, 2007). Communities must document debris and costs using standardized forms known as project worksheets to receive federal financial assistance (FEMA, 2007). Project worksheet records are also a data source for researchers investigating debris generation in urban areas affected by hurricanes (Escobedo et al., 2009; Staudhammer et al., 2009).

Urbanized regions of the Southeastern U.S. are annually threatened by hurricanes and tropical storms. In spite of hurricane frequency in this region, there is still a great need among local governments for hurricane planning and response tools that can be used to manage hurricane events (Burban and Andresen, 1994; Margoles and Umpierre, 2005). This need was realized in the aftermath of Hurricane Andrew in 1992, as plans to deal with hurricane damaged trees were lacking among municipal governments in Florida (Burban and Andresen, 1994).

Development of hurricane response tools is further supported by research that suggests hurricane events will likely increase in frequency and intensity throughout the coming decades (Pielke and Landsea, 1998; Balsillie, 2002). In addition, the Southeastern U.S. is one of the fastest growing regions of the United States (Campbell, 1997). Such rapid growth suggests that inherent risks to life and property from hurricane events will also increase as urbanizing areas of the Southeastern U.S. continue to develop (Pielke and Landsea, 1998).

Objectives

The objective of this thesis is to develop a model to estimate landscape-scale tree debris volumes in units of cubic yards/acre within urban, hurricane-affected ecosystems of the Southeastern U.S. This model and analysis can provide a framework and methods for developing a GIS based tool that communities can use to generate volumetric and spatial estimates of post-storm tree debris (See Appendix A). In addition to post-storm debris, estimates of interest include pre-storm urban forest biomass.

This study will develop a statistical debris model utilizing spatial data as model inputs. This research is unique in that it will investigate estimations of tree debris as a percentage of total pre-hurricane biomass to improve spatial estimates. To more accurately assess the distribution of pre-storm tree debris in cities' urban forests, relationships between tree biomass and land-cover will be examined.

Hypotheses

Two principal hypotheses guide this study:

- **Hypothesis 1**: Pre-storm tree biomass is positively and significantly correlated with post-storm tree debris.
- **Hypothesis 2**: Land cover data is a statistically significant proxy variable that characterizes pre-storm tree biomass and post-storm tree debris.

CHAPTER 2
METHODS

The first steps in this study were to simplify research goals through identification of data sources and opportunities for analysis. This study used urban forest data from hurricane-affected areas of the Southeastern U.S. to characterize urban forest variability. Urban Forest Effects (UFORE) data were available for the cities of Gainesville, Miami, Pensacola and Tampa, Florida (FL), and Houston, Texas (TX). Post-storm measurements of hurricane-caused tree debris were collected in Houston, TX, after the landfall of Hurricane Ike in 2008. Thus, alignment of pre- and post-storm data focused the investigation on the city of Houston, Texas.

Analysis for this project was performed using English units rather than Metric units because the dependent variable (e.g. debris) is reported to the Federal Emergency Management Agency (FEMA) in units of cubic yards (FEMA, 2006, 2007). Therefore, reporting estimates of debris using English units facilitates user-friendliness of proposed models and may increase models' appeal among potential U.S. users.

All spatial analysis procedures were performed with the software package ArcGIS 9.3 and the ArcGIS 9.3 Spatial Analyst extension. All statistical analyses were performed using the statistical analysis software SAS (version 9.1) and the statistical package R (version 2.9.1). In particular, the SAS procedure PROC GLM (General Linear Model) was selected due to the capacity of this procedure to incorporate and test categorical variables such as land cover.

Methods of analysis are based on those used by Oswalt and Oswalt (2008) in their investigation of forest damages in Mississippi caused by Hurricane Katrina in 2005. In this study, researchers visited permanent FIA plots to quantify the scope and extent of

damage to trees and forests. Data were then compiled at the plot level and interpolated spatially using GIS to generate maps of damage. Their results were assessed by comparing plots' pre-storm conditions with post-storm damage. Research by Kupfer et al. (2008) utilized methods similar to Oswalt and Oswalt (2008) but also introduced hurricane data, such as a variable for each plots' distance to the hurricane track and variables for wind speed, wind direction, wind steadiness, and wind duration, from the spatial dataset produced from the NHC's H*wind model. Methods associated with incorporation of USGS land cover data to estimate biomass (and thereby estimate debris according to Hypothesis 1 of this research) at large spatial scales are based on citations from Blackard et al. (2008).

Data Collection

Four spatial datasets contain variables used in this investigation.

Dataset 1: 2001 Houston UFORE data

These data represent pre-storm variability of the Houston area's regional urban forests. The following tree-level and plot-level variables were collected:

- Plot location data: geographic coordinates of plot centroid, street address, and distance & direction measurements to permanent reference objects such as fire hydrants, streetlights, or corners of buildings for plot re-location purposes
- Land use category (as defined by data collectors)
- Distribution of plot surface covers: % cement, % asphalt, % pervious rock, % maintained grass, % unmaintained grass, % shrub, % tree, % duff/mulch, % herbaceous, % water
- Tree measurements: species, # of stems, number of trees, diameter at breast height (DBH; 4.5 feet), height, crown dimensions, % missing, % dieback, crown light exposure, distance & direction from plot center

The research area was defined as the eight Texas Counties surrounding the Houston metropolitan area (Figure 2-1) which were in non-attainment of the Environmental Protection Agency's (EPA) minimum thresholds for air quality established by the Clean Air Act of 1970 (Merritt, 2009, personal communication). Results of the study were intended to demonstrate importance of urban trees to air quality and classify urban trees as options for reducing air pollution in State Implementation Plans, as outlined in section 110 of the Clean Air Act (Merritt, 2009, personal communication.

A UFORE study typically consists of 200 randomly-located 0.1 acre circular plots within research areas most often defined by political boundaries (Nowak, 2002). Furthermore, woody shrubs and trees with DBH greater than 1" are considered trees and measured for inclusion in the data (Nowak, 2002). The Houston study however did not utilize typical UFORE design elements (Nowak, 2005). Under a modified UFORE protocol, the Houston study implemented 332 systematically-located 0.6 acre circular plots throughout the study area (Nowak, 2005). The study area was divided into a systematic grid and four discrete points were randomly located within each square of the grid (Merritt, 2009, personal communication). In urban areas, three of four points/grid square were randomly selected as UFORE plot centroids; in suburban areas, two of four points/grid square were randomly selected as UFORE plot centroids; and in rangeland/agricultural areas, one of four plots/grid square was randomly selected as a UFORE plot centroid (Merritt, 2009, personal communication). In addition, since the plots were increased in size from 0.1 to 0.6 acres, only trees with DBH greater than 5" were measured to increase the speed and efficiency of data collection (Nowak, 2005;

Merritt, 2009). To capture variability of small trees (<=1" diameter to >5" diameter), a 0.075 acre micro-plot was randomly located within each UFORE plot (Nowak, 2005).

The UFORE model outputs from the 2001 study consist of various measured and estimated urban forest structure and function variables. For each tree on each plot, UFORE outputs include: species, diameter (cm), height (m), condition (e.g. "good", "fair", "poor"), leaf area (m2), leaf biomass (kg), carbon sequestration (kg/year), carbon storage (kg), tree value (U.S.D), notation if tree was located along a street, and notation if tree was a native species (Nowak, 2002).

UFORE data were used in this analysis based on its documented common use in other studies of urban forests (Nowak, 2002, 2006) and because of its similarity to data, objectives, and methods used by the Oswalt and Oswalt (2008) study.

Dataset 2: Post-Ike 2008 Houston UFORE and debris data.

This dataset included volumetric measurements of post-storm[6] tree debris in addition to the following tree- and plot-level variables, collected according to methods used in the 2001 Houston UFORE study:

- Plot location data: geographic coordinates of plot centroid, street address, distance & direction to permanent reference objects
- Tree-level variables: species, # of stems, # of trees, diameter, height, crown dimensions, crown light exposure, % of crown damage, % of defoliation, notation of wind damage and distance & direction from plot center
- Plot level-variables: % Tree Cover and %Palm Cover
- Plot-level measurements of tree debris volumes

[6] Hurricane Ike made landfall along the Texas coastline on 13 September 2008 as a strong Category 2 Hurricane on the Saffir-Simpson Scale and affected local communities throughout the greater Houston metropolitan area.

These data were collected in October and November 2008, approximately one month after Hurricane Ike made landfall. A stratified random subset of treed UFORE plots (roughly 10% of the original plots measured) were selected for re-inventory and measurement of on-the-ground tree debris. The process of plot selection for re-inventory was two-tiered. Plots with at least one tree greater than 20' in height and within 15m of a building were selected in the first tier. This selection of plots was mainly located west of the storm track and clustered within Houston city limits. A second tier was selected to better represent the geographical distribution of plots in relation to the path of the storm. Criteria for the second tier of plots dictated that selected plots must have at least one tree greater than 20' but also be distributed east of the storm track or outside the Houston city limits. Plots problematic to revisit due to access or safety issues, plots severely damaged by hurricane storm surge effects, or plots having undergone major land-use change between 2001 and 2008 were eliminated from the selection of re-measurement plots according to expertise and consultation provided by the Texas Forest Service (Merritt, 2009). As a result of this process, thirty-four plots were re-inventoried and analyzed (Figure 2-1).

Dataset 3: NOAA NHC H*Wind data

These data were produced by the National Hurricane Center (NHC) at the National Oceanographic and Atmospheric Administration (NOAA) to model behavior of hurricane winds at varying spatial scales. The H*Wind model estimates hurricane wind behavior and assigns estimates to discrete spatial locations across landscapes (Powell et al., 1998; Powell et al., 2004). Estimates of winds' behavior are based on analyses of data from aircraft flyovers, ships, ground-based towers, and research buoys located across spatial and temporal extents of Atlantic tropical cyclones (Powell and Houston, 1996;

Powell et al., 2004). Datasets produced by the H*Wind model are developed in conjunction with NHC forecast periods, which take place every six hours while storms are over open ocean and every three hours once a storm makes landfall (Powell and Houston, 1996; Powell et al., 1998; Powell et al., 2004).H*Wind variables include:

- Maximum sustained surface wind speed (in m/s, knots, and mph).
- Wind direction (in degrees)
- Wind steadiness (indexed value, 0-1)
- Wind duration (in minutes)

Maximum sustained surface wind speed refers to winds blowing at a consistent rate of speed for a minimum of one minute, at a distance of 10 meters from the ground surface (Powell et al., 2004). The threshold of one minute is a standard measure used by the NHC to designate wind speeds of tropical storms and hurricanes. Wind speed rates are reported in three units: meters/second, knots, and miles/hour. The direction variable reports direction of the maximum sustained winds at the time they were recorded (Powell et al., 2004). Steadiness values measure consistency of the maximum sustained winds' direction for all recorded wind speeds. This variable is more specifically defined as the variation in directional change from mean wind directions over the course of the storm, where low values indicate increased variation in wind direction compared to high values which indicate relative wind steadiness (Powell et al., 2004; Kupfer et al., 2008). Duration refers to the amount of time maximum winds were blowing at the time they were recorded, however duration values are only assigned to H*Wind data points for modeled wind speeds greater than the minimum wind speed threshold for designation as a category 1 hurricane on the Saffir-Simpson scale (e.g. 74 mph).

The H*Wind data are spatially expressed as a grid of points. Modeled values for each of the four variables listed above are attributed to each point on the grid. A combined dataset is produced at the conclusion of the storm that contains maximum values for each point of the grid recorded throughout the storm's duration (Powell et al., 2004). This output of H*Wind data was used to characterize storm winds for analysis of tree debris caused by Hurricane Ike (Figure 2-2). Alternatively, the user could determine which forecast period dataset would be best for use in the debris estimation model; however, the latter option was deemed more appropriate for this project. The H*Wind data were specifically included in this study based on methods of Kupfer et al. (2008). Use of this dataset is further supported by its incorporation with the HAZUS-MH hurricane module. Also, in general, H*Wind data were selected to characterize hurricane wind behavior according to the assumption that wind behavior is partly responsible for damage to urban vegetation (Duryea et al., 2007a).

Dataset 4: USGS NLCD 2001 Land Cover data

These data are produced by the United States Geological Survey's (USGS) National Land Cover Dataset (NLCD) (Homer et al., 2007). This dataset classifies land cover across the geographical extent of the United States, including Alaska and Hawaii. Land cover classifications are represented by $30m^2$ rasterized pixels and were developed according to alignment among several datasets including multi-seasonal Landsat 5 and Landsat 7 satellite imagery, Forest Inventory & Analysis (FIA) data from the USDA Forest Service, crop land data from the National Agricultural Statistics Service, and ancillary data including maps, orthoimagery, and the 1992 USGS National Land Cover Dataset (Homer et al., 2007).

Five of sixteen land cover classifications within the eight-county research area were sampled for this study (Table 2-1). The five sampled land covers were: Developed High Intensity (DH), Developed Medium Intensity (DM), Developed Low Intensity (DL), Developed Open Space (DO) and Woody Wetlands (WW). These land covers were classified based on alignment with locations of post-storm re-measurement UFORE plots and represent a clear majority of the land area within Houston City Limits (Figure 2-3).

USGS land cover data were incorporated in the analysis to represent variation across urban landscapes (Anderson, 1977; Ridd, 1995; Cadenasso et al., 2007) and to test the hypothesis that land cover can be used as a proxy variable to characterize pre-storm biomass and post-storm debris in urban forests (Hypothesis 2) based on alignment with 2001 Houston UFORE data. This land cover dataset is appropriate because it is standardized across broad regions, readily available, and free to download from the USGS NLCD Multi-zone Download Site (www.mrlc.gov/nlcd_multizone_map.php).

Synthesis of Datasets

Spatial data for County and City boundaries were downloaded from the Texas General Land Office (www.glo.state.tx.us), which is the State of Texas' clearinghouse for GIS data. Counties of interest included Brazoria, Chambers, Fort Bend, Galveston, Harris, Liberty, Montgomery, and Waller (Nowak, 2005). City limits of interest were those for the City of Houston. County data were used to spatially identify the study area and the Houston city limits layer was used to facilitate comparisons of model results with project worksheet data. Data were displayed in Albers projection using North

American Datum 1927; this datum and projection is used by the Texas General Land Office to represent data layers of Texas' counties and cities.

The USGS land cover Region 10 raster dataset was downloaded and extracted using the research area data layer as a mask to isolate land covers of interest. Land covers were then assigned to re-measurement UFORE plots by extracting land covers' raster cell values to points representing the plots. This procedure appends land cover attributes to UFORE plot data.

The most common land covers included: Woody Wetlands (WW); Developed Open Space (DO); Developed Low Intensity (DL); and Developed High Intensity (DH). Four plots were found to have land covers different from the four previously listed. In these cases, one of the common land covers (WW, DO, DM, DL) found to be directly adjacent was re-assigned to re-measurement UFORE plots based on proximity. The intent of this procedure was to limit the number of land covers included in the analysis. Although reducing the number of categories can reduce model precision, a categorical variable such as land cover reduces the experimental error degrees of freedom by one for each category, thus minimizing categories can have a mitigating effect of increasing the sensitivity of statistical tests. Moreover, with four plots having unique land covers, a perfect correlation would be made between the dependent variable (debris) and the explanatory variable of land cover. This is neither realistic nor practical for developing a sound statistical model.

Hurricane wind attributes were also assigned based on proximity to re-measured UFORE plots. The grid of H*Wind data points was overlain with the re-measurement UFORE plot layer. A join operation was performed to append H*Wind attributes to

UFORE data based on the shortest distance between re-measurement UFORE plots and the nearest H*wind data point. The “distance-to-track” variable was derived by first downloading a layer of points representing the official forecast track of Hurricane Ike made available by the NHC through their website (Kupfer et al., 2008). A smoothed line connecting each of the points representing the hurricane track was generated; this created the best estimate of the storm’s track. Once overlain with UFORE points, the ArcGIS Near tool was used to determine proximities of each plot to the storm track. Plot-to-track distance measurements were then appended to UFORE data.

Results of GIS procedures listed above include an attribute table for 2008 UFORE plots containing data on debris volume, land cover, and wind characteristics. These data were concatenated with pre-storm data summarized at the plot level from the 2001 Houston UFORE study. Three steps were taken to summarize 2001 dataset at the plot-level. First, all trees with DBH less than 5” were eliminated from the dataset since these small trees were recorded only within 0.075 acre micro-plots during the 2001 survey. Although this posed a problem for summarizing plot variables because not all trees could be accounted for, elimination of these data is supported by results of Duryea et al. (2007a) which indicate that small trees are not responsible for significant hurricane damage in urban forests (Duryea et al., 2007a). Second, all but 34 plots re-measured in 2008 were eliminated from the 2001 UFORE dataset to align pre- and post-storm data. Results of these procedures reduced 2001 UFORE data to trees with DBH >= 5” within 34 UFORE plots representing 2008 post-storm debris measurements. Thirdly, 2001 UFORE variables were summarized by calculating the total number of trees; average

DBH; average height; and total carbon storage per plot. Carbon storage was then mathematically converted to fresh weight biomass.

Carbon storage as estimated by the UFORE model can be used to determine biomass. Tree biomass is not estimated by the UFORE model however the UFORE model calculates biomass as part of the process of calculating carbon storage (Nowak, 2002). Carbon storage is determined by multiplying dry-weight biomass values by 0.5 (Nowak, 1993; McPherson, 1994; Hu and Wang, 2008). Thus, UFORE outputs of carbon storage were converted to dry-weight biomass values by multiplying carbon storage outputs by two. Hurricane-caused tree debris however, will be fresh weight rather than dry weight (FEMA, 2007). To obtain values for fresh-weight biomass, the dry-weight biomass values require an additional multiplication of two (Nowak, 1993; McPherson, 1994). To generalize relationships between carbon storage, dry weight, and fresh weight, stored carbon is roughly 25% of trees' total weight and dry weight reflects roughly 50% of trees' total weight.

A master dataset was constructed from plot-level tree, land cover, wind behavior, and distance-to-track variables. This dataset included fields for: plot identification #, debris (in cubic yards), average tree diameter (in inches), average tree height (in feet), total number of trees, total tree biomass (in pounds/plot), percent tree cover, land cover classification, maximum surface wind speed (in mph), wind steadiness (indexed value), wind duration (in minutes), and distance-to-track (in miles). Debris volumes collected from the 2008 re-inventory were used as the dependent variable in statistical analyses; plot-level variables as described above were used as explanatory variables.

Average diameter and average height variables were included for statistical analysis based on literature that shows strong correlations with tree biomass (Jenkins et al., 2003), especially at large spatial scales (Sales et al., 2007; Blackard et al., 2008). Tree biomass was included for analysis based on the assertion that carbon storage is highly correlated with tree and forest inventory measurements such as tree height and diameter (Jenkins et al., 2003) and is influenced by natural disturbances such as hurricanes (Jenkins et al., 2003). The number of trees per plot and percentage of tree cover were included for analysis according to findings that measures of density help to explain urban forest structure (Xiao et al., 2004) and might be statistically significant predictors of hurricane-caused tree damages and associated debris (Stanturf et al., 2007; Escobedo et al., 2009). Other UFORE variables such as tree crown dimensions, tree condition, percentage of missing foliage, and type and percentage of surface covers were excluded from analysis due to a lack of evidence in the literature demonstrating landscape-scale relationships between these variables and either biomass or damage and debris estimation, especially in urban landscapes (Francis and Gillespie, 1993; Everham and Brokaw, 1996; Jenkins et al., 2003; Sales et al., 2007; Duryea et al., 2007a; Duryea et al., 2007b; Blackard et al., 2008; Kupfer et al., 2008; Oswalt and Oswalt, 2008).

Also excluded from analysis was the wind direction variable from H*Wind data. Significance associated with wind direction is specifically related to the unique angle and direction of Hurricane Ike's track in relation to the City of Houston's orientation to the Gulf coastline. The statistical transferability of this variable to other cities is therefore inappropriate. The wind duration variable from the H*Wind dataset was also

dropped from the analysis because duration values were only assigned to H*wind data points with modeled wind speeds greater than the Saffir-Simpson category 1 threshold of 74 mph (Powell et al., 1998; Powell et al., 2004). Nine of 34 re-measurement UFORE plots were assigned to H*Wind data points with wind speeds estimated to be less than 74 mph and therefore had no assigned value for duration. Any tree damages experienced in conditions of non-hurricane force winds cannot use duration as an explanatory variable for variation of debris estimates.

The distance-to-track variable was incorporated based on Kupfer et al. (2008) in their use of this variable to model hurricane damage in Mississippi's DeSoto National Forest after Hurricane Katrina in 2005. Land-use data was excluded from analysis in favor of land cover data because classifications of land use are socially and politically applied, whereas land cover classifications are applied based on observations (Ridd, 1995; Cadenasso et al., 2007).

Statistical Procedures

A scatter matrix was generated in SAS for non-categorical variables used in this study to look for relationships between and among the data. A subset of these graphs is shown in Figure 2-4.

Exploratory data analysis included descriptive statistics (Table 2-2.) and diagnostic tests (including those for Cook's D, DFFits, DFBetas, and Studentized Residuals performed in R, version 2.9.1) which highlighted outlying observations. In a comparison of strictly numerical variables, the debris value of one observation (observation # 34) appeared to be an outlier in the dataset. However considering it in context of other explanatory variables, this observation was within an acceptable statistical range for its "Woody Wetlands" land cover class. Woody Wetlands was the land cover class

characterized as having the highest average debris volume, and the plot itself was located east of the hurricane track and just outside of Ike's radius of maximum winds (National Hurricane Center, 2008) in the far northwest corner of Liberty County. The plot experienced 80-90 mph winds on average according to the H*Wind dataset.

Examination of the scatter matrix revealed no obvious relationships between any of the non-categorical variables and debris. This could imply that more post-storm data should be collected for future analyses or that other variables need to be sought out and tested. This could also imply that a complex multivariate relationship exists between groups of two or more explanatory variables which cannot be captured in a two-dimensional graph.

An algorithm was employed with the statistical analysis software R (version 2.9.1) to identify variables most desirable for inclusion as model inputs based on four statistical criteria: R^2 values, Adjusted R^2 values, Mallow's CP criteria, and Akaike's Information Criteria (AIC). This analysis cannot accommodate categorical variables and land cover was therefore not included.

Comparisons of variables selected through tests of these criteria reveal that number of trees, average diameter, average height, tree biomass, % tree cover, distance to the hurricane track, wind steadiness, and maximum wind-speed are significant variables for use as model inputs. Results reported below represent this subset of quantitative variables:

- CRITERIA "R^2": R^2-value = 0.4873
- CRITERIA "ADJUSTED R^2": Adjusted R^2-value = 0.3512
- CRITERIA "Mallow`s Cp": Cp-value = 8.02
- CRITERIA "AIC": AIC-value = 62.47

To further identify specific variables for inclusion in a statistical model, a stepwise regression analysis was used to systematically eliminate variables according to their contributions to explanations of debris estimates' variability. After performing statistical analyses using all selected variables in a "Full" model, this model is sequentially re-run after eliminating the variable with the lowest subsequent contribution to variability of estimates. This process is repeated until measures of model performance (e.g. R^2 and Root Mean Square Error values) stabilize.

Verification and Comparison of Results

Completion of a statistical model provides the opportunity to create plot-specific, volumetric estimates of debris by applying the model to 2001 Houston UFORE plots. . Spatial estimation of debris across the Houston city landscape is possible by spatially interpolating measured plot-specific volumetric debris estimates. In addition to estimates of debris, measurements of debris recorded during the 2008 post-storm re-measurement of Houston UFORE plots and biomass estimates derived from 2001 Houston UFORE plots can also be spatially interpolated so that visual comparisons can be made between:

- Pre-storm (2001) biomass and measured post-storm debris
- Pre-storm (2001) biomass and statistically modeled post-storm debris
- Measured post-storm debris and statistically modeled post-storm debris

All spatial interpolations were first conducted using pre- and post-storm data from the 34 plots re-measured in 2008. Interpolations performed using these plots could then be more accurately compared. Post-storm debris values per plot (both measured and modeled) were subtracted from pre-storm biomass values to obtain a mathematical

estimate of the mean differences between pre-storm biomass and post-storm debris in units of cubic yards.

Additional interpolations of biomass and modeled debris were performed using all 348 original (2001) UFORE plots. The proposed model is based upon five distinct land cover classifications within the Houston city limits. Debris estimates for unsampled land covers were assigned in two ways: 1.) unsampled land covers having measured UFORE plot values for average tree DBH and height were assigned the mean value of sampled land cover parameter values; or 2.) unsampled land covers without measured UFORE plot values for average DBH and height (e.g. UFORE plots without trees) were assigned a debris value of zero.

Performing interpolations using all plots provided more accurate visual estimates of debris. These interpolations also more accurately characterized debris within the Houston city limits so that comparisons could be made with other derived debris values such as a mathematical extrapolation based on mean plot debris values, project worksheet records of total debris removed, and results of other debris models applied to the study area. A comparison with actual project worksheet records from the City of Houston was used to verify the proposed model results, as project worksheet data submitted to FEMA represent the official record of debris removed by the City of Houston. Other model results for comparison were those from the U.S. Army Corps of Engineers' Hurricane Debris Estimating Model and the Storm Damage Assessment Protocol—FL Adaptation. Comparisons of proposed model results with other debris models applied to the study area might indicate which model most closely estimates

project worksheet recorded post-hurricane tree debris in Houston, Texas as a result of Hurricane Ike.

The United States Army Corps of Engineers' Hurricane Debris estimating model requires as inputs a base value for the number of households and multiplier values for the following: debris (in cy) as indexed by Saffir-Simpson storm category, vegetation as indexed by density, commercial/industrial development as indexed by density, and storm precipitation as indexed by quantity. The number of households in the City of Houston, TX is roughly 718,000 according to United States 2000 Census data. The multiplier values are pre-determined by the model but the user can select which of those values to use. Eight cubic yards was selected as the debris multiplier based on the designation of Hurricane Ike as a Category 2 hurricane on the Saffir-Simpson scale. Median values of 1.3 and 1.2 were selected as multiplier values for vegetation and commercial/industrial densities, respectively, to account for variation amongst these categories across the Houston city landscape. A storm precipitation multiplier of 1.3 for medium-high precipitation was selected based on documentation of rainfall amounts from Hurricane Ike (National Hurricane Center, 2008)

The Storm Damage Assessment Protocol – Florida Adaptation requires only the total number of street miles and a user-defined designation of the storm event's severity and subsequent debris generating capacity, referred to as "debris rate". The total number of street miles in Houston was determined to be roughly 8,107 according to geo-spatial roads data for the City of Houston, Texas obtained from the Texas General Land Office. The user-defined debris rate was set to each possible value of "medium", "low" and "high" to compare with results of other models.

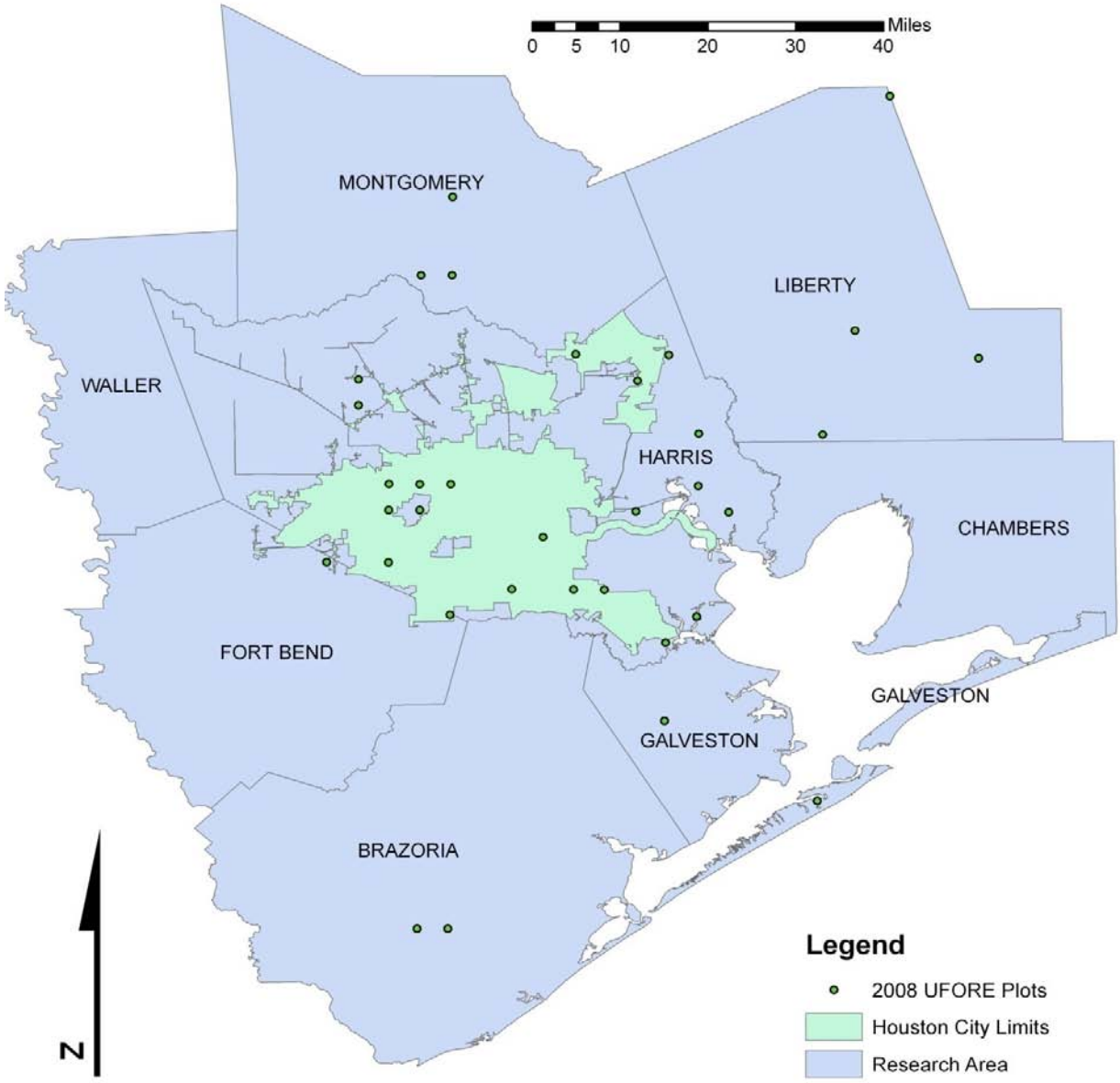


Figure 2-1. Research area and 2008 re-measurement UFORE plots

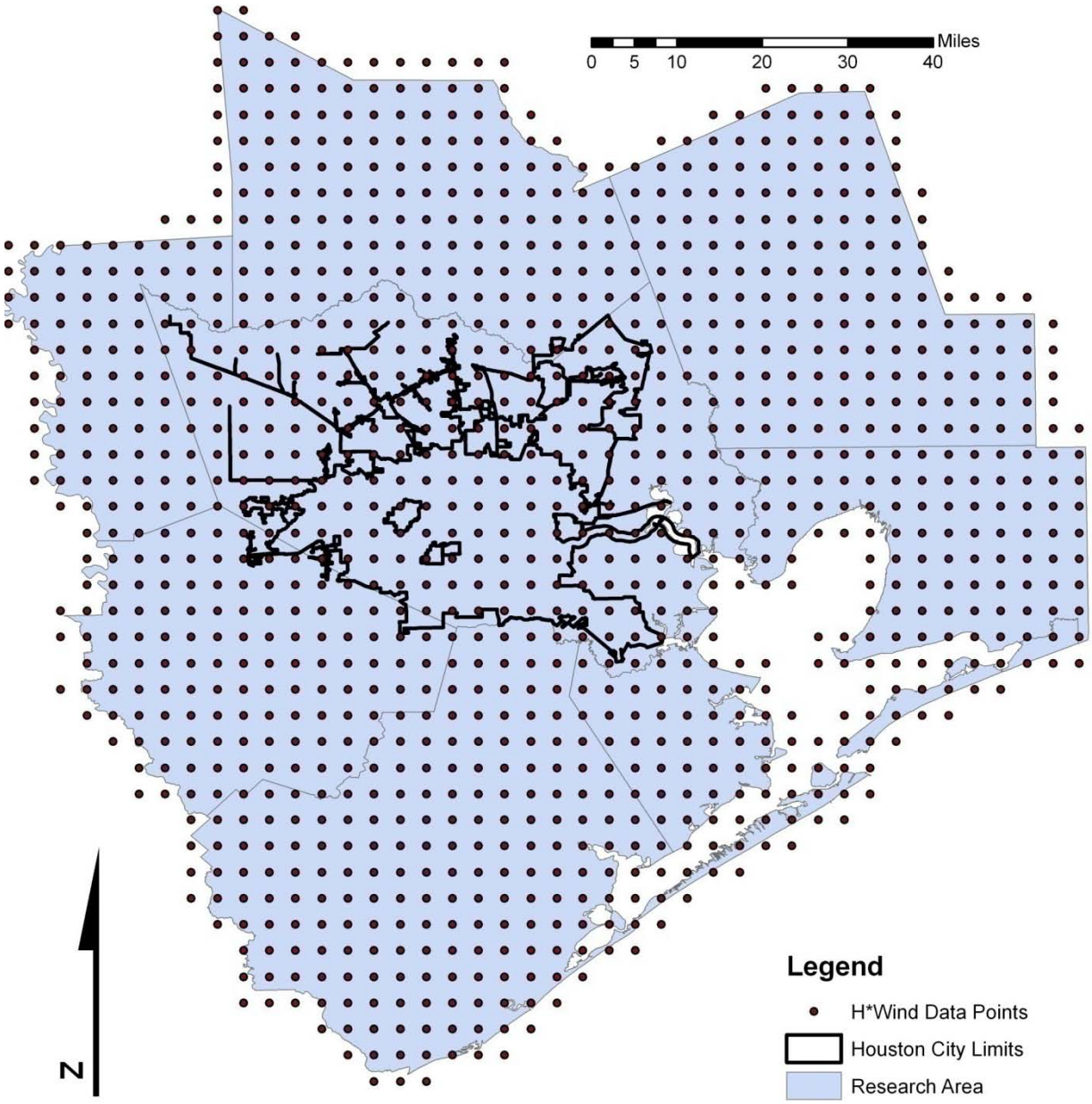


Figure 2-2. H*Wind model gridded points data for the greater Houston area

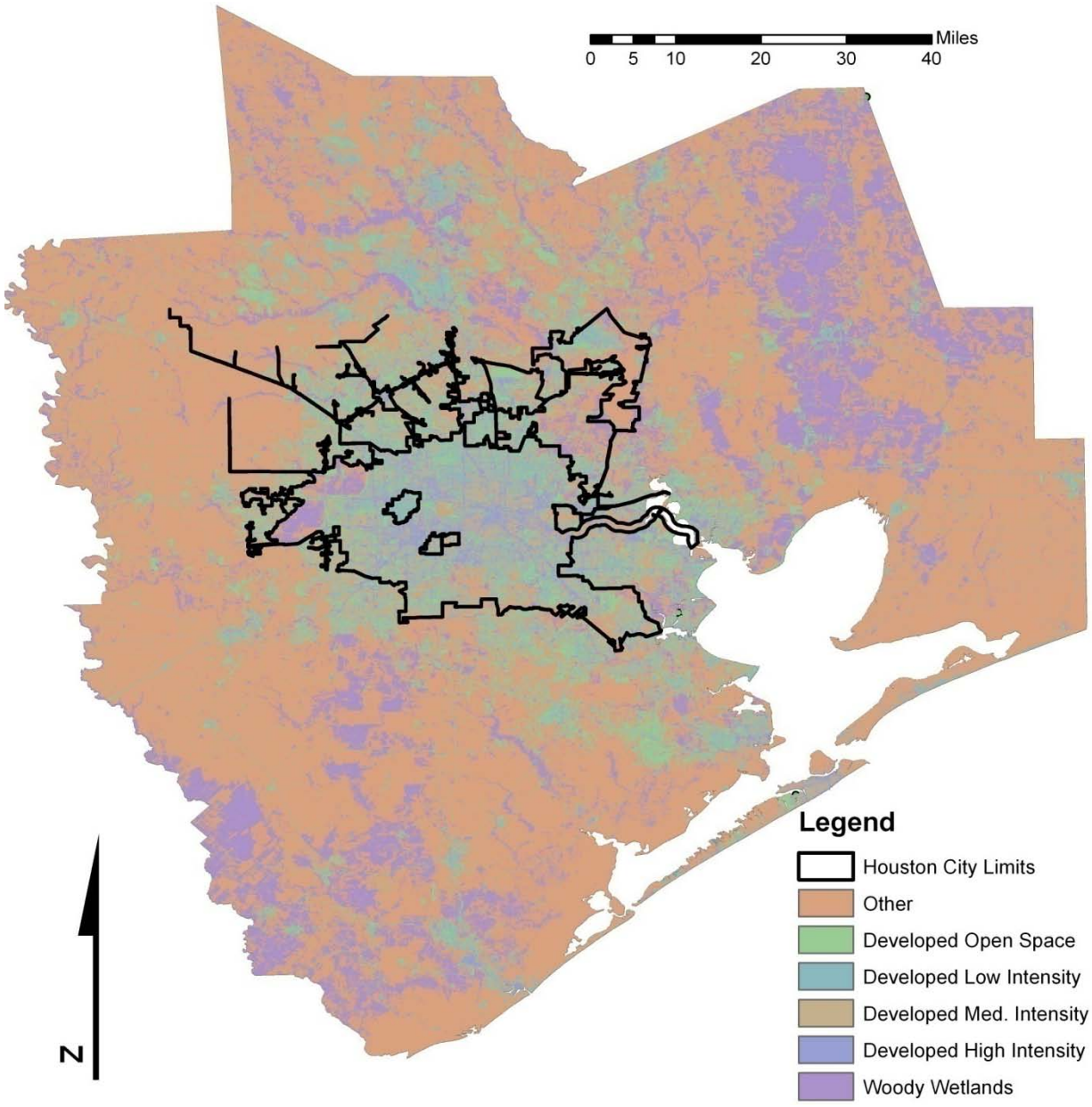


Figure 2-3. Sampled land covers in the greater Houston area including developed open space, developed low intensity, developed medium intensity, developed high intensity, woody wetlands, and other (note:“other” represents all un-sampled land cover classes)

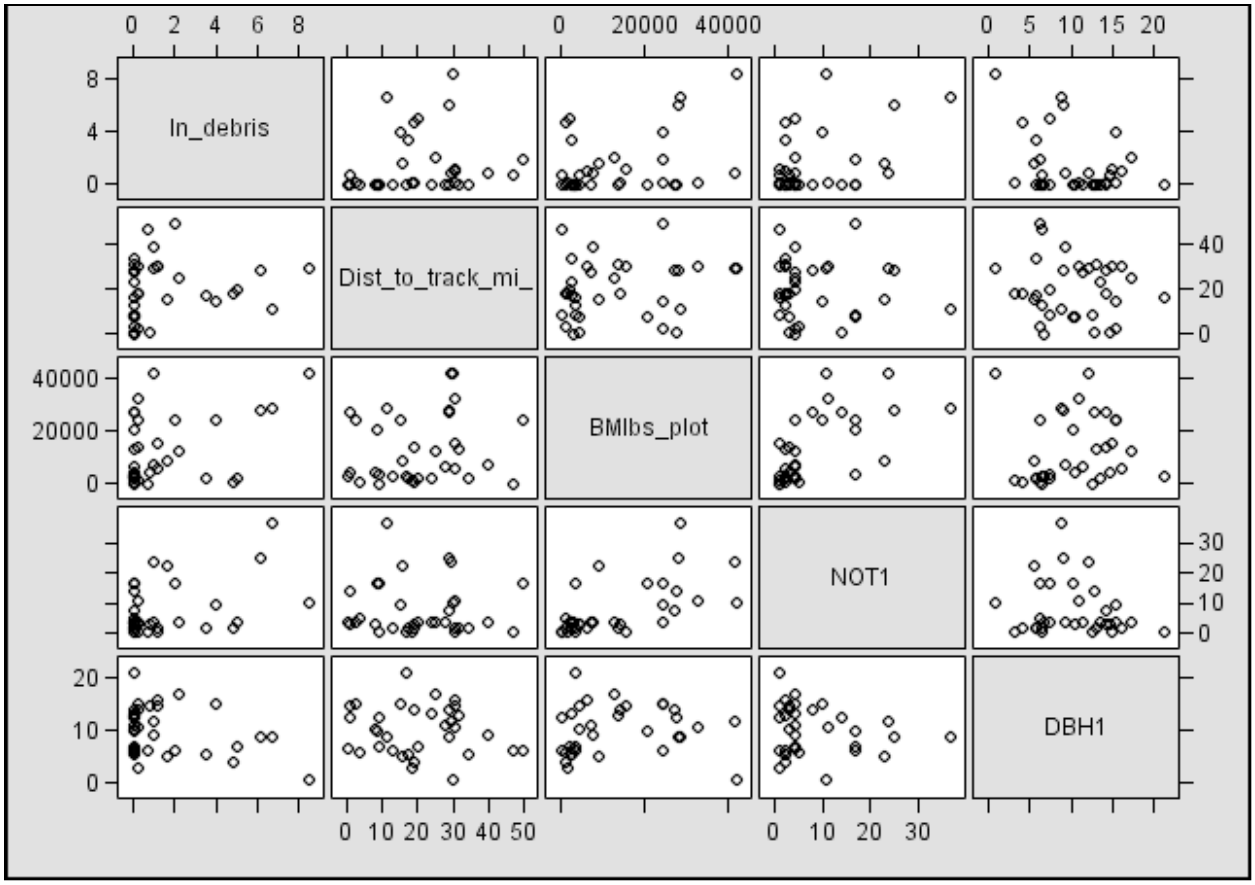


Figure 2-4. Scatter matrix of the dependent variable and a sample of explanatory variables. ln_debris is the log-transformed dependent variable, debris. Explanatory variables include: distance to the hurricane track = dist_to_track_mi_; biomass = bmlbs_plot; number of trees = not1; and diameter = dbh1.

Table 2-1. Descriptions of sampled USGS land cover classifications

USGS land cover classification	Descriptions of USGS land cover classifications
Developed open space	Includes areas with a mixture of some constructed materials, but mostly vegetation in the form of lawn grasses. Impervious surfaces account for less than 20 percent of total cover. These areas most commonly include large-lot single-family housing units, parks, golf courses, and vegetation planted in developed settings for recreation, erosion control, or aesthetic purposes
Developed low intensity	Includes areas with a mixture of constructed materials and vegetation. Impervious surfaces account for 20-49 percent of total cover. These areas most commonly include single-family housing units.
Developed medium intensity	Includes areas with a mixture of constructed materials and vegetation. Impervious surfaces account for 50-79 percent of the total cover. These areas most commonly include single-family housing units.
Developed high intensity	Includes highly developed areas where people reside or work in high numbers. Examples include apartment complexes, row houses and commercial/industrial. Impervious surfaces account for 80 to100 percent of the total cover.
Woody wetlands	Areas where forest or shrubland vegetation accounts for greater than 20 percent of vegetation cover and the soil or substrate is periodically saturated with or covered with water.

Table 2-2. Descriptive statistics of variables selected for analysis of post-storm effects from hurricane Ike on Houston Texas' urban forests.

Statistic	Measured post-storm debris (cy/ac)	# of trees*	DBH (in)	Height (ft)	Distance to hurricane track (mi)	Pre-storm tree biomass (cy/ac)	Tree cover (%)	Wind speed (mph)	Wind steadiness (indexed value, 0-1)
Minimum	0.00	1.00	6.18	11.00	0.03	12.08	5.00	64.37	0.11
Maximum	5007.98	32.00	29.60	83.00	49.88	42273.73	90.00	87.29	1.00
Mean	197.77	7.53	12.76	38.51	20.42	13035.25	37.97	78.23	0.33
Median	0.25	4.00	12.43	33.75	18.79	7300.83	35.00	79.60	0.34
Standard deviation	865.86	7.94	4.92	16.72	13.06	12686.00	26.59	5.96	0.17

*Per 0.6 acre Urban Forest Effects plot

CHAPTER 3
RESULTS

Debris Models

Three statistical models of debris were developed. Models are referred to hereafter as the Full, Final, and Alternate Model. The Full Model includes all variables selected for analysis including land cover (e.g. categorical variable), distance to the hurricane track, number of trees, tree biomass, tree diameter, tree height, % tree cover, maximum wind speed, and wind steadiness. The Final Model was derived from the Full Model, selecting only those predictor variables that contributed significantly or contributed to model stability. The Alternate Model is a competing model which uses variables from each of the datasets to explain variability of debris. Variables tested are detailed in Table 3-1.

Full Model

> Log of Debris = -0.64 + Land cover (DL=-3.07; DM=-2.84; DO=-4.59; WW=0.00)) + Distance to hurricane track*-0.04 + Biomass*-0.00003 +# of trees*0.06 + Tree diameter*-0.13 + Tree height*0.06 + % Tree cover*-0.02 + Wind speed*0.05 + Wind steadiness*3.70

This model produced an R^2 value of 0.59; the independent variables explain 59% of the variation in the dependent variable (log of debris). This model also has a Root Mean Square Error (RMSE) of 1.78. According to measures of significance outlined in the Analysis of Variance table (Table 3-2) for the Full Model, Land cover and height are the most significant variables (alpha<0.10) explaining variation in debris.

Final Model

> *Log of Debris = 5.08 + Land cover (DL=-3.31; DM=-3.00; DO=-4.89; WW=0.00) + Distance to hurricane track*-0.04 + Tree diameter*-0.17 +Tree height*0.06*

The Final model produced an R^2 value of 0.53; independent variables explain 53% of the variation in the dependent variable (log of debris). This model has a Root Mean Square Error (RMSE) of 1.74, slightly less than that of the Full Model. According to measures of significance outlined in the Analysis of Variance table (Table 3-3) for the Final Model, Land cover, height, and DBH (Alpha<0.10) are the most significant variables explaining variation in debris.

Alternate Model

*Log of Debris = 1.45 + Land cover (DL=-2.59; DM=-2.59; DO=-3.91; WW=0.00) + Tree height*0.055 + Tree diameter*-0.16 + Wind speed*0.03*

The Alternate model produced an R^2 value of 0.49; independent variables explain 49% of the variation in the dependent variable (log of debris). This model has a Root Mean Square Error (RMSE) of 1.80, slightly more than that of the other two models. According to measures of significance outlined in the Analysis of Variance table (Table 3-4) for the Alternate Model, like the other two models, Land cover, DBH, and height (alpha <0.10) are the most significant variables explaining variation in debris.

The residuals from the Full, Final and Alternate Models showed some patterns of heteroscadasticity (Figures 3-1, 3-2 & 3-3), which is a violation of the assumptions necessary for testing a regression relationship. However, no alternate transformation of the data mitigated this problem in any of the three models.

Development of Debris Estimates

The Alternate Model was applied to all 348 UFORE plots measured in 2001 to estimate debris within the study area. The DH land cover was initially aggregated with the DM land cover prior to statistical analysis and no additional aggregations of NLCD land covers were performed. Mean separation tests following model development

revealed that DM and DL were not statistically different. The DO land cover was however statistically different from DM and DL, and WW was statistically different from all other land covers. Organization of NLCD data aggregates DM, DL, and DO into the Developed category. These land covers were not however aggregated as “developed” because of statistical differences. Parameter estimates generated for each land cover cannot be applied to untested land covers and therefore parameter estimates from sampled land covers were averaged and applied to un-sampled land covers with associated UFORE plot data. Un-sampled land covers without associated UFORE data (e.g. UFORE plots without trees) were assumed to have zero debris.

Modeled debris values from all 348, 2001 UFORE plots were used to generate a spatial estimate using GIS (Figure 3-4). Predicted values for all modeled plots were spatially interpolated by Ordinary Kriging using the Gaussian semi-variogram model. Ordinary Kriging was used because it is the most common form of Kriging and is therefore most familiar to potential users of the methods and models outlined in this study. The cell size of the Kriging output raster was set to 49.2759 (m) so that each predicted cell would match the 0.6 acre size of the UFORE plots from which the predicted values were interpolated. Raster cell values within the Houston City Limits were then extracted using the city limits layer as a mask. Cells were next converted to points so that an attribute table of debris values could be exported to calculate debris across the landscape.

The spatial estimate resulted in an average of 15.28 cubic yards of debris per acre. Multiplied by the total acreage of Houston, TX, (~407,465 acres) this method estimates 6,227,691 total cubic yards of post-storm debris were generated within

Houston, Texas' city limits (Figure 3-5). Forty-Eight of the 2001 UFORE plots within Houston city limits were isolated to mathematically extrapolate modeled debris values. These plots demonstrated a calculated average of 14.05 cubic yards of debris per acre. When multiplied by the entire acreage in Houston, total debris was estimated to be 5,726,587.43 cubic yards.

Project worksheet information provided by the City of Houston (which is the data model results will be compared to) report 6,116,000 cubic yards of debris removed within the Houston City Limits (Victor Ayres, Deputy Director, Solid Waste Management Department, City of Houston, TX, 2009, personal communication). Staff from the City of Houston estimate that 75% of that total, or 4,587,000 cubic yards, to be strictly vegetation debris (Victor Ayres, 2009, personal communication). The remaining 25% was categorized as mixed debris which includes unknown amounts of vegetation debris. Debris volumes recorded as post-Ike project worksheet data from the City of Houston and debris estimates from other debris models applied to the study area are compared with mathematical and spatial estimations of debris results from this study in Table 3-5.

Results of Hypothesis Testing (Hypothesis 1)

A model of debris was developed using plot-level tree biomass values as the only explanatory variable to test significance of the biomass/debris correlation. This model had a root mean square error of 2.147 and an R^2 value of 0.15; tree biomass explains roughly 15% of debris variation. The p-value of 0.0256 shows the relationship to be statistically significant (Table 3-6).

An analysis of the biomass/debris relationship in Houston, TX can be made through comparisons between interpolated maps of pre-storm tree biomass (Figure 3-6) and post-storm debris measurements (Figure 3-7). Figures 3-6 and 3-7 represent

respective variables in cubic yards per acre. The raster for pre-storm tree biomass in cubic yards was derived by converting debris volumes from lbs./acre to cubic yards/acre using the conversion factor of 300lbs = 1 cubic yard of vegetation debris as outlined in FEMA's debris management guide (FEMA, 2007). A visual comparison of Figure 3-6 with Figure 3-7 supports Hypothesis 1; areas of higher tree biomass North and East of Houston were the same regions that experienced greater debris. The positive correlation between pre-storm tree biomass and post-storm tree debris is further illustrated in Table 3-7 that shows the calculated difference between pre-storm biomass and post-storm debris for the 11 re-measurement UFORE plots that are within Houston city limits.

Results of Hypothesis Testing (Hypothesis 2)

A model of tree debris was created using land cover as the only explanatory variable to test significance of the variables' relationship. This model was statistically significant (Table 3-8) and had an R^2 value of 0.39; land cover explains roughly 39% of debris variation.

Results of this statistical analysis is supported by all statistical models, as they show land cover to be explain roughly between 30% and 40% of debris variation. Table 3-9 shows a detail of the estimates of biomass and debris by land cover based on the 34 re-measurement UFORE plots.

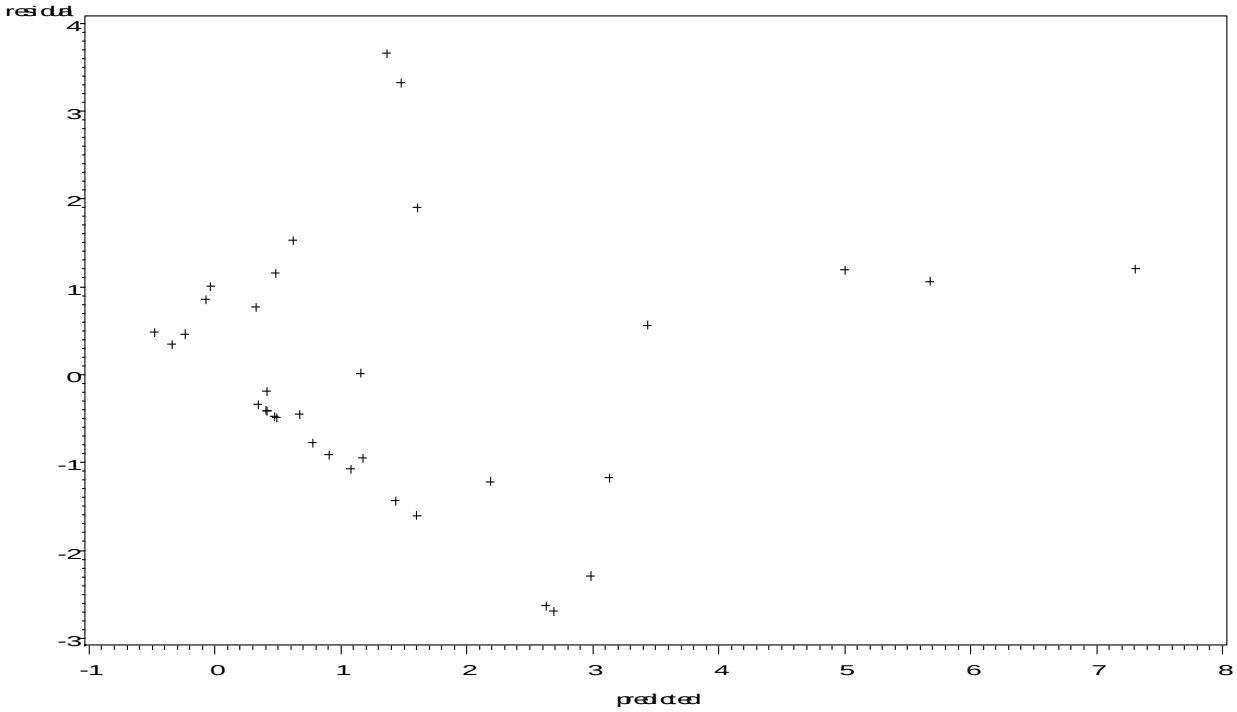


Figure 3-1. Plot of predicted versus residual values for full model

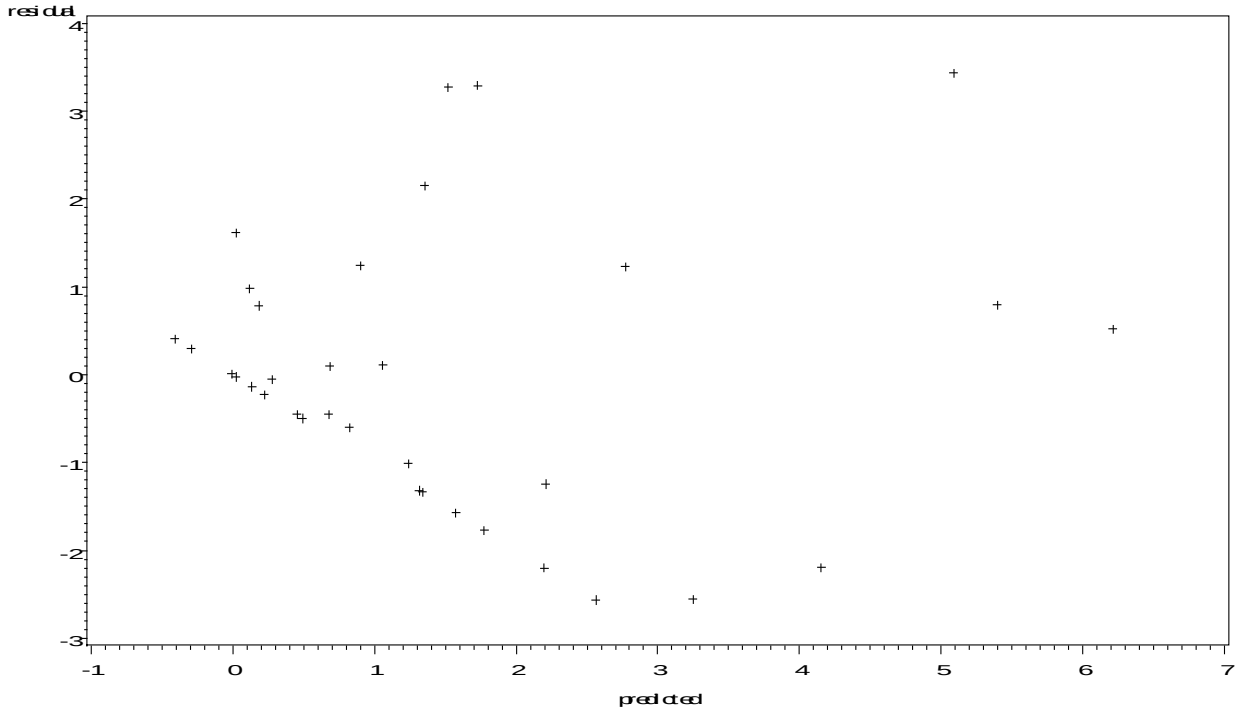


Figure 3-2. Plot of predicted versus residual values for final model

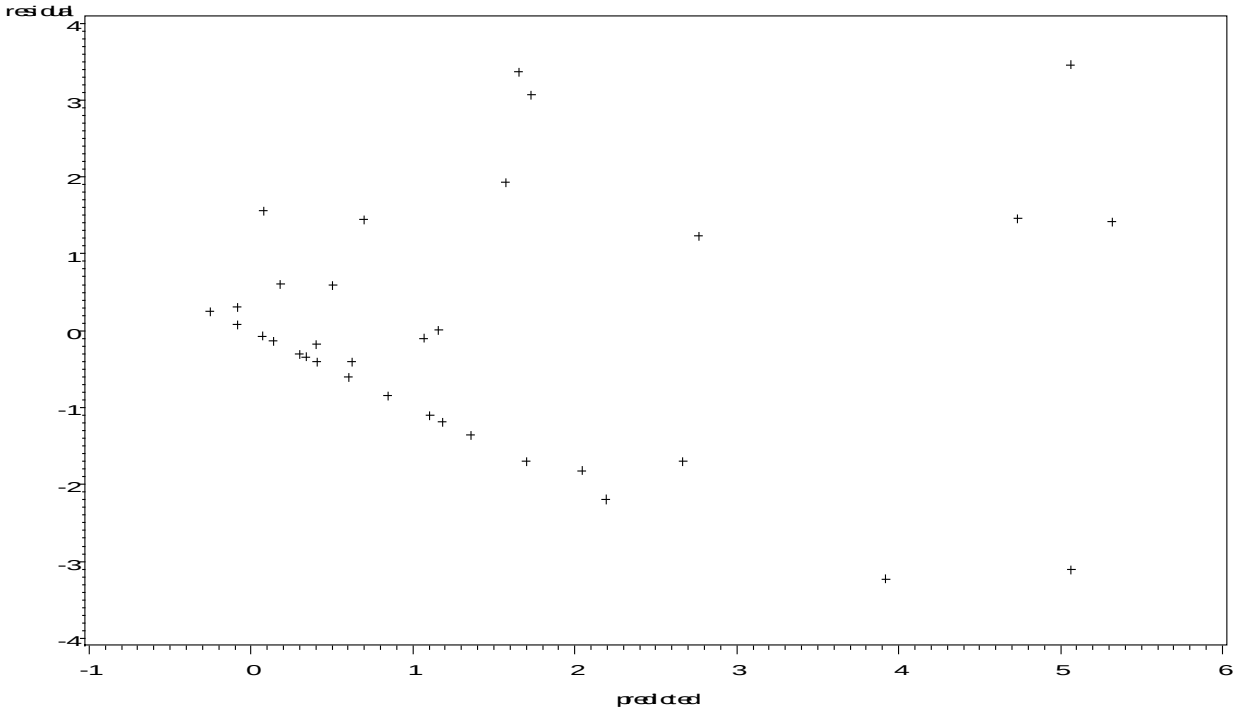


Figure 3-3. Plot of predicted versus residual values for alternate model

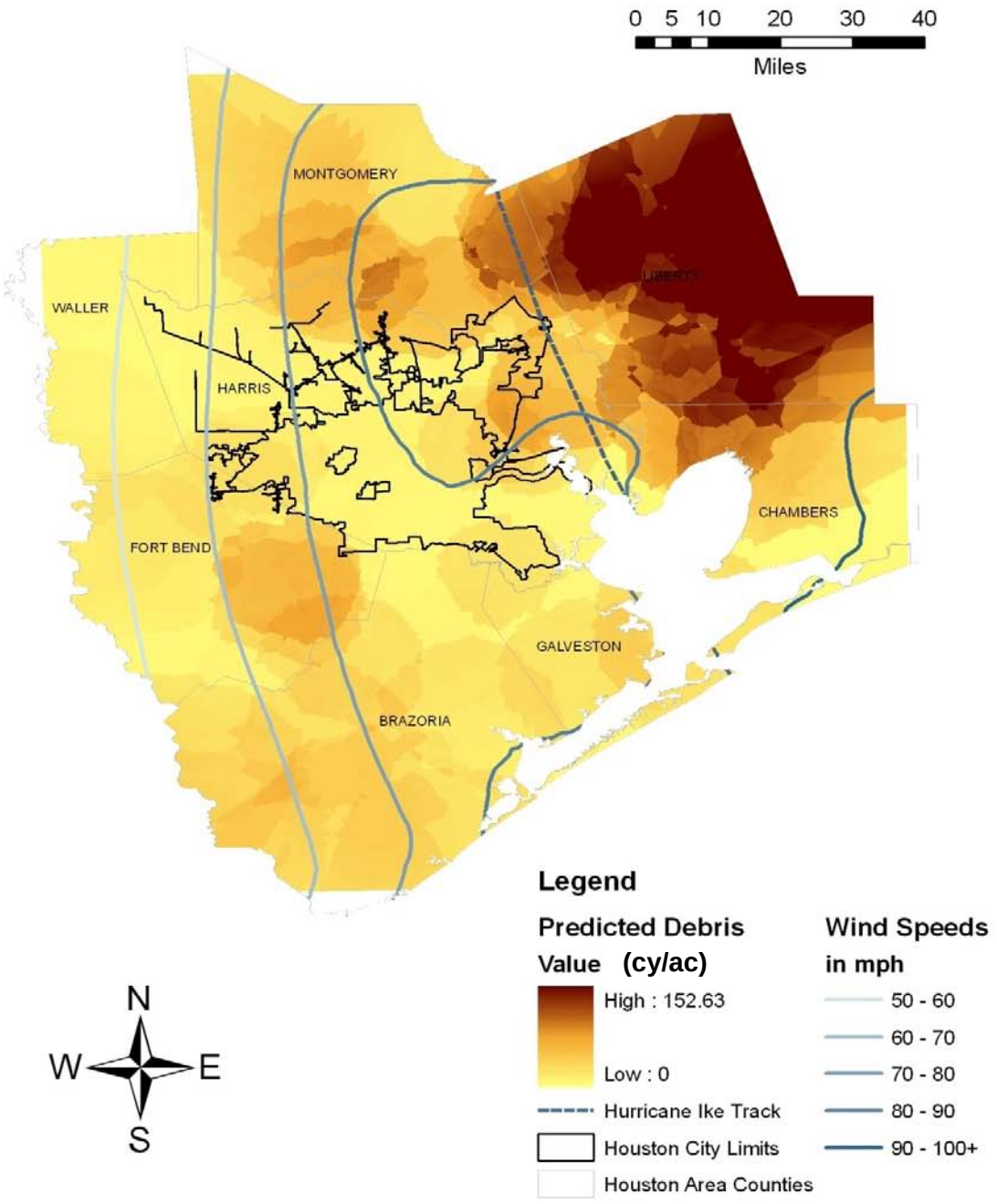


Figure 3-4. Interpolated raster of post-storm tree debris estimates based on alternate model predictions (n= 348)

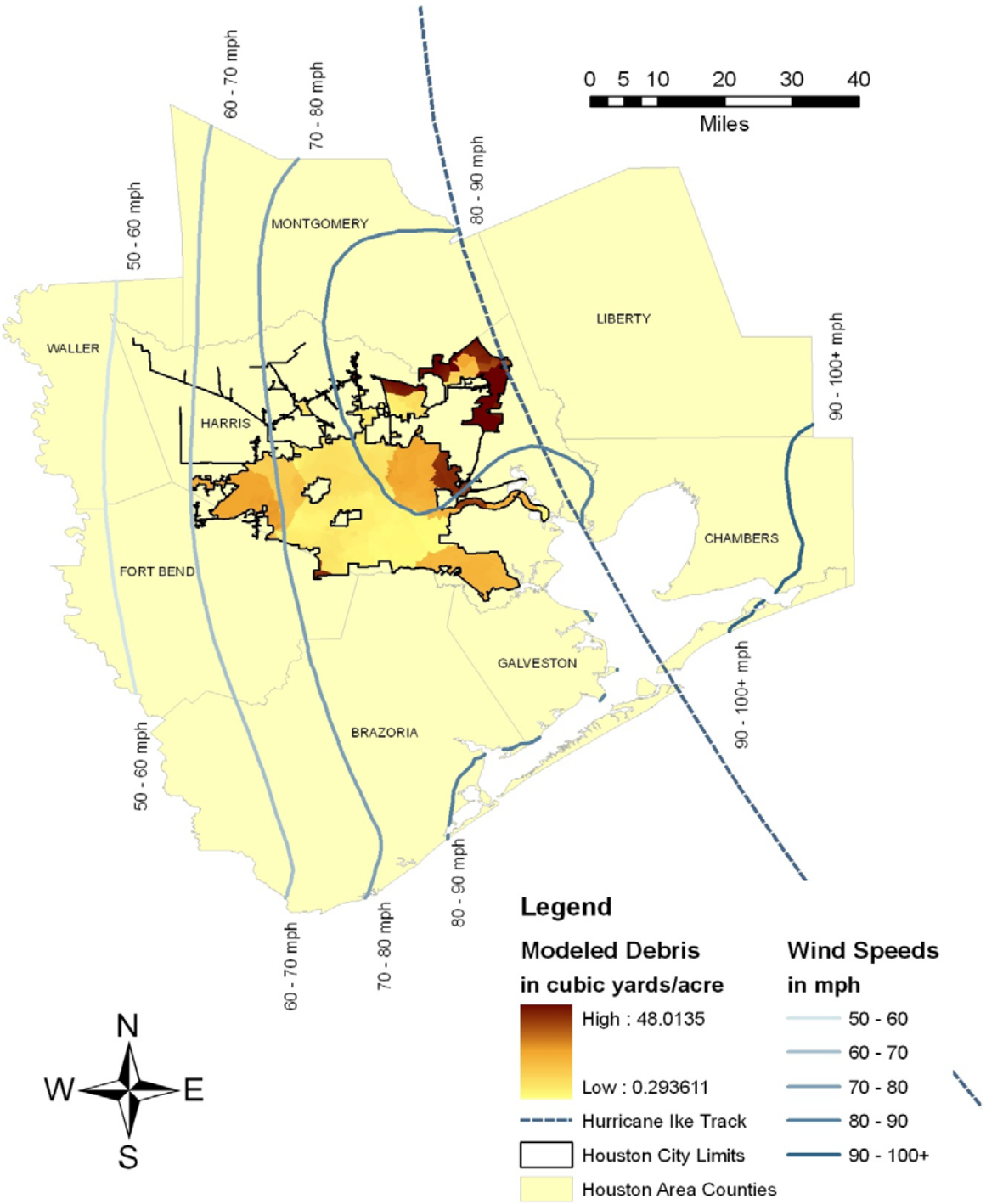


Figure 3-5. Interpolated raster of post-storm tree debris estimates within Houston city limits based on alternate model predictions (n= 348)

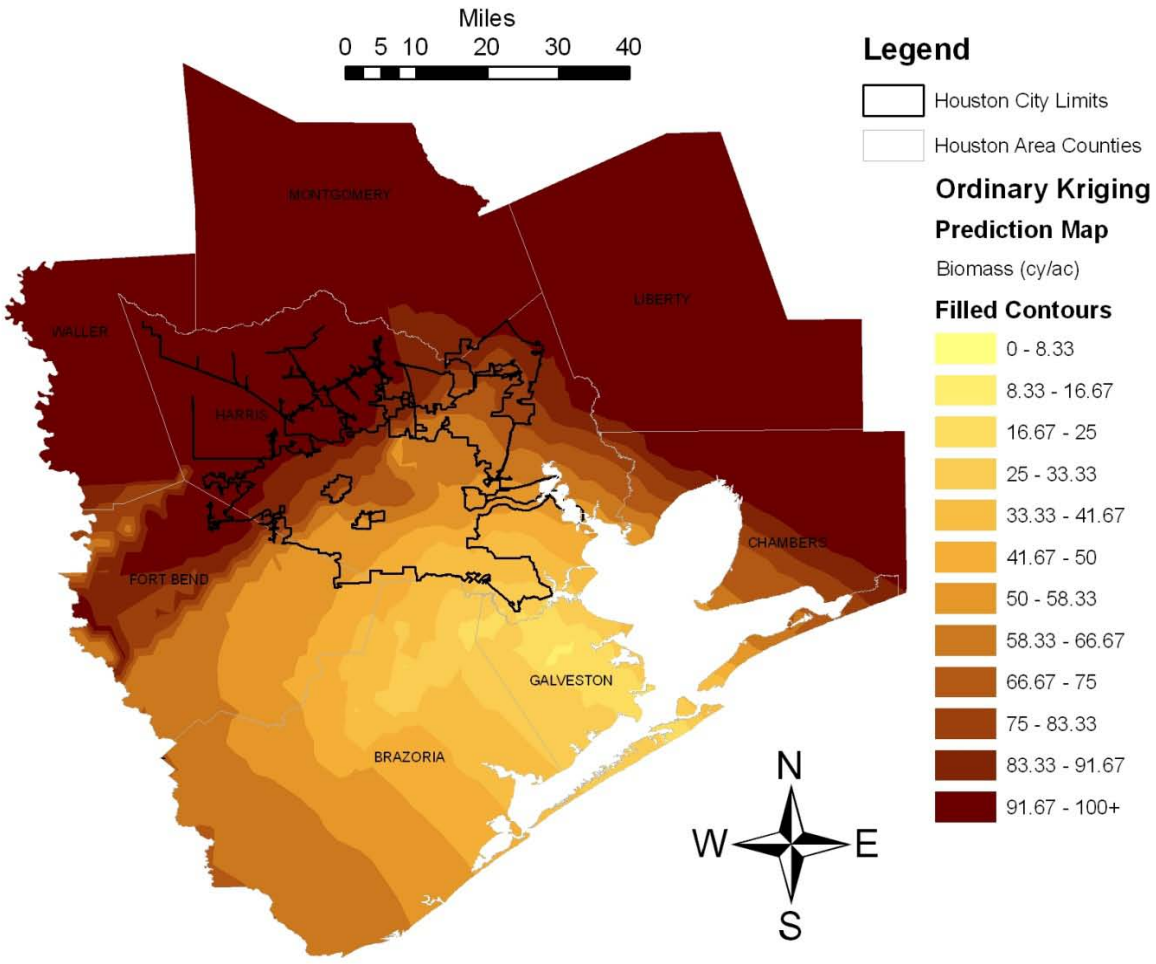


Figure 3-6. Interpolation raster of pre-storm, standing tree biomass in cubic yards/acre (n=34)

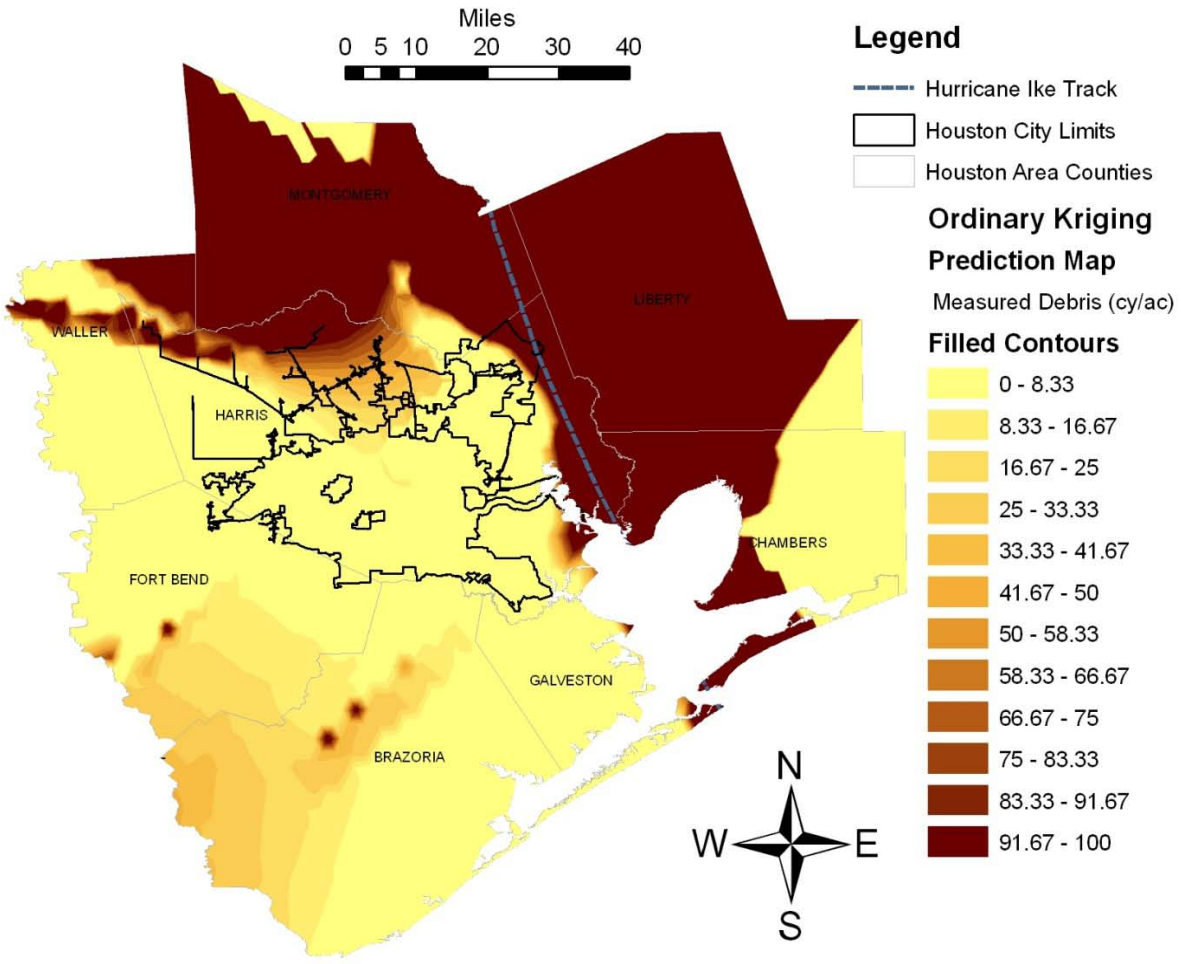


Figure 3-7. Interpolation raster of measured post-storm, downed tree debris in cubic yards per acre (n=34)

Table 3-1. Explanatory variables tested

Description	Units	Variable
Land cover associated with each plot	0.22 acre pixels	Land cover
Distance of plots to hurricane track	Miles	Distance to track
Total tree biomass per plot	Lbs	Biomass
Total number of trees per plot	# trees	Number of trees
Average tree diameter per plot	Inches	DBH
Average tree height per plot	Feet	Height
Percentage of tree cover per plot	%	Tree cover
Maximum sustained surface wind speed	Miles/hour	Wind speed
Relative wind steadiness	Indexed value (0-1)	Wind steadiness

Table 3-2. Analysis of variance (ANOVA) table for final model

Source	DF	Type III SS	Mean square	F value	Pr > f
Land cover	3	26.898	8.966	2.91	0.0564
Distance to track	1	3.787	3.787	1.23	0.2793
Number of trees	1	0.517	0.517	0.17	0.6859
Dbh	1	5.392	5.392	1.75	0.1991
Height	1	9.082	9.082	2.94	0.0996
Tree cover	1	2.283	2.283	0.74	0.3985
Wind speed	1	1.916	1.916	0.62	0.4386
Steadiness	1	8.385	8.385	2.72	0.1128

Table 3-3. Analysis of variance (ANOVA) table for final model

Source	DF	Type III SS	Mean square	F value	Pr > f
Land cover	3	48.781	16.260	5.36	0.0050
Distance to track	1	6.662	6.662	2.20	0.1500
DBH	1	10.882	10.882	3.59	0.0690
Height	1	18.513	18.513	6.10	0.0201

Table 3-4. Analysis of variance (ANOVA) table for alternate model

Source	DF	Type III SS	Mean square	F value	Pr > f
Land cover	3	38.394	12.798	3.95	0.0187
Wind speed	1	1.003	1.003	0.31	0.5826
DBH	1	10.419	10.419	3.21	0.0843
Height	1	14.905	14.905	4.59	0.0412

Table 3-5. Modeled debris estimates based on alternate model predictions and comparison with other debris model estimates and official debris volumes as recorded on post-Ike project worksheet data from the city of Houston.

Debris assessment within Houston city limits	Debris value (average cubic yards/acre)	Debris value Total (1000 cy)	Comparison with project worksheet data (vegetation & mixed)*	Comparison with project worksheet data (estimated vegetation)*
Project worksheet debris (mixed & vegetation)	15.01	6,116.00	0	N/a
Project worksheet debris (estimated vegetation)	11.26	4,587.00	N/a	0
Modeled debris (mathematical)	14.05	5,726.43	-6%	+25%
Modeled debris (spatial)	15.28	6,227.34	+2%	+36%
Hurricane Debris Estimating Model (USACE)[1]	8.58	3,494.60	-43%	-24%
Storm Damage Assessment Protocol (SDAP-FL)[2]	4.65	1,896.00	-69%	-59%
Storm Damage Assessment Protocol (SDAP-FL)[3]	.81	329.00	-95%	-93%
Storm Damage Assessment Protocol (SDAP-FL)[4]	25.66	10,457.00	+71%	+123%

* Comparisons represent the % deviation of modeled debris estimates from project worksheet data recorded by the city of Houston following hurricane Ike. Comparison with both the total recorded debris (vegetation & mixed) and vegetation debris (estimated) was incorporated at the request of Houston city staff (Victor Ayres, 2009, personal communication)

1. The Hurricane Debris Estimating Model was developed by the United States Army Corps of Engineers (USACE) and represents the following values as model inputs: # of households = 718,000; debris multiplier = 8 cy; vegetation multiplier = 1.3; commercial/industrial multiplier = 1.2; precipitation multiplier = 1.3
2. The Storm Damage Assessment Protocol—FL Adaptation (SDAP-FL) was developed by the University of Florida and represents the following values as model inputs: total # of street miles = 8,107; debris rate = “medium”
3. The Storm Damage Assessment Protocol—FL Adaptation (SDAP-FL) was developed by the University of Florida and represents the following values as model inputs: total # of street miles = 8,107; debris rate = “low”
4. The Storm Damage Assessment Protocol—FL Adaptation (SDAP-FL) was developed by the University of Florida and represents the following values as model inputs: total # of street miles = 8,107; debris rate = “high”

Table 3-6. ANOVA table for biomass-debris model

Source	DF	Type III SS	Mean square	F value	Pr > f
Biomass	1	25.289	25.289	5.48	0.0256

Table 3-7. Differences between pre-storm biomass and post-storm debris within Houston city limits using urban forest effects (UFORE) plots

UFORE plot number	Pre-storm biomass (cy/ac)	Post-storm measured debris[1] (cy/ac)	Post-storm modeled debris[2] (cy/ac))	Pre-storm biomass minus post-storm measured debris	Pre-storm biomass minus post-storm modeled debris
663	34.772	3.333	2.523	31.438	32.249
704	49.704	6.883	0.632	42.821	49.072
703	7.715	0.417	4.481	7.298	3.234
701	14.022	0.000	2.225	14.022	11.797
733	11.941	0.000	3.758	11.941	8.183
774	79.460	0.417	3.075	79.043	76.385
805	74.557	0.000	0.163	74.557	74.394
843	71.086	12.500	4.367	58.586	66.719
842	39.272	0.000	6.339	39.272	32.933
841	86.935	3.700	3.885	83.235	83.050
1027	113.864	0.000	19.727	113.864	94.137
Average	53.030	2.477	4.652	50.552	48.378
% of biomass	100.000	4.600	8.700	95.400	91.300

1. Measured debris values are those recorded from post-Ike data collection of 2008 re-measurement UFORE plots
2. Modeled debris values are those estimated for the same re-measurement UFORE plots based on alternate model predictions

Table 3-8. ANOVA table for land cover-debris model

Source	DF	Type III SS	Mean square	F value	Pr > f
Land cover	3	68.213	22.737	6.52	0.0016

Table 3-9. Averaged estimates of pre-storm biomass and modeled post-storm debris by land cover classification

Land cover classification	Pre-storm biomass (avg. cy/ac)	Post-storm modeled debris (avg. cy/ac)	% of Pre-storm biomass by land cover
Developed low intensity	80.21	8.24	10
Developed medium & high intensity	39.47	5.11	13
Developed open space	75.13	3.56	5
Woody wetlands	137.72	169.42	123
Other (averaged values from sampled land cover classifications)	83.13	46.59	56

CHAPTER 4
DISCUSSION

Review of Statistical Models and Comparison of Results

The Full Model explained the largest percentage of debris variation, however independent variables' overlap in explanations of variability contribute to high model error compared to the Final and Alternate models. The mean square error of the Full Model is higher than both the Final and Alternate Models (Tables 3-2, 3-3, & 3-4), indicating higher levels of error associated with estimates of debris. The Final and Alternate Models are therefore more realistic in terms of best fit.

Independent variables used in the Final Model explain the greatest variation of debris estimates given this analysis. The Alternate Model has a lower R-squared value and a higher error compared to the Final Model, however the Alternate Model may be more appropriate for estimating debris based on its inclusion of wind speed as a variable in place of the distance to track variable of the Final Model.

While the distance to hurricane track variable is significant as detailed by the Final Model, it was dropped as a variable for the Alternate model due to presumed error that may be present due to Hurricane Ike's unique morphology and large radius of maximum winds (National Hurricane Center, 2008). Wind speed, as modeled throughout the temporal course of hurricane events, may therefore be better suited for inclusion as an independent, storm-specific variable in a predictive model. The Alternate model can be further justified based on a slightly better distribution pattern of data spread when comparing graphs of residual versus predicted values generated by the model, implying that the model is more consistent in its predictions than the Final Model.

Analysis of predicted versus residual graphs for any of the three models developed in this study reveals apparent heteroscadasticity. The wedge-shaped gap in the data spread of these graphs (located in the lower left corner of Figures 5, 6, & 7) indicates that any of these models have higher degrees of error when making low estimates of debris in comparison to higher estimates. Although data transformation can usually mitigate this issue, statistical analysis did not reveal any worthwhile transformation. This indicates the model could benefit from additional data sources not collected or included for analysis. Models developed in this study are based on data that only include pre-storm trees greater than five inches in diameter. It is therefore likely that the exclusion of small trees from the dataset is a contributing factor to heteroscadasticity of models' results.

A comparison of statistical and spatial debris estimates (using the Alternate Model) with reported project worksheet debris volumes indicate that model results over-predicted debris generated as a result of Hurricane Ike. Accuracy of project worksheet data however is suspect (Victor Ayres, 2009, personal communication). Debris removed in Houston could have been altered by homeowner's blending yard debris with hurricane debris, debris remaining uncollected in natural areas or difficult-to-access sites, or private removal of debris (FEMA, 2007). The comparison with total debris removed (Table 3-5) is based on personal communications with Houston city staff who indicate that while only 75% of the total debris (4,587,000 cy) can be said to be strictly vegetation, the impacts of the storm did not generate much building/construction debris and it is therefore likely that vegetation debris represents the overwhelming majority of total debris removed. This is in-line with other southeastern US debris assessments

which have determined that vegetation consistently makes up the majority of post-hurricane debris (Escobedo et al., 2009; FEMA, 2006).

Despite Alternate Model over-prediction, this model estimated debris within a small percentage of error (Table 3-5). Spatial estimates from the Alternate Model suggest there were 6,227,000 cubic yards of debris that were generated by Hurricane Ike in Houston, TX; total debris recorded on project worksheets indicate 6,116,000 cubic yards of debris, or 2% less than the Alternate Model's spatial estimates for the same area. The perceived accuracy of the spatial estimate is encouraging because it lends validity to accuracy of modeled debris location in addition to debris volume. The Alternate model's performance is not too surprising since project worksheet records of tree debris and data used to develop the Alternate Model are both based on post-storm conditions resulting from the impacts of Hurricane Ike.

Although the SDAP—FL model is also based on post-storm conditions from a sample of communities affected by hurricanes during the 2004-2005 Florida hurricane season (Escobedo et al., 2009; Staudhammer et al., 2009), this model did not provide accurate estimates of debris compared with Alternate Model estimates and post-Ike project worksheet records from Houston, TX. The total debris estimated using the SDAP—FL "low" debris rate is clearly far too small to make reasonable comparisons with recorded debris volumes. Use of the "medium" debris rate would seem appropriate based on the designation of Hurricane Ike as a strong category two hurricane (National Hurricane Center, 2008), yet "medium" results under-estimated debris by roughly 60–70% compared with debris volumes recorded on post-Ike project worksheets. The "high" debris rate from the SDAP—FL over-estimated debris by roughly 70-120%,

clearly far above recorded volumes of debris. The relatively poor performance of the SDAP-FL model is not surprising considering the geographic, biological, and meteorological differences between the Houston study site and the data upon which this model is based.

The Army Corps of Engineers' Hurricane Debris Estimating Model also produced relatively inaccurate estimates of debris compared with project worksheet data and results from the Alternate Model. One possible explanation for the poor results is that this Hurricane Debris Estimating Model is empirical in nature whereas the Alternate Model is based on scientific analyses. Another possibility is related to the debris value multiplier of eight cubic yards which is assigned based on the designation of Hurricane Ike as a Saffir-Simpson category two hurricane (National Hurricane Center, 2008). Hurricane Ike was a strong category two storm on the verge of the category three wind speed threshold at landfall (National Hurricane Center, 2008). The relative strength of Hurricane Ike as a category two storm could have generated greater debris than is estimated by the Hurricane Debris Estimating Model using eight cubic yards as the debris rate multiplier.

Other relatively poor outcomes of this study were related to the statistical contributions of storm-related variables to estimates of debris. Hurricane wind variables derived from the H*wind model made little contributions to explanations of debris variation. Wind is often assumed to be the primary driver of debris generation, yet as determined by this and other studies, the wind speed variable is a poor predictor of vegetation debris (Kupfer et al., 2008; Staudhammer et al., 2009).

Hurricane variables such as steadiness explained even less variability of debris estimates when compared to wind speed. One possible explanation is that tree damage related to pre-existing decay or weak tree structure may occur at wind speeds far below maximum values modeled by H*Wind, and therefore the model may not capture this relationship using extreme values for wind as model inputs. Other studies of hurricane-force winds on forested ecosystems support findings that storm-related variables explain less variation of damage or debris than non-storm variables (Stanturf et al., 2007; Kupfer et al., 2008; Staudhammer et al., 2009) and indicate that interactions between forest damage and hurricane winds are complex and difficult to analyze statistically.

Review of Hypothesis Testing

The positive correlation and statistically significant relationship between pre-storm urban forest biomass and post-storm debris results in a failure to accept the null hypothesis of Hypothesis 1. Limitations and error associated with the data may be responsible for pre-storm biomass explaining only 15% of debris variability and being therefore excluded as a model input through the stepwise process. The positive correlation implies however that future development of a spatial debris estimation tool can utilize measures of pre-storm biomass to partition post-storm debris estimates as a percentage of total biomass. To better understand the biomass/debris relationship in Houston, TX as a result of Hurricane Ike, Table 3-7 shows that total post-storm tree debris in Houston represents between 4.6% and 8.7% of Houston's 2001 total urban forest biomass.

Table 3-9 displays averaged estimates of debris per acre by land cover within the study area, and shows those estimates as a percentage of the average biomass in

cubic yards per acre by land cover. The developed land covers show Hurricane Ike to have generated between three and nine cubic yards per acre which represent between five and thirteen % of total biomass per land cover in cubic yards per acre. The Woody Wetlands land cover however shows a dramatic increase to over 164 cubic yards of debris per acre representing 123% of the total biomass per acre. Debris estimates' exceeding the total biomass by such a large margin is seemingly improbable and is likely a consequence of the extremely high debris values measured on plots with Woody Wetlands land cover during the post-Ike data collection. Such high debris values from the data skew the models' parameter estimate for Woody Wetlands UFORE plots of within the study area.

Land cover is responsible for roughly 40% of the variability of debris estimated by the models. The strength of this variable is demonstrated by its inclusion in all three models developed by this study. While this cannot confirm nor disprove the hypothesis that land cover can be used as a proxy for variation of urban forest pre-storm biomass and post-storm debris (Hypothesis 2), it does lend support to this concept and is therefore a highly recommended for future research.

Applicability of Findings

Many results of this study are in line with scientific principles and related research (Kupfer et al., 2008; Oswalt and Oswalt, 2008; Escobedo et al., 2009; Staudhammer et al., 2009). A qualitative comparison of interpolated maps of measured biomass and debris (Figures 3-6 & 3-7) reveals that areas of greater pre-storm biomass to the north and east of the City of Houston also yield the greatest measures of post-storm debris. These results can also be justified by methods of analysis used in the initial 2001 Houston UFORE study, where the Northern regions of the study were analyzed

separate from Southern regions based on ecological differences between the type, percentage, and density of tree and forest cover within those regions (Nowak, 2005). The Northern region is more rural and has greater forest density, particularly pine forest (Nowak, 2005). The southern region however, is more urbanized and therefore has lower tree density and percent canopy coverage (Nowak, 2005) which is likely responsible for lesser debris volumes.

Similarly, it was expected that greater debris would be measured east of the hurricane track based on meteorological knowledge of hurricane wind intensities (Elsner and Birol Kara, 1999). Indeed, greater wind speeds were generally found east of the hurricane track, where greater post-storm debris was also measured by this study. This is supported by Figure 3-4 showing greater volumes of tree debris east of the hurricane track and lesser volumes to the west. It is possible however that the greater debris volumes to the North and East of Houston are related to both the path and morphology of hurricane Ike and the ecological landscape structure throughout the study area.

A review of Figures 3-4 and 3-7 showing modeled and measured debris, respectively, shows that lesser debris volumes were recorded within the highly urbanized boundaries of the City of Houston. Greater debris volumes were observed in suburban and rural areas throughout the study region, with a bias toward more debris in the more densely forested Northern regions. Of the variables used, both tree height and diameter were demonstrated to be the strongest explanatory variables for debris variation compared with other plot-level urban forest measurements (Tables 3-2, 3-3, & 3-4). This is supported by related research of both biomass estimation (Jenkins et al.,

2003; Blackard et al., 2008) and hurricane damage to forests (Everham and Brokaw, 1996; Kupfer et al., 2008; Oswalt and Oswalt, 2008).

Despite evidence from related research showing significance of forest density to forest damage or vegetation debris generation, measures of forest density used in this study (% tree cover and number of trees) showed little contribution to explanations of debris variation. One possible reason for this is that debris variation explained by measures of forest density may have been overshadowed by the categorical USGS land cover variable, which is modeled according to overlap of ancillary datasets including landscape-scale estimates of percent tree cover derived from USDA Forest Service FIA measurements (Homer et al., 2007).

Statistical results of hurricane variables' explanation of debris variation included in this study were similar to findings of the study by Kupfer et al. (2008). In both studies, the distance to track variable made similar contributions to overall debris or damage estimates and the H*Wind variables explained very little variation of debris or damage. The Distance to track variable, as well as H*Wind variables may have been confounded by the morphology of Hurricane Ike. Hurricane Ike had an unusually large eye estimated to be 74 Kilometers in diameter (National Hurricane Center, 2008), which is 4 Km larger than the upper range of average hurricane eye diameters as outlined by Elsner and Kara (1999). Such a large diameter for this hurricane extends the radius of damaging winds across the landscape and thereby may be responsible for patterns of damage observed, measured, and modeled by this study. As an example, 19 of 34, or roughly 56% of the selected post-storm re-measurement UFORE plots fell within the radius of Hurricane Ike's eye as it moved across the landscape and only two re-

measurement UFORE plots on the more damaging (east) side of the hurricane track were outside the eye wall of Hurricane Ike.

Yet despite the intensity of Hurricane Ike, perhaps the most important implication from results of this study is that debris generation in Houston's urban forest is mostly dependent on non-storm variables from a statistical perspective. Determination of non-storm variables having significant influences over debris generation is supported by both Kupfer et al. (2008) and Staudhammer et al. (2009) in their studies of hurricane-related damage and debris of forested landscapes. Additional support comes from observations of Hurricane Andrew's effects on vegetation and research by Duryea et al. (2007a), suggesting that hurricane-caused tree damage can be attributed to trees' being improperly located, poorly maintained, or consisting of species with low tolerances to hurricane forces (Burban and Andresen, 1994; Duryea et al., 2007a). The benefit of this finding is that managers of urban systems have relative control over non-storm variables. Hurricanes cannot be prevented, whereas land cover and urban forest structure and condition can be manipulated using management strategies and governing policies.

Limitations

Due to financial and staffing constraints, post-storm data collection did not take place until 8 October 2008, approximately twenty-five days after landfall of Hurricane Ike. During this timeframe, much of the debris may have been moved, or removed from plots during any debris clean-up and disposal operations. Lesser volumes of debris were therefore likely to have been recorded throughout the study area.

The timing of data collection may have contributed to this study's limitations, however debris measurements relation to geographic, environmental, social, and

political attributes of the plots selected for re-measurement should also be taken into consideration. The selection of re-measurement UFORE plots was influenced by input from the Texas Forest Service (TFS). In consultation with data collectors, TFS staff advised exclusion of particular plots from the original tiered selections of re-measurement UFORE plots based on local knowledge of the study area. Plots with safety or access issues, plots severely damaged by storm surge, and plots experiencing major land-use change were eliminated from the dataset. Decisions to eliminate plots may have streamlined the data collection process but may have also introduced unquantifiable bias.

It is also likely that the full extent of interactions between debris-dependent variables during hurricane events has not been fully quantified through scientific research. Model results may be adversely affected by complexities of such interactions. Also, variables selected for analysis may not accurately model tree debris generation in urban areas given the data available for this study. Particularly notable is the seven year gap between pre- and post-storm data. The 2001 data are only representative of that year and do not account for changes to urban forest health and structure that occurred between 2001 and 2008. Such changes include but are not limited to factors such as tree growth, tree pruning, tree mortality, tree planting, and/or tree removal.

Another explanation for variables' inability to accurately capture variation in debris estimates could be the increased error associated with the use of modeled data as explanatory variables. Both the H*Wind data and the USGS land cover data are modeled data products based on incorporation and analyses of related datasets. Indirect data sources will have higher error than direct measurements of the same

variables; this error therefore affects accuracies of any analyses utilizing them. Furthermore, spatial estimates of debris are affected by compounding the error of statistical analyses with error associated with interpolation of the data.

CHAPTER 5
CONCLUSIONS

Results show that non-storm related variables explain greater variation of debris estimates than storm related variables such as wind speed. This finding implies that tree failures and resulting debris are more closely associated with tree- or site-specific factors than meteorological variables. Another possibility may be that most tree failures occur at winds speeds below the modeled maximum values offered by the H*Wind dataset, and therefore the data does not accurately capture the full extent of relationships between wind speed and hurricane-caused tree debris generation. These results did however reinforce similar findings from related studies (Kupfer et al., 2008; Oswalt and Oswalt, 2008; Staudhammer et al., 2009).

While the U.S. Army Corps of Engineers' Hurricane Debris Estimating Model and the Storm Damage Assessment Protocol—FL Adaptation produced relatively poor estimates of debris in Houston, TX, the results from the Alternate Model developed by this study estimated tree debris within a relatively small margin of error compared with project worksheet data. Rationales for the performance of the SDAP-FL and Hurricane Debris Estimating Model in Houston, TX, remain speculative until additional data collection, analysis, and research is performed to test debris estimations produced using these models. Similarly, the Alternate Model may be further verified using results and data from future post-storm inventory of UFORE plots in other hurricane-affected cites.

Overall, the sample size and other limitations of the data hinder the accuracy of models developed in this study. These models may be improved through the exploration and incorporation of yet untested variables. New models with greater

accuracy and precision may be developed in the future with the aid of additional data such as post-storm debris measurements from future hurricane events and finer scale representations of both wind behavior and land cover variation.

In the biomass-debris model, the tree biomass variable demonstrated a positive correlation with debris, implying that debris increases as tree biomass increases. This result supports Hypothesis 1; however the relationship was not as strong as expected. Limitations of the dataset and interaction with other variables are likely responsible for the relative weakness of this result. In addition, further efforts to include biomass as a statistically significant input variable in a debris estimation model were also likely hampered by limitations of and interactions among the data and therefore further testing of this hypothesis is recommended.

In spite of a weak relationship between pre-storm tree biomass and post-storm debris, the biomass debris relationship did not seem to adversely affect Hypothesis 2 that land cover is a proxy for capturing variability of pre-storm tree biomass and post-storm tree debris. Statistical analyses, results of all three debris models, and the land cover-debris model show that land cover explains between roughly 38% and 49% of variability associated with debris estimates. This percentage, compared with R^2 values of the Final and Alternate models, suggest that land cover is responsible for a disproportionally large contribution to variability of debris estimates. Further analysis and testing of this hypothesis with future datasets may reveal an even stronger relationship.

The use of urban forest structure data as inputs to a post-storm tree debris model highlights the opportunity for exploration of yet another new, practical, and scientific

application of UFORE data. Other unique implications of this research include the introduction of two concepts that (assuming verification though additional analyses and tests) may prove useful for generating vegetation debris estimates at large spatial scales in urban areas: 1.) Estimation of post-storm tree debris as a percentage of pre-storm tree biomass; and 2.) Estimation of debris using land cover data as a proxy variable for capturing variation of urban forest pre-storm biomass and post-storm debris.

Hurricane-caused tree debris can be modeled in urban forests; however analysis of future storm events may lead to more accurate verifications of results. Continued refinement of both NLCD land cover data and H*Wind modeling by the USGS and the NHC respectively will facilitate availability of more accurate and/or precise data for analysis in future investigations of a similar nature.

Future Research Opportunities

The scope, scale, and original intentions of this study reveal numerous possibilities for continuing research. The presence of UFORE data in Houston, TX in addition to other Southeastern U.S. cities including Miami, Tampa, Gainesville, and Pensacola, FL, indicate that many opportunities exist for future data collection and analysis. This is especially true considering that each of these cities is likely to experience future hurricane events. Therefore, future post-hurricane debris data should ideally be collected and analyzed from any and all hurricane affected cities with UFORE data to test debris model results from this study and compare them with project worksheet data and estimates provided by other debris models. Additional analyses seeking explanations for low correlations between hurricane variables and hurricane-caused tree debris generation should also be pursued.

Furthermore, it is recommended that variables excluded from this analysis should be tested for correlations with post-storm debris. Such variables include but are not limited to: geographic variables such as soil type, topography (elevation and aspect), ground surface cover percentages, and urban development patterns; storm variables such as rainfall amounts, storm size, forward storm speed, Saffir-Simpson storm category, wind direction, radius of maximum winds and hurricane eye wall diameter; and tree and forest variables such as, forest-edge effects, rooting space, measures of tree condition/health, and tree characteristics such as wood density, wood elasticity, plant allometry, tree crown density and dimensions, average tree lifespan, size at maturity, and categorical variables such as native vs. non-native, and deciduous vs. coniferous. Many of the yet-untested variables as described above represent a challenging but potentially important area of study, to model species' hurricane response at landscape scales according to incorporation of results from Duryea et al. (2007a, 2007b).

Findings from Duryea et al. (2007a, 2007b) and Jenkins et al. (2003) may also be used to model species-specific contributions to overall debris from partitioned components of tree structure such as leaves, stems, branches, and roots. Furthermore, development of biomass equations for tree species common to urbanized, hurricane-affected cities of the Southeastern U.S. can also improve estimations of biomass and debris at the individual tree or species level. Although species-specific variables may be difficult to extrapolate to varying spatial scales, results from such analyses could produce far more accurate debris estimations. In addition, modeling hurricanes' capacities to alter urban forests through tree canopy cover or tree density changes may

be worth pursuing as such forest measures have been shown to have significant relationships with hurricane damage at landscape scales (Everham and Brokaw, 1996; Stanturf et al., 2007)

Improvements to accuracy of landscape-scale debris estimation will also yield related improvements to landscape-scale estimation of urban forest biomass. Further exploration of this relationship with future datasets may yield more robust results that can be used to develop more advanced and accurate models of debris (both statistical and spatial), including the development of a spatial GIS-based debris estimation tool (Appendix A). Incorporation of a statistical model, such as those offered by this study, with the geospatial capabilities of GIS can enable model estimates to be interpolated across landscapes and thereby generate spatially explicit estimations of debris which are not currently outputs of other debris models.

Provided that methods outlined in this study lead to improvements in biomass estimation of urban forests, another opportunity for related research is in developing landscape scale estimation of urban forests' stored carbon. Several articles reviewed for this study indicate the importance of the biomass/carbon relationship and the importance of carbon storage estimation to emerging trends in tree and forest management (Nowak, 1993; McPherson, 1994; McNulty, 2002; Jenkins et al., 2003; Myeong et al., 2006; Woodbury et al., 2007; Hu and Wang, 2008).

In this study, biomass was calculated as a proportion of carbon storage values provided by UFORE model outputs. Therefore similar methods can be used to statistically analyze and spatially interpolate UFORE values of carbon storage. Cities with UFORE data can estimate pre-hurricane values for carbon storage and biomass

based on UFORE model outputs. As such, debris models produced with methods outlined by this study can enable users to also estimate post-hurricane tree debris and post-hurricane changes to urban forest biomass and carbon storage at landscape scales.

Results of this project provide urban forest managers in Houston, Texas, with a verified debris estimation model that can be implemented for use and tested for effectiveness against future hurricane events. Also, this project has identified another new and practical application of UFORE data. The design and outcomes of this research project reinforce evidence from the literature that methods for data collection and analysis of forest ecosystems can also be effectively applied to the study of urban ecosystems. Opportunities for continued research are numerous and results from this study will provide future researchers and urban forest managers with greater insights into disturbance responses of urban forests and related factors which drive hurricane-caused tree debris generation in urban ecosystems.

APPENDIX A
A FRAMEWORK FOR DEVELOPING A GIS-BASED DEBRIS ESTIMATION TOOL

Introduction

This appendix describes a framework for integrating this study's results into a GIS-based tool that relies on statistical models using data that are representative of the Southeastern United States. Incorporation of statistical models' can allow the GIS tool to be used to either predict or verify post-storm debris volumes. Any models or tools developed should meet the following criteria:

- It should be relatively easy to use
- The data should be readily available and come at little to no cost to the user.
- It must cover the broad geographical scope of the Southeastern U.S.
- It must be temporally relevant

The incorporation of GIS and other technologies for measurements of spatial relationships will play an important role in the development of a debris estimation tool. However, methodologies for debris estimation by the end-user must remain simple and practical in order to ensure that they compliment rapid-assessment protocols. The use of GIS technology provides flexibility for future research and incorporations of other data. For example, supervised classifications via remote sensing and GIS analysis may be found to have relevance or positive relationships to methods outlined in this project. If methods used in this study are found to contain commonalities for debris estimation in conjunction with remote sensing, then this could lead to developments in methodologies that improve accuracy and ease of use for both statistical models and any GIS interface that may be developed.

The following pages of this appendix describe a framework for a GIS-based tool used to calculate hurricane-caused tree debris both spatially and volumetrically within a

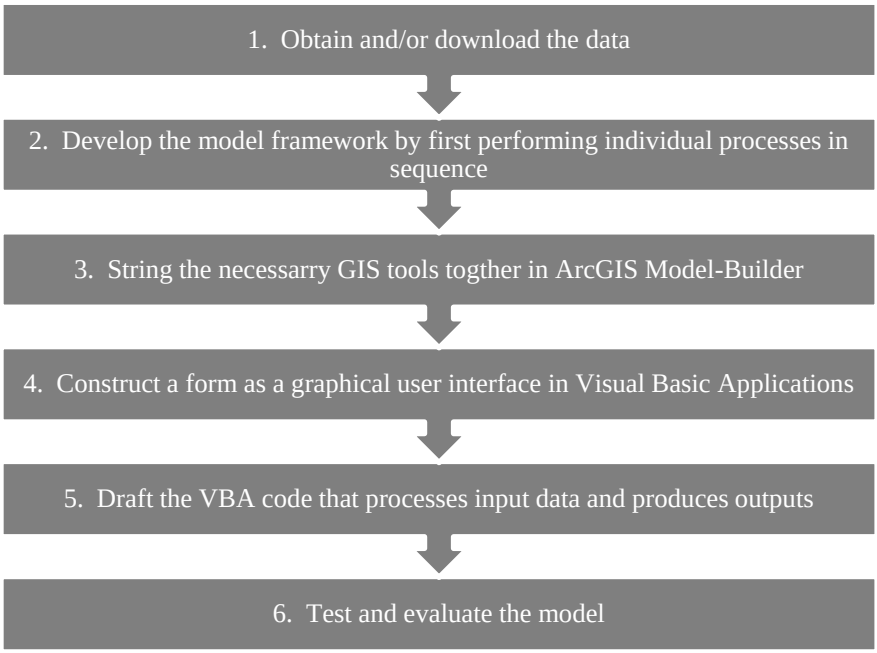
predefined area for a selected storm, and is based on statistical models referenced in Chapter 3. The spatial analysis and calculations of debris will be performed within the model-builder tool that is packaged with ArcGIS 9.3. This first iteration of the model provides a basic framework of programming language upon which future improvements may be made to finalize the tool.

The framework for this tool has two major components: 1.) prediction of debris based on statistical and spatial analyses; and 2.) extraction of debris values according to user-defined criteria and provision of outputs that describe debris volumes and locations. The work performed as outlined in this appendix focuses solely on the second component: Assessing, quantifying, and determining relative spatial locations of hurricane-caused tree debris. This was possible due to having debris data collected in Houston, TX in the wake of Hurricane Ike. As a result, the tool as described here utilizes the actual post-storm data from Hurricane Ike. The two primary objectives for producing this component of the tool are:

- To return an output data layer to the map of the area of interest as a Points shapefile that expresses values of tree debris in terms of pounds/acre within a 60 meter buffer of all major roads in Houston, TX.
- To return output that reports the total amount of debris in terms of pounds/acre for the entire extent of the map of the area of interest.

Methods

The debris model was built in six general steps. A listing and breakdown of each step is as follows:



Step 1: Obtain and/or download the data

There are two input data files for this project. The first file is a polyline shapefile of roads data available from the Texas General Land Office: (http://www.glo.state.tx.us/gisdata/gisdata.html). The second is a points shapefile of Urban Forest Effects (UFORE) plot data collected by the Texas Forest Service in 2001. This data was updated by researchers from the University of Florida in August of 2008 following Hurricane Ike. As described in Chapter x of this study, 348 UFORE plots were randomly located throughout the greater Houston Metro Area for the 2001 measurement; 34 of them were re-inventoried following the storm (see Appendix A for description of how these plots were selected). These 34 plots are the foundation upon which the statistical model was built. The data are displayed in ArcGIS 9.3 using the NAD 1983 UTM Zone 15N coordinate system and Transverse Mercator projection.

Step 2: Develop the model framework by first performing individual processes in sequence.

A series of tools from ArcGIS 9.3 were used to produce the final output data layer. This process helped to determine exactly which tools were necessary and how those tools should be executed. For example, through iterative trials it was determined that a 60-meter buffer of the major roads was the optimal distance for capturing the values of interest (debris). A 60-meter buffer effectively captures data from the 30x30 meter cells that comprise the interpolated raster of debris in ArcGIS.

Step 3: Stringing the necessary GIS tools together in ArcGIS 9.3 Model-Builder

A screen capture of the model and a breakdown of the specific tools (Fig A-1) are as follows where blue ovals = input data; yellow rectangles = ArcGIS tools performing functions on data; green ovals = data resulting from ArcGIS tool processes; and "P" indicates which data are model parameters.

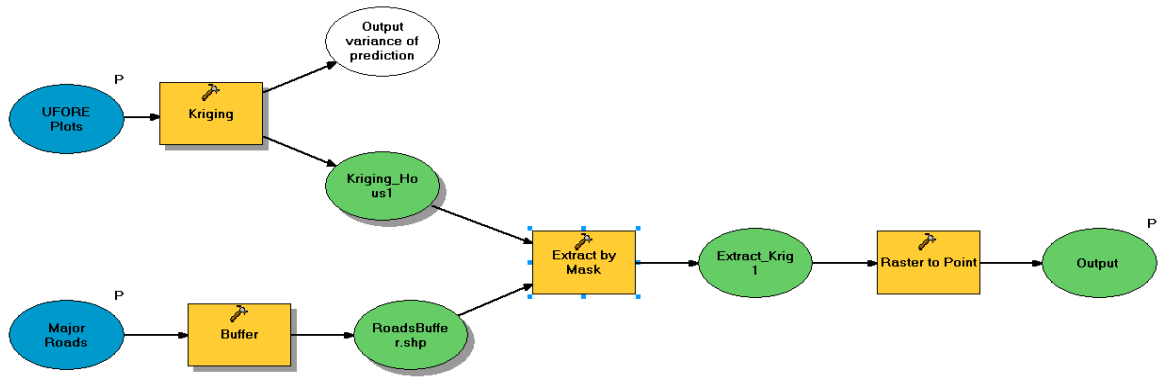


Figure A-1. Model developed using ArcGIS' Model-Builder

Kriging (Figure A-2):

The plot layer is the input layer for this tool. Based on debris values in the UFORE plot layer's attribute table, this operation constructs a rasterized prediction map of debris for unsampled portions of the map. The output cell size is set at 60 (m) to strike a

balance between detail of the output and efficiency of the tool. A larger cell size covers more land area and limits spatial detail whereas a smaller cell size, while providing greater detail, slow down the performance of the tool due to doubling the size of the data produced. Default settings were used in all other cases.

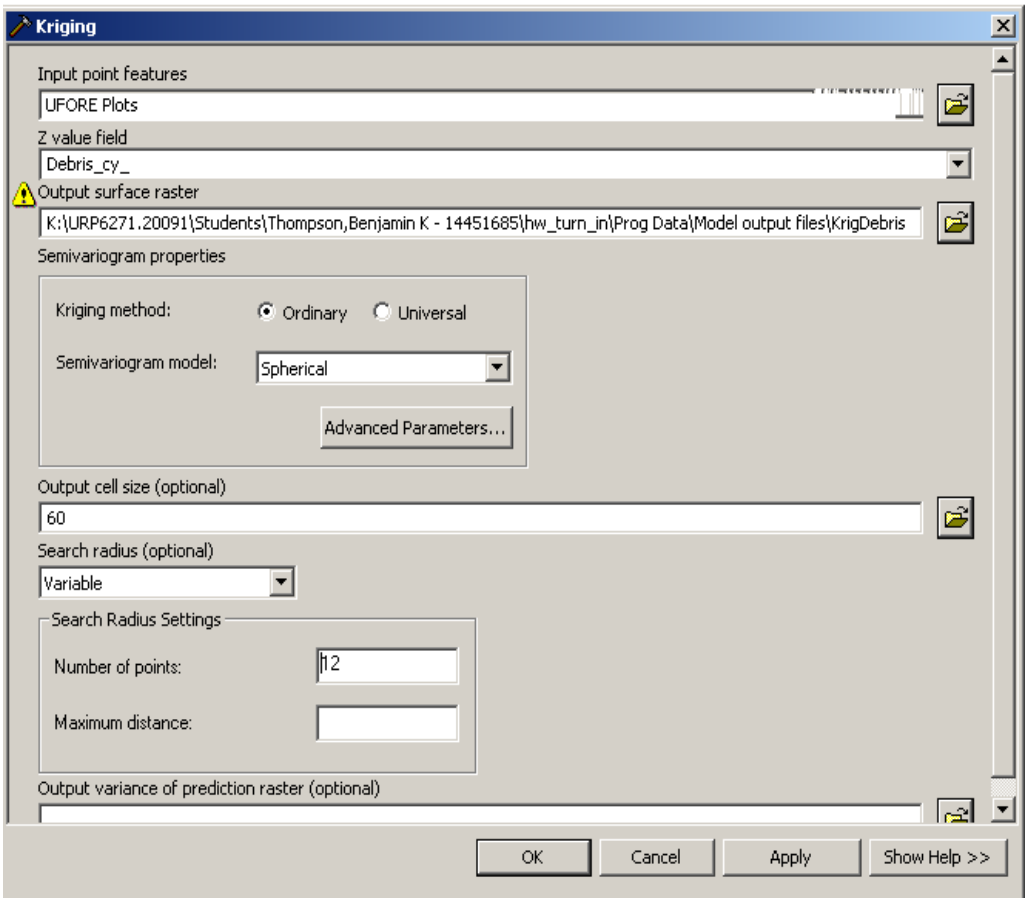


Figure A-2. Screen capture of ArcGIS' Kriging operation

Buffer (Figure A-3):

The roads layer is the input layer for this tool. A 60 meter buffer that integrates the data by dissolving "ALL" boundaries is designated as the optimal buffer. Default settings for kriging method, semivariogram model, search radius, and number of points were used in all other cases. The following tool creates the buffer.

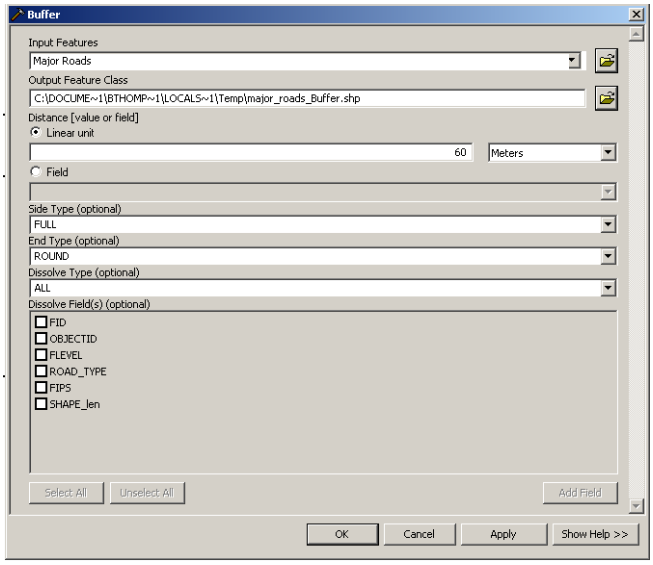


Figure A-3. Screen Capture of ArcGIS' Buffer operation

Extract by Mask (Figure A-4):

The results from the Kriging and Buffer operations are the input layers for this tool. The roads buffer is a mask used to extract the raster values for debris predicted by the Kriging result.

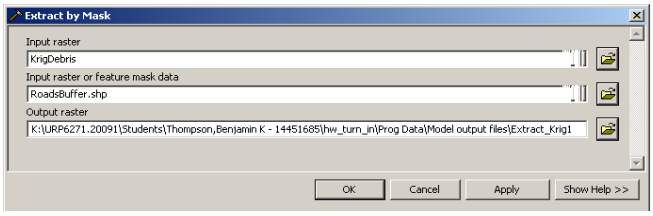


Figure A-4. Screen capture of ArcGIS' Extract by Mask operation

Raster to Point (Figure A-5):

The result from the extract-by-mask tool is the input layer to this raster-to-point tool that converts the raster cells to a points file and returns this final output layer to the map.

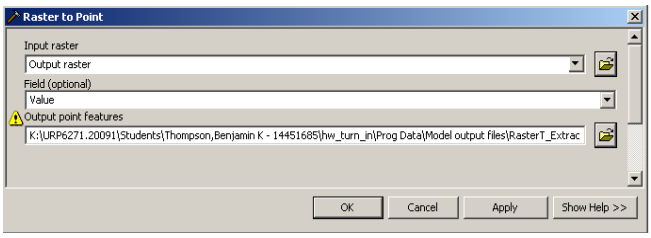


Figure A-5. Screen capture of ArcGIS' Raster to Point operation

Step 4 (Figure A-6): Construct a form as a graphical user interface in Visual Basic Applications scripting language.

The user interface for the tool prompts the user for a roads layer, a plot layer, and a filename to run the tool and produce the end result.

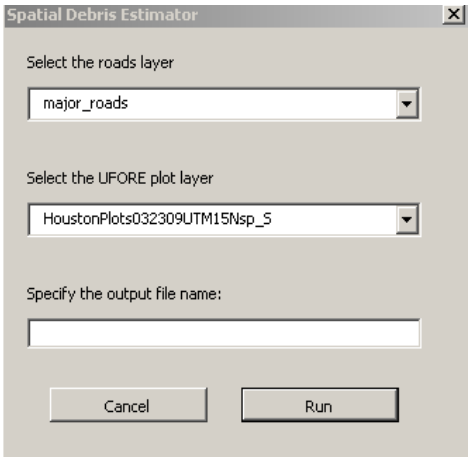


Figure A-6. Screen capture of graphical user interface developed for this tool with ArcGIS.

Step 5 (Figure A-7): Draft the VBA code that processes input data and produces outputs.

The following flowchart outlines the process of the VBA code:

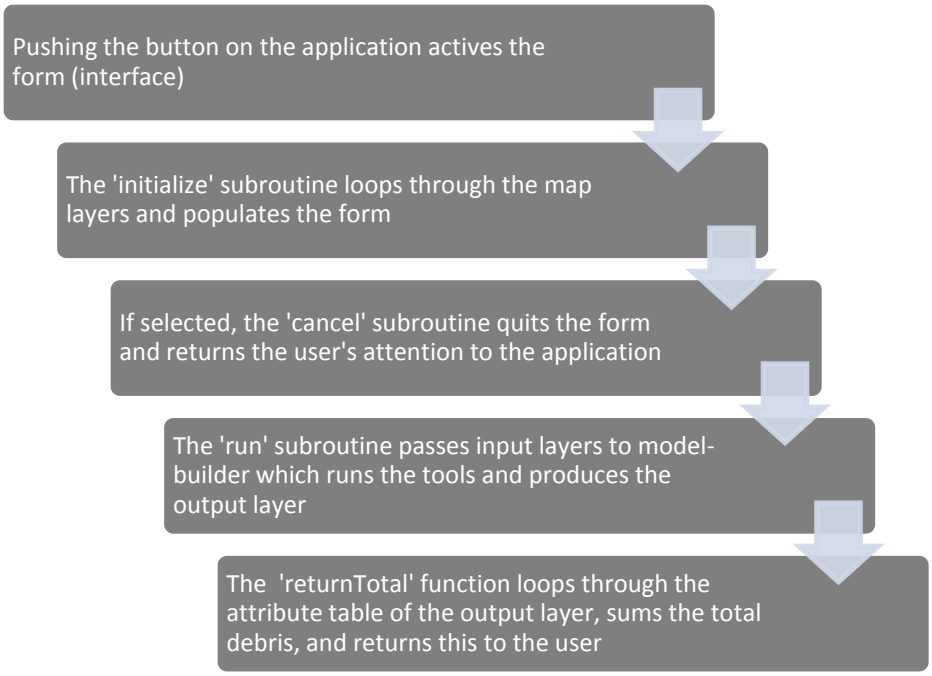


Figure A- 7. Process of ArcGIS programmed subroutines to execute the debris estimation tool.

Step 6: Test and evaluate the model.

Once all the components of the model were drafted, an iterative process was undertaken to search for mistakes and problems that hindered the model's performance.

Results

This project generated the following results which are displayed below in two screen-captures of the final output layer (Figures A-8 and A-9).

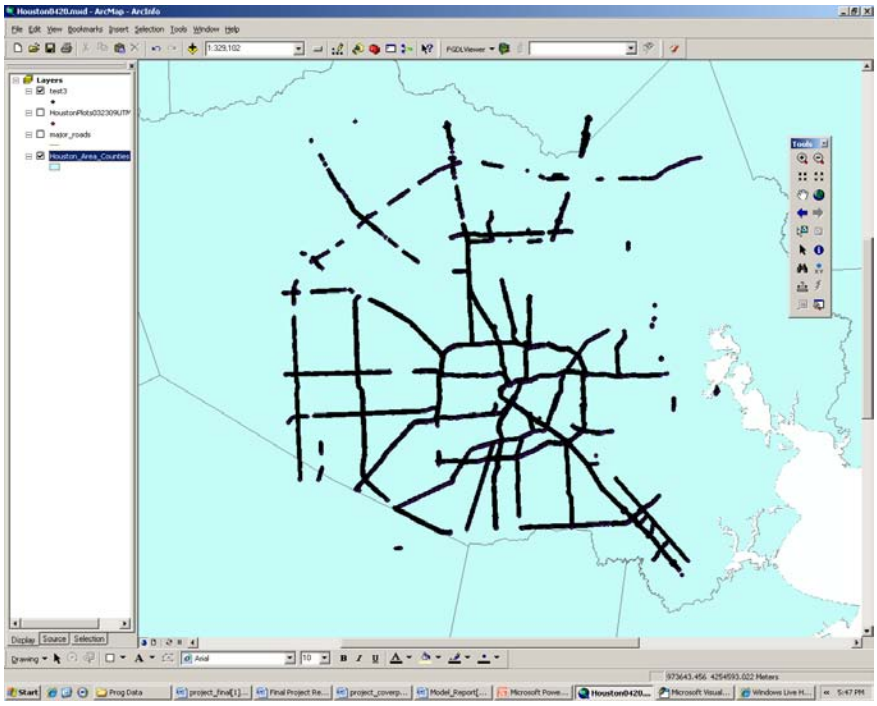


Figure A-8. Screen capture of a “points” file of tree debris values expressed in pounds/acre.

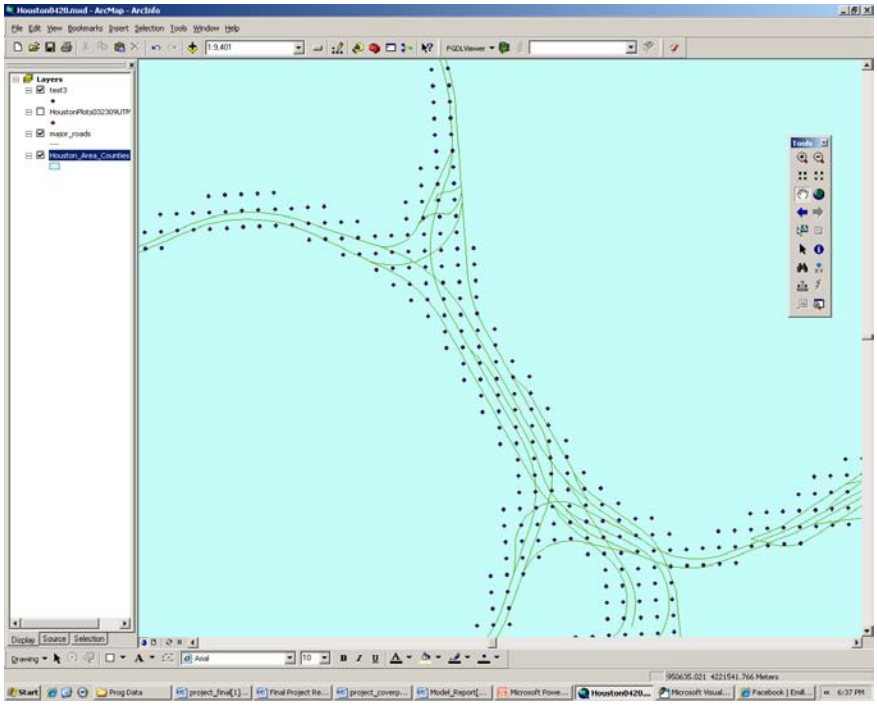


Figure A-9. An enlargement of Figure A-8 showing finer detail

As shown in the screen capture below (Figure A-10), the total hurricane-caused tree debris along major roads in Houston, Texas is 659065 lbs/acre (screen capture below is in error; it should read lbs/acre instead of cubic yards). The caveat is that this number is not divided by the acreage of the roads buffer which was used as a mask to extract the values and therefore is not specific to the actual land area of interest. This figure is helpful for determining total debris within the user-designated area; however a per-acre average cannot be determined without dividing the total debris by the acreage of the area.

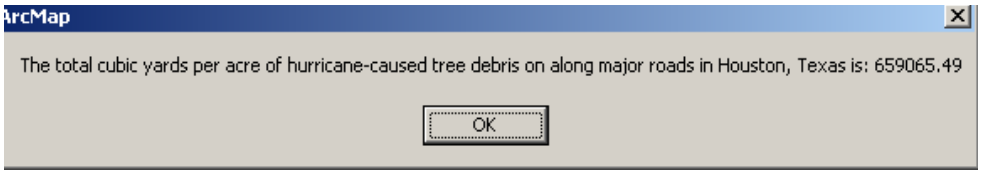


Figure A-10. ArcGIS 9.3 message box returned to user with model results

This screen-capture of the output layer's attribute table (Figure A-11) shows the debris values in the column named "GRID-CODE". The model generated a total of 26,425 unique points along major roads in the City of Houston. The vast number of points generated demonstrates the explicit spatial nature of the output. For example, the user can identify specific points within specific areas of interest to identify a unique debris volume that is estimated to be found there.

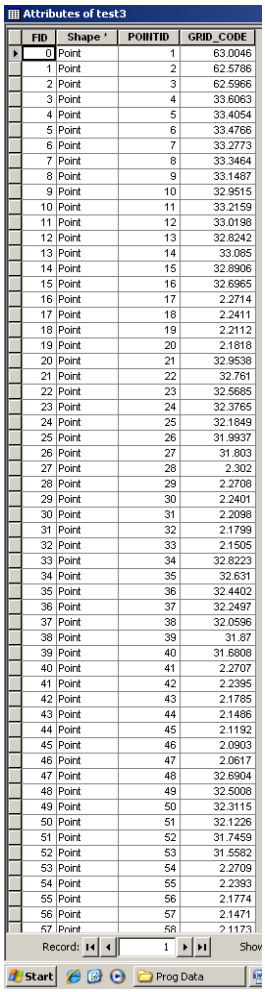


Figure A-11. Sample of interpolated debris values extracted to points layer

Discussion:

Despite limitations of the tool, the results from this study and methods outlined in this framework can be used to develop a GIS based debris estimation tool. Using this study and framework, the city of Houston now has a simple and user-friendly means to spatially and volumetrically estimate post-storm, hurricane-caused tree debris whereas no such method has previously existed. In general, the graphical interface of ArcGIS' Model-Builder facilitated smoother and more efficient development of this tool by

comparison to the rigorous and less intuitive script-writing process in Visual Basic Application.

To determine accuracy of the tool's result for Houston (659,065 lbs/acre), debris estimates produced by this tool may be tested and verified by comparing them with actual debris values recorded on project worksheet data submitted to FEMA by affected communities for reimbursement purposes. The most import test will be a comparison of the tool's results with actual project worksheet data submitted by the City of Houston for reimbursement of post-Ike debris disposal.

Limitations

There are several limitations of the model, ways that it may be improved, and options for development of future models.

The value of debris reported is in lbs/acre, whereas measurements in cubic yards are a more desirable measure as these are the units requested by FEMA for submittal of project worksheets. Simple conversion factors can be programmed into the tool so that lbs/acre can be converted to cubic yards. In doing so, it is possible to have the tool report estimates of debris in both lbs/acre and cubic yards. The value of total debris reported doesn't consider the acreage of the buffer. The value returned to the user is in units of lbs/acre, however this number is not divided by the total acreage of the area of interest, which in this case is the buffer of major roads. Steps should be added to model builder that first convert the debris values from pounds of debris/0.1 acre to pounds of debris/acre. This currently does not exist and can be done by using ArcGIS tools that add and calculate a new field within the UFORE Plot layer attribute table. The same process can be employed to convert the area of the roads buffer from square meters to acres.

The next step is to build another Inquire Cursor in VBA that loops through the acreage of the buffer, sums it, and then divides the total debris/acre by the total acreage in order to return to the user a value of total debris for the area of interest. Ideally, this tool should be predictive. The true benefit is that it may predict debris quantities before a storm strikes; the input data used to determine debris was based on post-storm measurements. At this time, the tool has no predictive capacity. The statistical analysis of available data (Chapter 2) needs to be incorporated so the tool can estimate debris based on pre-storm input variables. This will enable the model to be predictive and therefore be far more useful to the user.

This tool does not rely on estimations of biomass derived from pre-storm UFORE data. The nature of this relationship may prove useful to the ultimate development of an accurate, predictive, spatial model of hurricane-caused tree debris. Further exploration and analysis of the relationships between pre-storm urban forest biomass post-storm tree debris may yield results that can be applied to the tool's programming processes in order to produce more accurate spatial predictions of hurricane-caused tree debris.

This model assumes the user will have performed all necessary data manipulation prior to importing data to the model as inputs, which includes synchronizing the projections and coordinate systems and determining what specific roads shall be considered "major". In this case, the major roads were first extracted with a "Select by Attributes" and then constrained to the Houston City limits using the ArcGIS Clip tool. The lack of local knowledge of major roads in Houston may have resulted in the selection of inappropriate roads such as elevated Interstate Freeways that are outside the city's jurisdiction and are unlikely to have high amounts of debris based on their

physical characteristics. The assumption that the user possesses local knowledge cannot be addressed; local knowledge is required. Ideally, a short companion document should be developed as a user's manual for the debris model in order to address frequently asked questions and assumptions the model makes of the user's ability to correctly manipulate the data prior to inclusion in the model. Development of such a document, while recommended, is beyond the scope of this project.

This model is limited in its lack of flexibility to extract debris values by mask and by the cell size of the Kriging prediction map—the mask in this model is hardcoded as a 60-meter buffer of major roads with a prediction map cell size of 30. Flexibility in choosing an extraction mask (i.e.—a layer of city properties or a layer of residential properties) and the prediction map cell size can be incorporated into the VBA interface as selectable parameters. While this model is simple in its design, there are ways that the user experience could be improved. Adjustments to the model interface such as the addition of a "Browse" command button to set the filepath of the output file will make the model more adaptable. In addition, the inclusion of an "About" command button and/or a related image may better define the intent and scope of the model's capability.

Conclusion

In summary, this tool posed by this framework should be considered a pilot project that is foundational for the development of more sophisticated models and tools in the future. While this tool helps the user to better understand the generation and distribution of tree debris, its many assumptions and limitations hinder the tool's results and applicability. The adoption of the aforementioned recommendations to address the assumptions and limitations is planned and will lead to the development of a relatively accurate and predictive debris estimation tool.

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BIOGRAPHICAL SKETCH

Benjamin K. Thompson was born in Oxford, CT. He earned his Bachelor's of Science degree in Urban and Community Forestry from Unity College in Maine in May of 2000. After five years of employment as the Community Assistance Forester for the Washington State Department of Natural Resources' Urban and Community Forestry Program, Benjamin came to Gainesville, FL to pursue his Master of Science degree in the School of Forest Resources and Conservation at the University of Florida. He received his M.S. from the University of Florida in December 2009.