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INTEGRATION OF GEOSPATIAL TECHNIQUES IN THE ASSESSMENT OF VULNERABILITY OF TREES TO ICE STORMS IN NORMAN, OKLAHOMA

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INTEGRATION OF GEOSPATIAL TECHNIQUES IN THE ASSESSMENT OF VULNERABILITY OF TREES TO ICE STORMS IN NORMAN, OKLAHOMA

A DISSERTATION APPROVED FOR THE
DEPARTMENT OF GEOGRAPHY

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Table of Contents

List of Tables

Table		Page

List of Figures

Figure		Page

Abstract

Every year, natural hazards such as hurricanes, floods, wild fires, droughts, earthquakes, volcanic eruptions, and ice storms destroy millions of trees across the World and cause extensive damage to their species composition, structure, and dynamics. Recently within the last decade, ice storms has caused catastrophic damage to trees, infrastructures, power lines in Oklahoma, and has taken over several dozen human lives. However, studies pertaining to the vulnerability and assessment of tree damage from ice storms in Oklahoma are almost non-existent. This study aims to fulfill that gap by first integrating remote sensing (RS) and geographic information systems (GIS) to assess and estimate tree damage caused by the December 8-11, 2007 ice storm that struck the north-central part of Oklahoma. It also explores the factors that contributed to the tree damage and created multiple regression models based on the factors. Finally, it examines the vulnerability of trees to ice storms by creating an ice storm tree damage vulnerability index for the City of Norman, Oklahoma.

The integrated RS and GIS method assessed tree height and crown damage with high degree of accuracy. The thickness of ice accumulation has emerged as the most important predictor, followed by tree branch angle and

pre-storm crown, wind, stem, and branch diameters for tree damage from ice storms. Results indicate that the vulnerability index accurately predicted several areas that are highly vulnerable.

Results from this study are significant from both theoretical, and methodological and implication perspectives. The present study contributes significantly by identifying the geographic conditions of the City of Norman that make its urban forestry vulnerable to ice storm damage. In doing so, it initiates steps for future tree vulnerability research. Methodologically, the study contributes significantly to geospatial technology paradigm in geography by integrating RS and GIS to assess tree damage not only on a change/no change basis, but also by quantifying the damage. Finally, the methods and techniques developed in this study can not only assess damage from future ice storms, but can also quantify damage from other natural disasters in other parts of the world as well.

CHAPTER I

INTRODUCTION

Analysis of tree vulnerability and tree damage estimation are an integral part of sustainable forest management, urban landscaping, and environmental conservation. Every year, natural hazards such as hurricanes, floods, wild fires, droughts, earthquakes, volcanic eruptions, and ice storms destroy millions of trees across the World and cause extensive damage to their species composition, structure, and dynamics (Bragg et al. 2003). For trees, vulnerability to natural hazards varies over geographic regions with spatial variations of biological, climatic and edaphic conditions. "What makes tree species vulnerable to natural hazards?" and "How quickly and efficiently can their damage can be estimated?" are fundamental, yet unexplained questions.

Contemporary natural hazard research has taken its widest diameter encompassing social, technologically built environments and has shifted its approach from traditional impact assessment to a broad environmental risk and vulnerability analysis. In this paradigm of geography, disaster damage risk is viewed as the function of the hazard, and social, economic, and technological vulnerability of a place (Mileti 1999; Tobin and Montz 1997;

Turner et al. 2003; Wisner et al. 2004). Analysis of vulnerability and assessment of risks are necessary to predict the probability of damage, and to develop a viable emergency rescue and mitigation plan for future hazardous events. Geographers, along with other social and natural scientists, have played a vital role in understanding the impacts of hazards on people, place, society and environment, and in the formulation of hazard adjustment and mitigation strategies (Cutter 2002; White and Haas 1994).

In North America, natural hazards such as hurricanes, floods, wildfires, and volcanic eruptions affect the urban trees and forests along coastal areas. However, ice storms cause substantial damage to trees in the sub-arctic and arctic climates of the North American “snow belt” that encompasses Canada and the northeastern and central parts of the United States (Bragg et al. 2003). Therefore, existing ice storm tree damage studies were mostly conducted in southern and southeastern Canada, and in the northern and northeastern United States. However, ice storm tree damage study in Oklahoma is virtually non-existent despite the fact that the annual catastrophic ice storms impacted the State in recent years (Table 1.1). These individual storms caused millions of dollars worth of damages and injures and killed dozens of people (Bragg et al. 2003; Irland 2000; Smith 2000; Van Dyke 1999). The present study will examine the vulnerability of trees to ice storms in the City of Norman, Oklahoma. It will develop and test an integrated RS and GIS assessment methodology using a case study from tree

Table 1.1: Major ice storms affecting the State of Oklahoma from 2000 – 2007. (Data gathered from weather and damage reports)

Date	Amount of Ice (in Inches)	Number of Counties Affected (Total = 77)	Property and Crop Damages (in Millions of USD)	Number of People Without Power	Fatalities
Dec. 25-27, 2000	2 – 3	64	170	170,000	27
Jan. 28-30, 2002	2 – 3	45	200	NA	NA
Dec. 3, 2002	0.75 – 1.75	32	4.5 (power utility)	55,000	NA
Dec. 18-20 & 28-29, 2006	Up to 1.5	3	2 (power utility)	NA	0
Jan. 12-15, 2007	Up to 3	26	75	> 100,000	32
Dec. 8-11, 2007*	**1 – 1½**	**48**	**250**	**1.5 Million**	**27**

*Storm under consideration for this study.

damage caused by the December 8-11, 2007 ice storm. It will utilize the case study to also explore the factors that contributed to ice storm tree damage in order to develop an index of tree vulnerability to ice storms. The study will be based on a conceptual framework that will encompass hazard risk and vulnerability research and geospatial technology with implications on geography and forestry.

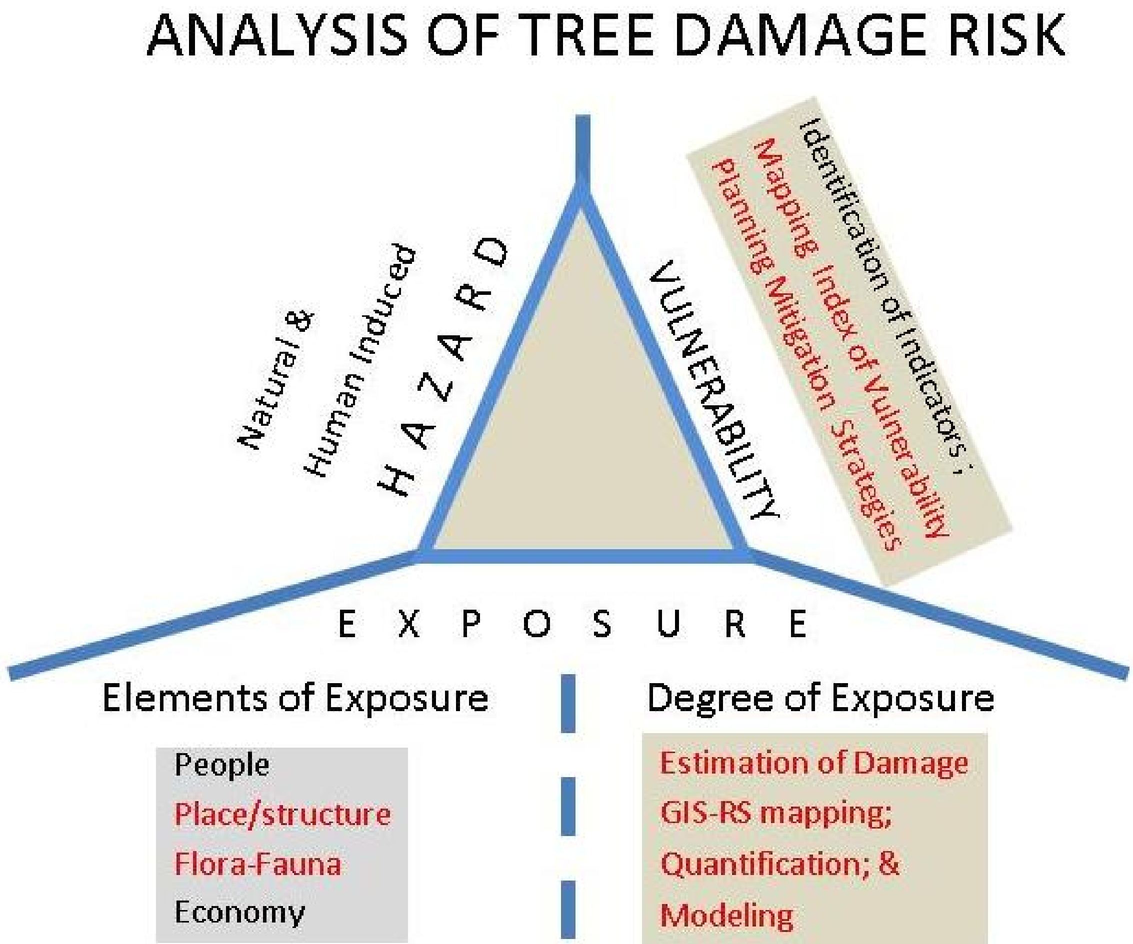
Although ice storm tree damage assessment began in the early 20^{th} century (Harshberger 1904; Illick 1916), current tree damage assessment methods involve time consuming manual counting of individual damaged trees of certain species within sample areas. Since ice storms affect large geographic regions and large number of tree species, the manual damage assessment method yields limited database that is inadequate for predictive modeling of tree damage, an issue that is important for planning effective tree loss mitigation strategies. The motivation of this research stems from the potential geospatial technologies (GIS & Remote Sensing) can offer to this area of study, and this to enable a rapid and accurate assessment of ice storm tree damage over larger geographic regions.

The Analysis of Risk: A Conceptual Framework

One of the most important contributions of hazard research is the analysis of risk based on the nature of hazard, exposure, and vulnerability. The risk analysis exercise involves identification of hazard and elements exposed, measurement of the consequences of exposure (damage assessment), search for indicators of vulnerability, mapping damage and index of vulnerability of place and element, and formulation of mitigation strategies (Figure 1.1). Hazard can be natural, and human induced (technological, famine due to entitlement failure, war, terrorism and violence); exposure includes the elements of human, social, and ecological systems; and vulnerability indicates the likelihood of an element to be impacted by hazards. People, flora and fauna, roads, building structures, economy are elements of exposure and they are vulnerable to hazards. Measurement of the consequence of hazard exposure involves the assessment of damage of elements by way of direct field assessment and analysis of remotely sensed images and mapping the damage area using geographic information systems (Hodgson and Cutter 2001). The computation of indices of vulnerability involves the identification of indicators of vulnerability and factors that make an element susceptible to the hazard.

The term vulnerability refers to an extent to which a socio-ecological system, or its component elements, is likely to be damaged due to exposure to a hazard that originates either outside the system (purturbated) or within the system itself (stress/stressor) (Adger 2006; Turner et al. 2003). Theories of vulnerability fall into: risk and hazard (RH), pressure and release (PAR), human/political ecology (HPE), entitlement failure (EF), and place-based (PB) categories (Adger 2006; Rashed et al. 2007; Turner et al. 2003).

Figure 1.1: Conceptual framework of Ice Storm Tree Damage Analysis.



Burton and colleagues developed the risk-hazard theory which assumes a process that begins with the hazard, experiences exposure and ends with its impacts; and contends that the impact of hazard is a function of exposure to the hazard and the dose-response (sensitivity and adaptability) of the entity exposed (Burton et al. 1993; Turner et al. 2003). In this theory, vulnerability is implicitly measured as a residual of impacts after adaptation (Adger 2006; Kelly and Adger 2000). Human ecologists Hewitt and Watts formulated the human/political ecology theory of vulnerability and explored a direct relationship between political economy and vulnerability (Hewitt 1983; Hewitt 1997; Watts 1983). The theory contends that economic disparity increases the vulnerability of marginalized population to natural hazards.

The pressure-and-release (PAR) theory proposed by Blaikie et al. (1994), synthesizes the natural hazard and human ecological perspectives and assumes that the risk is a product of hazard and vulnerability; and that disaster depends upon the conditions that produce vulnerability and increase *pressure* or stress on a system *and* the opportunity to release the pressure in the form of natural hazard event (Blaikie et al. 1994; Wisner et al. 2004). Vulnerability progresses from *root causes* and filters through a *dynamic pressure* from process and activities inherent in local geography and political economy that transforms the root cause into *unsafe conditions* under which the occurrence of a natural hazard will cause disaster.

The entitlement theory of vulnerability, developed by Sen (1981, 1984), assumed a link between economic and institutional factors and captured the notion that the vulnerability of famine and food security is a result of failure of entitlement rather production shortfalls of food (Sen 1981; Sen 1984). The theory ignores the impact of physical environment as a cause of vulnerability to famine.

Cutter (1996) and Cutter et al., (2003) proposed the place-based theory of vulnerability and argued that vulnerability of socio-ecological system to hazard should be analyzed in the context of place. The theory argued that earlier vulnerability theories has been formalized either in the context of exposure (condition that make the element vulnerable to hazard) or in the context of social conditions (conditions that make the element resilient to hazard), and ignored the context of place (conditions of place that make the element vulnerable or resilient to hazard). Cutter et al (2003) suggested a synthesis of exposure and social resilience with a focus on place because the location of place significantly affects the degree of vulnerability of people to hazard (Cutter 2002; Cutter et al. 2003).

The place-based theory has been extended to emphasize the hierarchy of place (global-national-regional-local) in which socio-ecological systems operate and are exposed to hazards. Rashed et al (2007) integrated basic components of risk-hazard, pressure and release, cultural ecological theories of vulnerability within the context of a hierarchy of place (in terms of scale e.g., neighborhood, city, region, country) in which hazard occurs, and affects the people who resides in those areas. They proposed the concept of urban vulnerability to examine the vulnerability of city as socio-ecological system having the capability of intervention, resistance and resilience to cope with hazards (Rashed et al. 2007).

The existing risk analysis research has examined the vulnerability of people, economy and urban structures as elements of exposure to hazards. However, they have ignored the fact that both flora and fauna living in an ecosystem are also exposed to hazards, suffer damage, and cope with and develop resilience to hazard. The analysis of risk of tree damage due to natural hazards is an important research question and should be examined in the context of place where they exist such as natural vegetation and urban forestry. The present study aims to examine tree vulnerability to ice storms in the City of Norman. The basic assumption underling this study is that trees are exposed to hazards; they suffer damage, cope with the post-hazard situation according to their adaptive capacity; they become resilient over time and continue to grow; and their vulnerability depends upon their biological characteristics and the bio-physical conditions of the place where they are located. This assumption demands a synthesis of the risk-hazard, pressure and release, ecology, place-based theories of vulnerability into a hybrid model.

The proposed hybrid model of vulnerability of urban trees to natural hazards addresses the hazard (ice storm); trees which are exposed to the hazard and suffer damage; and the degree of damage resulting from biological and physical conditions that determine their degree of adaptation (dose-response or sensitivity). Vulnerability of trees progresses from *root causes* (thickness of ice, wind speed, etc.) and is filtered through a *dynamic pressures* embedded in local geography (soil, elevation, and slope) and biological characteristics that transform the root cause into *unsafe conditions* under which the occurrence of ice storms will cause substantial tree damage. The location of trees in the context of their ecological niche determines the extent to which the trees will be vulnerable to hazard damage. Finally, tree vulnerability to hazard exposure varies with the hierarchy of place in which they live: trees of natural vegetation respond differently to hazards than the urban trees because the ecological conditions, species composition and tree structures of natural vegetation is different from those in urban areas.

The study is organized into **three components**. The *first component* is devoted to estimate the magnitude of tree damage from the December 8-11, 2007 ice storm in Norman Oklahoma by using an integrated RS and GIS technique. It utilizes Light Detection and Ranging (LiDAR) data to assess individual tree damages to answer:

- *How accurate would the ice storm tree damage assessment be using RS and GIS?*

Based on literature review and field research data, the *second component* of the study attempts to develop tree damage models in order to address the question:

- *"What factors affect tree damage and make urban trees vulnerable to ice storms?"*

Finally, based on an extensive review of literature on ice storm and tree damage, the *third component* addresses the question:

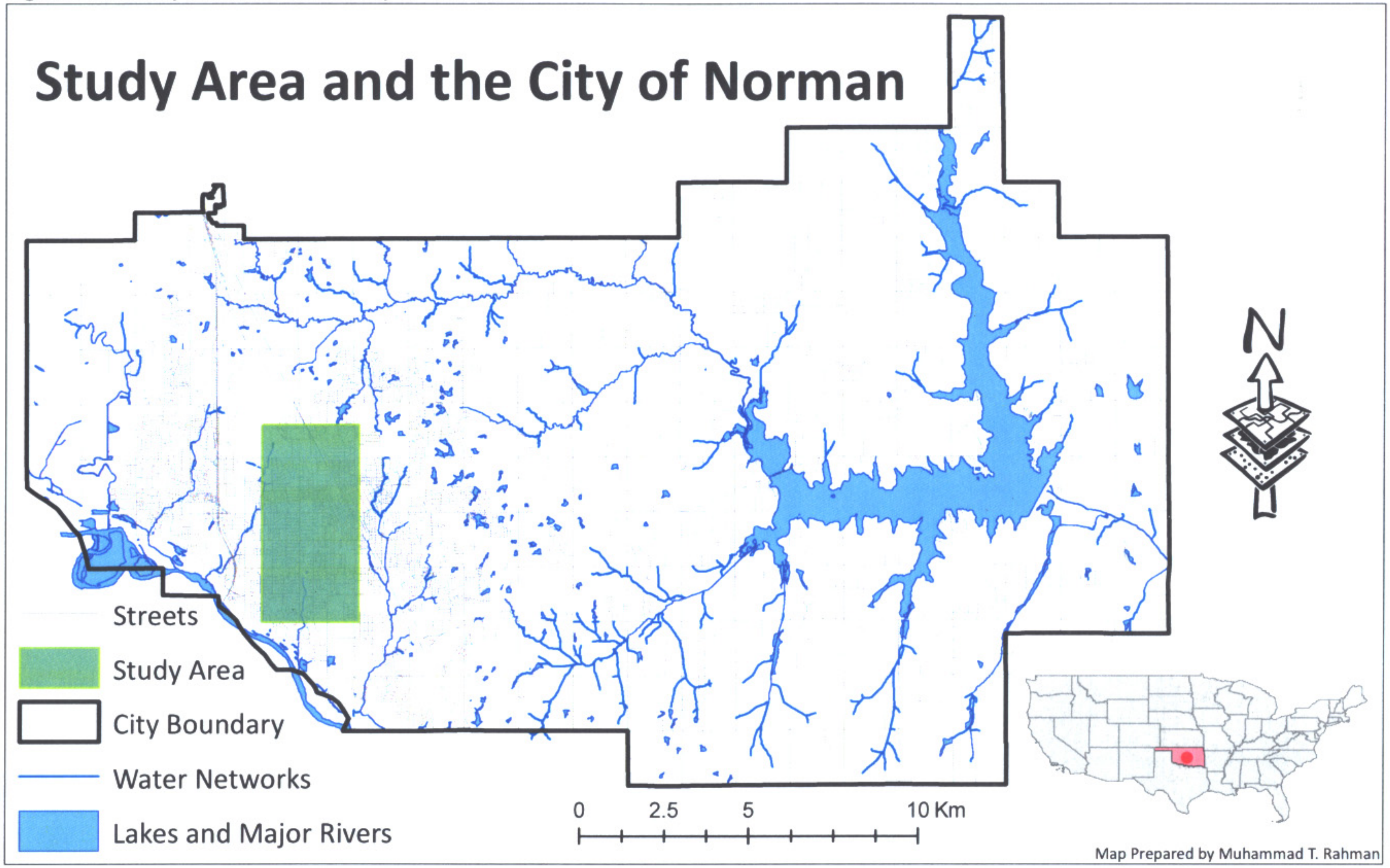
- *"Based upon the estimated tree damage data from the December, 2007 ice storm and the factors affecting its magnitude, which areas of the City of Norman are vulnerable to ice storm tree damage; and which tree species are most vulnerable?"*

Study Area

The three components will all be addressed within approximately 18 sq. km in the center of the city of Norman (Figure 1.2). The city was selected for this study because of its frequent exposure to ice storm in recent years that has increased its vulnerability of tree damage. Located in Cleveland County, about 32 km south of Oklahoma City, Norman is a small town with an area of 492 sq. km and population of 102,827 (U.S. Census, 2006). The city is characterized by an undulating surface topography with an elevation ranging from 332-378 m above mean sea level. Several small creeks cut across the city creating slope and topographic variations. The city contains 9 major soil types that reach up to 2.14 m, with Kirkland soil covering the majority of the study area. The average clay concentration among these soils is almost 40%. The City enjoys a humid subtropical climate and annually receives about 15-12 cm of snow with freezing temperatures starting around the first week of November and ending during the first week of April (Oklahoma Mesonet, 2009). Most of the ice storms typically affect the city during the months of December and January.

Norman's vegetation is characterized by a mosaic of Tallgrass prairie and Postoak-Blackjack Oak forest. A tree inventory conducted during 2000 within 1.3 sq. km found a total of 48 tree species in which 13 species were found to be predominant (more than 1.5% of total sample) (Appendix I).

Figure 1.2: Study area within the City of Norman.



Significance of Study

The study results are significant from both theoretical, methodological, and policy implication perspectives. First, the study examines the city of Norman's vulnerability to ice storm tree damages. In the literature on natural hazard and vulnerability, geographers and other social scientists have attempted to identify human vulnerability to natural disaster by building models and identifying indicators of vulnerability. However, they have ignored the question of vulnerability of plant and animal species to natural disasters. Spatially, some geographic regions offer unsafe climatic and edaphic conditions that make trees more vulnerable or resilient to ice storm. Foresters, as pioneers in tree research, have developed ice storm sustainability index for various plant species (Mou 1999). However, they have not examined what geographic conditions make those species more vulnerable to ice storm. The present study contributes significantly by identifying the geographic conditions of the City of Norman that make its urban forestry vulnerable to ice storm damage. Although the study is limited to a small part of the state of Oklahoma, its underlying concept of vulnerability of tree species can be applied to examine vulnerability of forest in other parts of state and the country.

Methodologically, the study makes a significant contribution to geospatial technology paradigm in geography. Previously, the LiDAR data has been successfully used to estimate tree heights, canopy sizes, crown diameters, and tree volumes of individual and group trees in natural forest at a single time period. However, this technology has not been used to study tree damage in an urban setting where previous studies using passive RS data have yielded some confusing results. This study used airborne pre- and post-ice storm LiDAR data to detect tree damage caused by the December, 2007 ice storm in the City of Norman. The accuracy of the LiDAR data is evaluated by comparing the LiDAR data results with the field data collected from the study area. Once evaluated its accuracy level, the estimated tree damage data will be mapped using GIS platform to identify the areas and trees species damaged by the ice storm. Thus, the proposed method will open a new venue to study tree damage by natural hazard.

Third, form policy implication perspectives, an accurate measurement and mapping of the degree and areas of tree damage immediately following a natural hazard will help city managers, state agencies, urban landscape planners, emergency respondents to plan the response operation fairly quickly and easily after the occurrence of a natural hazard. The method will also help commercial forest growers to take inventory of trees, their growth and damage due to various disease, deforestation measurements, timber production, and forest planning. The State of Oklahoma has over 35,000 acres of pecan orchards that suffers severe damage after ice storm. The method developed here will help farmers to immediately identify those trees that are damaged and are at risk of dying. One concern of this method, however, would be the cost of obtaining LiDAR data from commercial LiDAR companies. With increasing users, newer instruments, and improving technologies, the collection of LiDAR data is expected to decrease significantly over the next decade. The method has greater advantage over the ground assessment of tree damage as the LiDAR sensors are able to collect data over larger geographic regions.

Organization of the Dissertation

This dissertation will be organized into five chapters. Chapter one has outlined the theoretical framework for this study and scope of this research. It has also outlined the research questions, and the significances of this study. The next three chapters are presented separately discussing the three separate components, their objectives, underlying hypotheses, methodology, results and their analysis in research paper formats that are ready for submission as three major scientific journal articles. Finally, chapter five summarizes the study and makes concluding remarks focusing on the objectives and the hypotheses and findings regarding tree damages due to ice storms in Oklahoma and provides directions for future research.

The first paper presents the integrated RS-GIS method used in the assessment of ice storm tree damage from the December, 2007 ice storm within the study area. In this paper, various RS and GIS technologies are discussed and their advantage and disadvantages in estimating tree damage due to natural disasters are outlined. In addition, the effectiveness of LiDAR data in estimating tree damage from ice storms is discussed by using Norman as a case study. This paper will be submitted to the *International Journal of Remote Sensing* for possible publication.

The second paper identifies the factors affecting tree damage. It proposes and tests the ice storm tree damage model for the city, and identifies the factors and conditions affecting tree damage. It also identifies the indicators to vulnerability of tree damage from ice storm. This paper will be submitted to the *Professional Geographer* for possible publication.

Using the regression coefficient weights gathered from 8 individual factors from the second paper, the third paper constructs and index of vulnerability to ice storm tree damage for Norman. It identifies the areas and tree species that are vulnerable to ice storm damage. The paper will be submitted to *Natural Hazard Review* for possible publication.

CHAPTER II

ICE STORM TREE DAMAGE ASSESSMENT USING AN INTEGRATED AIRBORNE LiDAR DATA AND GIS APPROACH

An important component in risk analysis and hazard mitigation research is the assessment of damage of resource due to its exposure to natural hazard. Rapid and accurate assessment of damage is the key to launch successful relief and recovery operations. The integrated use of Remote Sensing (RS) and Geographic Information Systems (GIS) allows quick and accurate estimation of damage, identification and mapping of areas affected by the disaster, the spatial attributes of damage; and hence, contributes significantly to risk analysis (Hodgson and Cutter 2001). This technique is particularly useful when comparing pre- and post-hazard resource inventory data, thus allowing researchers to efficiently estimate the damage caused by natural hazards.

Estimation of tree damage from natural hazards has received wide attention from biologists, foresters, bio-geographers, city planners and environmental geographers for creating inventories of trees in commercial forests and monitoring changes and its effects on the ecosystem and in the landscape. A natural hazard may affect small and/or large geographic areas but the degree of tree damage varies with tree characteristics, climatic, and edaphic conditions of the region. Tree damage estimation, which involves the collection of large quantity of data on factors affecting the degree of damage, poses a major methodological and technological challenge for hazard researchers. Despite its frequent use in hazard research, an integrated RS and GIS has not been used to estimate tree damage from ice storms. Various types of RS data are available to perform tree damage assessment, but each comes with certain advantages and limitations. For example, Landsat ETM+ data may be used, but the data is only available every 16 days during which severe changes can take place. So, it is important for any RS-GIS methodology for tree damage assessment to incorporate a strategy for determining the ideal RS data source that will be useful for accurate estimation of tree damage from ice storms and other natural hazards. The present study develops an integrated RS-GIS methodology to estimate tree damage caused by the ice storm of December 8-11, 2007 in the City of Norman, Oklahoma.

Objectives

The present study examined the utility of an active LiDAR aided RS in the assessment of tree height and canopy damages caused by the above mentioned ice storm in Norman. It compared the pre- and post storm LiDAR data and analyzed tree damages from the 2007 ice storm by: identifying the locations of individual trees; extracting the heights and crown diameters or outlines of those individual trees; and calculating the difference between pre- and post-storm tree heights and total canopy coverage of those trees. Once the tree height and canopy damages are assessed, the study performed a hot spot analysis to identify the areas where trees were completely damaged.

Several studies have found tree heights derived from LiDAR data for forest areas to have RMSEs of less than 1 m while the accuracy for estimating canopy diameters is much lower (R^2 values between 0.53 and 0.74) (Leckie et al. 2003; Maltamo et al. 2004; Persson et al. 2002; Popescu 2007; Falkowski et al. 2006; Næsset and Bjerknes 2001; Hyyppä et al. 2000). Since this study was undertaken in an urban setting with variations in tree species and presence of buildings and infrastructures, it is expected that high degree of accuracy may still be achieved in detecting individual tree heights, crown diameter and canopy damage compared to previously used passive RS. Based on this assumption, the following two hypotheses were examined:

I) *In an urban setting, the LiDAR aided RS can detect tree height and canopy damage more accurately than a passive RS (possibly better than 70% accuracy as yielded in passive RS).*

II) *In an urban setting, the LiDAR aided RS can detect tree canopy outline more accurately than the passive RS.*

The study is organized in three sections. First section is devoted to examining the existing studies those have used LiDAR and passive RS data to assess tree characteristics and their damage. Second section describes the detailed methodology of two tree extraction techniques that were used in this study and integrated with GIS to isolate individual trees and calculate their trunk and canopy damage from the storm. Finally, the last section explains the analyses and results that were obtained from the study. Concluding remarks and possible future studies are also given following this last section.

Geospatial Techniques of Tree Damage Assessment

Tree damage by natural hazards takes three major forms: breakage of branches and limbs, breakage of tree trunks, and complete breakage or uprooting. All three forms of damage result in decrease in height and crown diameter of an individual tree. Therefore, measurement of change in height and crown diameter of individual trees during the pre- and post-hazardous event is the most important task in tree damage assessment. Remote sensing allows detection and mapping of tree damages and monitoring of vegetation changes in forest and urban areas by capturing the vegetation reflectance for pre- and post-hazard periods over a large geographic area (Olthof et al., 2004).

Based upon their operational principles, remote sensing data can be of passive and active types. Passive remote sensing data (e.g., Landsat ETM+) are useful to detect forest cover change (growth or damage) within a large geographical region. Various studies have used passive remote sensing data to collect vegetation reflectance and create Normalized Difference Vegetation

Indices (NDVI) for an area. Taking the pre-hazard NDVIs as a base line and comparing them to the post hazard NDVIs has been found to have average accuracy level of approximately 70% in detection and mapping of damage and spatial patterns of changes in forest coverage due to various natural hazards (Cakir et al. 2006; Franklin et al. 2000; Olthof et al. 2004; Roberts et al. 1999; Rogan et al. 2002). However, passive remote sensing data suffers from two major weaknesses in context of visibility and classification of objects which severely hinder its utility in tree damage assessment at the individual tree scale. First, the clouds, gases, aerosol and dust particles present in the atmosphere absorb and scatter electromagnetic radiation signals, and distort the vegetation reflectance of leaves. Such distortions cause significant losses of information when the pre- and post-hazard images are compared to detect forest damage (Song et al. 2001). Second, the availability of data at proper time intervals (i.e., temporal resolution of imagery) could hinder rapid damage assessment following a disaster. With their limited spectral and spatial resolutions, passive remote sensing data only classifies pixels on a change/no change basis and most importantly, fails to indicate the magnitude of loss of heights and/or canopy coverage. Therefore, their suitability in assessing damages of individual trees within an urban neighborhood scale is very limited (Olthof et al. 2004; Popescu 2007; Rogan et al. 2002).

Some of the above mentioned limitations of passive remote sensing data in tree damage assessment may be resolved by using active remote sensing data (e.g. LiDAR). LiDAR data can be collected for a large area within a very short time and allows the estimation of height and crown diameter of individual trees (Clark et al. 2004; Næsset and Økland 2002; Popescu 2007). The data are collected by a sensor attached to a small airplane flying at a low altitude (<3,000 m). The sensor emits laser energy pulses from the airplane, which reach the tree-tops, its understory branches, and the ground surface and then reflect back to the sensor (Arp et al. 1982; Lim and Treitz 2003; Ritchie et al. 1993). The LiDAR system records the amount of time it takes for the laser pulses to return back to the sensor and the time measurement is converted into distance using the speed of light. The distance measurements are used to derive a three-dimensional view (with x, y, and z coordinates) of the surface using the Differential Global Positioning Systems (DGPS). When plotted, the continuous wave of laser reflections forms a three-dimensional model with x, y, and z coordinates. Taking the differences between the first and last return LiDAR points produces a model with dome-shaped clouds with peaks. Each cloud peak represents an individual tree and the distance from ground to the top of the peak indicates their location and maximum height (Anderson et al. 2006; Clark et al. 2004; Leckie et al. 2003; McCombs et al. 2003; Næsset and Økland 2002; Persson et al. 2002; Popescu et al. 2003). The laser pulse reflectance at different heights forms individual domes indicating canopy; and the width of the widest dome indicates the tree crown diameter (Maltamo et al. 2004; Popescu et al. 2003). Researchers have also found direct relationships between tree heights obtained from LiDAR data and other individual tree and forest parameters including above-ground biomass (AGB), Leaf Area Index (LAI), basal area, crown closure, stem density, and timber volume (Holmgren and Holmgre 2004; Jensen et al. 2008; Næsset and Økland 2002; Popescu et al. 2003).

LiDAR Data and Ice Storm Tree Damage Estimation

LiDAR data has been used in numerous studies to estimate tree losses from natural disasters such as hurricanes (Parker and Evans 2009; Weishampel et al. 2007), forest fires (Wulder et al. 2009), and insect defoliation (Eklundh et al. 2009). However, the technology has not been used to assess tree damage from ice storms which can be assessed from LiDAR data by first extracting the location and crown outline (diameter) of individual trees from the pre-storm LiDAR data. Once the crown outlines are extracted, the pre- and post-storm LiDAR data could be compared and differences between the maximum heights and the summation of pixel values (to represent crown coverage) within the crown outer boundaries could accurately indicate the magnitude of height and crown damage for each tree. However, several situations and factors may influence the degree of accuracy. For example, in cases where a damaged tree stem/trunk is bifurcated into two or more branches with same height, and or the highest tree top point is shifted, post-storm tree heights and canopy area may also shift creating some errors in height and canopy damage estimations. Also, in urban neighborhoods where groups of trees are often found with branches/canopies intertwined with each other, it may be difficult to extract the outline of individual tree canopies. Popescu (2008) used LiDAR data collected over a Sam Houston National Forest in southeastern Texas forest containing a mixture of hardwood and pine plantations and achieved about 53% overall accuracy in measuring tree canopy diameters. In urban areas, where individual trees with wide variety of species and tree characteristics are associated with buildings and other structures, tree heights and canopy diameters may be extracted with variable degrees of accuracies.

The December, 2007 Ice Storm and the Study Area

A massive ice storm struck and caused extensive damages in the state of Oklahoma and surrounding states between 8 to 11 December, 2007. The storm caused almost 2.54 to 3.81 cm thick ice to form on trees and power lines and the extra weight of the massive ice caused the branches of trees, power lines, and power poles to break, resulting in leaving over 1.5 million people without electricity for several days. The storm affected 48 out of Oklahoma's 77 counties; damaged property and crops valued over $250 million; and killed 27 people across the state. Over 100 structural fires from broken power lines and hundreds of auto accidents were reported (NOAA).

The storm severely affected trees and power lines in the city of Norman. Located about 32 km south of Oklahoma City in Cleveland County, Norman is a small city with an area of 492 sq. km and population of 102,827 (U.S. Census, 2006). It was chosen for this study because of its frequent exposure to ice storms in recent years.

The study site was in the center of the city with an area of approximately 18 sq. km (Figure 2.1). The area contains undulating surface topography with elevations ranging from 332 to 378 m above mean sea level. Several small creeks cut across the study area creating variations in the slope and topography. The City enjoys a humid subtropical climate and annually receives about 15-23 cm snow with freezing temperatures starting around the first week of November and ending during the first week of April (Oklahoma Mesonet, 2009). Most of the ice storms typically affect the City during the months of December and January.

An inventory conducted during 2000 has found a total of 48 tree species within 1.3 sq. km in the center of the study area. The distribution of the major trees based on their percentages is given in Appendix I.

Data and Methods

For this study, two primary LiDAR datasets (pre- and post-storm) were required and collected to assess tree damage from the ice storm. The pre-storm data was collected by Merrick & Company of Aurora, Colorado from February 27th through March 3rd of 2007 and was obtained from the City of Norman's GIS Department. The data was accumulated from a 1978 Cessna 402C plane with an attached Leica Geosystems ALS50 LiDAR sensor flying at an average altitude of 2100 m. The data was collected at pulse rates between 100 Hz and 85 kHz, variable scanning frequencies, and scan angles between 5 to 75^{o} degrees. The average Ground Sample Distance (GSD) for the raw LiDAR data was about 1.0 m and it was processed with auto-filtering algorithms followed by hand-filtering to remove erroneous points. A digital elevation model (DEM) at 0.30 m resolution was generated based on the data points. A total of 60 survey control points were used to conduct accuracy assessment of the LiDAR data and Merrick and Company reported a Root Mean Square Error (RMSE) of $<$15 cm for the vertical and horizontal accuracy of the pre-storm data.

The post-storm data was collected by Airborne 1 Corporation of El Segundo, California on July 10, 2008 with an Optech Airborne Laser Mapping Technology (ALTM) 33k LiDAR system mounted in a Cessna Skymaster aircraft. The aircraft flew at average approximate airspeed of 119 kts and at an average altitude of 1978 m on 15 separate flight lines. The sensor collected the data at a pulse rate of 33 kHz, scanning frequency of 21 Hz, and scan angle of 18^{o}. Similar to the pre-storm data, the post-storm data GSD was also approximately 1.0 m with a vertical accuracy of 22 cm. All flight lines were combined to form the final data set. Each data point included a Global Positioning System (GPS) time stamp and intensity value, as well as the spatial coordinates in three dimensions.

Integration of LiDAR aided RS and GIS

The study integrated the airborne LiDAR data in an ArcGIS 9.3 GIS platform. The former was used to collect height information of structures and trees while the latter was used to process the LiDAR data in order to estimate and map tree damage caused by the ice storm. The procedure required 3 major steps including (i) creation of the digital elevation model (DEM), digital surface model (DSM), and canopy height model (CHM); (ii) extraction of individual tree outlines along with their heights, and canopy coverage; and (iii) calculating the difference between pre-and post-storm tree heights, and canopy coverage to estimate damage. The detailed methodological procedure for each step is discussed below.

a) Creation of DEM, DSM and CHM

The DEM of the bare ground for the City of Norman was prepared by Merrick & Company and was used in this study. The DSM, representing elevations of the ground surface containing trees, buildings and other objects on it, was derived from the first return points received by the two LiDAR sensors. These points were then interpolated to create pre- and post-storm DSMs.

Numerous studies have previously compared the accuracy in DEM and DSM production by various local and global interpolation methods including Inverse Distance Weight (IDW), Ordinary Kriging (OK), Natural Neighbor (NN), and Regularized Spline Technique (RST). Lloyd and Atkinson found Kriging to create the most accurate DSM when there are few data points (Lloyd and Atkinson 2002b). Chaplot et al. found Kriging to be best suitable in creating DEMs for mountains and rugged terrains. However, for relatively plain landscapes, RST was found to produce the best estimates (Chaplot et al. 2006).

As the number of data points and sampling density increases (as in LiDAR data), there are no significant differences in accuracies between Kriging and IDW or NN (Lloyd and Atkinson 2002a; Liu 2008). Anderson et al. noted that use of IDW and smaller sample size of the LiDAR data can still produce accurate estimated elevations within 30cm (Anderson et al. 2005).

Another important factor in producing accurate DSMs is the spatial resolution (grid size) of the data which determines the computing power requirement and the accuracy level that could be expected from the data. Very high-resolution data may produce detailed representation of the landscape, but would require more computing time. Also, generating high-resolution DSMs with sparse data will represent the shape of the applied interpolator, rather than the true landscape. On the contrary, a lower-resolution DSM with high density elevation points will diminish the accuracy of the original data (Liu 2008). McCullagh suggested that grid size should be the same as the sampling density of the LiDAR data (McCullagh 1988).

To choose the interpolation method that would produce the most accurate DSMs within the study area, the above mentioned interpolation techniques were tested and compared. From a 1000 x 1000 m LiDAR data tile from the center of the study area containing a total of 883,372 first return points, 45,648 points were randomly chosen and separated as reference points. The interpolation techniques were carried out with 0.3 m grid size with the remaining 837,724 test points. Once the four DSMs were created by the four techniques, the interpolated values at the reference points were correlated and their RMSE with the actual LiDAR points were computed using the following formula:

$$RMSE = \sqrt{\frac{\sum (E_{DEM} - E_{\mathrm{Re}f})^2}{n}}$$

Where, n is the number of locations, E_{DEM} and E_{Ref} are respectively actual and estimated elevations. The results are given in Table 2.1.

Table 2.1: Correlation and RMSE values of the four interpolation methods at 0.3m grid size.

Interpolation Method	**Parameters**	**Correlation Coefficients**				**RMSE (m)**	**Time Required**
		IDW	**OK**	**NN**	**RST**		
IDW	Power: 2 Search Radius Type: Variable Number of Points: 12	1.00	0.986	0.989	0.611	3.23	5 Minutes
OK	Method: Ordinary Semivariogram Model: Spherical Number of Points: 12	0.986	1.00	0.978	0.592	2.98	19 Hours
NN	Not Applicable	0.989	0.978	1.00	0.652	3.27	6 Minutes
RST	Spline Type: Regularized Number of Points: 12	0.611	0.592	0.652	1.00	5.51	11 Minutes

It was found that the OK and IDW had a correlation coefficient of 0.986 with the differences in RMSEs of 0.25 m. The RMSEs are given in Table 2.2. Since both produced similar results with IDW requiring less time and computing power to create the DSM, it was preferred over OK for this study. The grid size was chosen by interpolating the data at 0.3 m, 0.61 m, and 1 m using the IDW, NN, and RST interpolation methods. It was observed that the DSM produced at 0.3 m grid size had the lowest RMSE when creating DSMs to estimate elevations of building roofs and tree-tops. Therefore, both the pre- and post-storm DSMs were created at this scale. Finally, the pre- and post-storm CHMs were created by subtracting the DEM from the DSMs using the raster calculator function of the ArcGIS software.

Table 2.2: RMSE values of the three interpolation methods at 0.3, 0.61, and 1 m grid sizes.

Interpolation Method	**RMSE (m)**		
	0.3m	**0.61m**	**1m**
IDW	3.23	3.24	3.24
NN	3.27	3.28	3.29
RST	5.51	5.54	5.49

b) Extraction of Individual Tree Heights

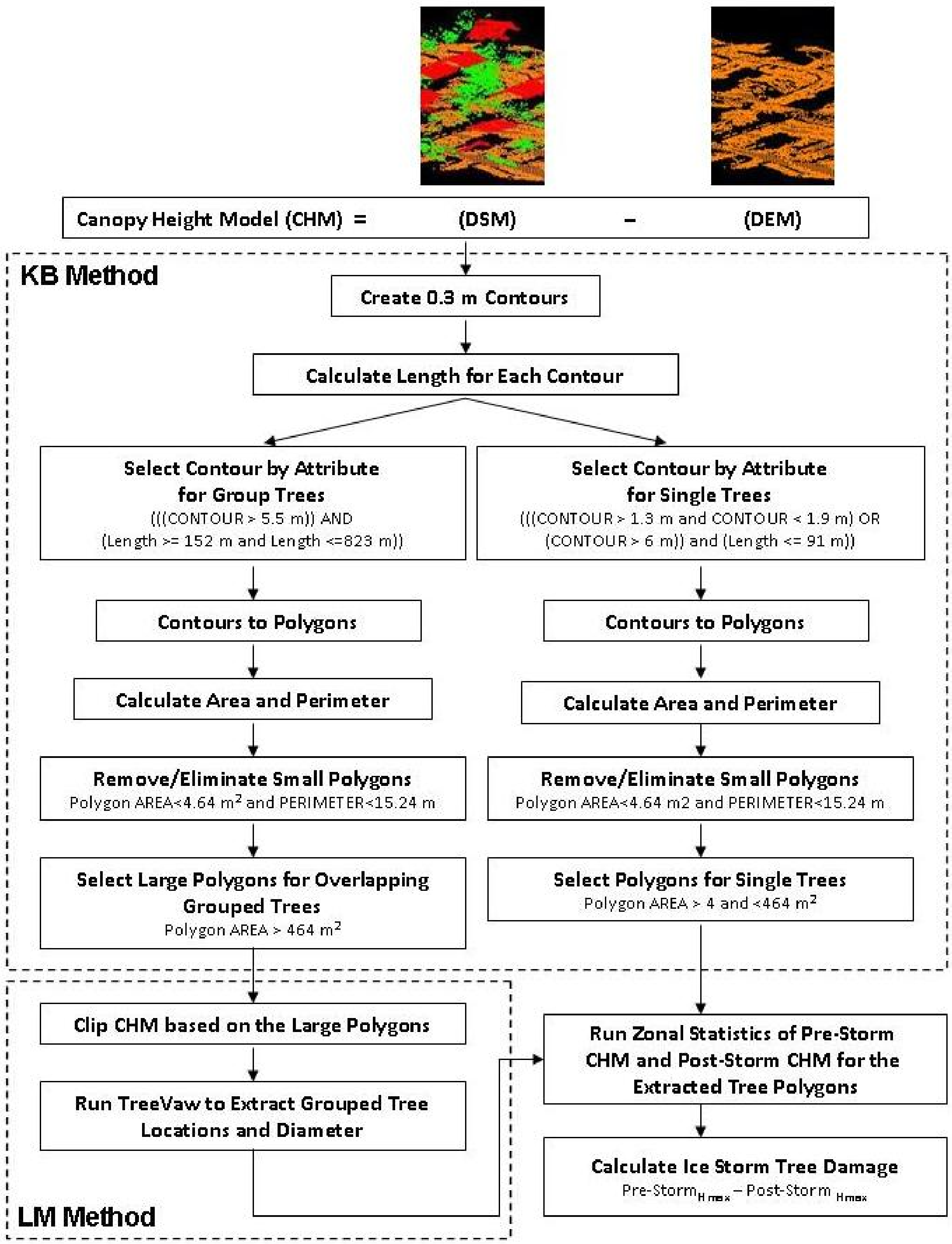
The two techniques that were used for extracting individual pre-storm tree crown outlines were the Koukoulas and Blackburn Approach (KBA) and the Local Maxima Approach (LMA). In this section, some methodological procedures of these two methods are discussed in brief.

i) <u>Koukoulas and Blackburn Method</u>

The KBA was originally developed to utilize LiDAR data on a GIS software platform to map the locations and heights of individual trees in forested areas (Koukoulas and Blackburn 2005). The approach uses specific contour lines created from the CHM produced from step a. Contours of 0.3 m intervals were drawn and the length of each individual contours were calculated. As shown in Figure 2.2, the KBA uses specific parameters (i.e. contour length and polygon areas) to separate houses, and individual as well as grouped trees. However, the various parameters within the method were modified from the original method in order to detect and identify trees in the study area. These parameters were chosen based on field surveys conducted by the authors.

It was found by the authors by manually surveying that the roofs of most residential houses in Norman are less than 6 m high. Lengths of each individual contours were calculated and in order to separate the houses from the trees, contours <1.3 m and between 1.9 and 5.5 m (indicating the base and the roof of the house) were selected and eliminated. Contours >6 m with

Figure 2.2: Detailed methodological steps showing the integration of the KB and the LM methods.



length <91 m were selected and these trees were believed to be single individual trees. For extracting group trees with mixed branches, contours >6 m, with contour lengths between 152 and 823 m were selected. The selected contours were converted into polygons, and only the large outermost polygon (representing the boundary of tree canopies that included all the smaller polygons within) was saved and the small polygons within the large polygons were dissolved. The area and perimeter of each individual polygon were then calculated. Polygons with areas <4.64 sq. m and perimeter <15.24 m were selected and removed since they represented small bushes and other unknown objects. Polygons with areas between 4.64 and 92 sq. m were classified as bushes and small trees; between 92 and 464 sq. m indicated single trees; and mega-polygons with areas greater 464 sq. m indicated groups of trees with overlapping canopies which were then separated to be extracted by the LMA.

ii) The Local-Maxima (LM) Method

The LMA also utilizes LiDAR data and a CHM to estimate the height of individual trees (Popescu et al. 2002). However, to ascertain the location of individual trees, the LM used either square of $n \times n$ dimension and/or circular of n radius search windows. The premise of the LMA is that the reflectance of a tree crown is typically greatest at its apex. When used with LiDAR data, the LMA assumes that the apex is where the laser elevation has the highest value among laser hits of the same tree crown. Based on this value, a successful identification of the tree location using this method requires careful selection of the filter window size; too large or too small filter size will create errors of commission or omission of trees (Koukoulas and Blackburn 2005; Popescu et al. 2002). Field sampling of 100 random trees were conducted to create a linear functional relationship between the height of each tree and their respective crown diameters. The following linear function (where *CW* is the crown width and *hgt* is the height) was found to mathematically represent the best fit model and it was used for the LM individual tree extraction approach:

$$CW = -0.006\, hgt^{\wedge}2 + 0.895\, hgt + 26.651$$

The LMA data were processed by the TreeVaw software (Popescu et al. 2002). The software used the above model to select a window for searching the location of each maximum height corresponding to the summit of the tree crowns on the CHM. The locations of individual trees along with their respective heights and radii were identified and shown in the TreeVaw result file. The individual tree points were then opened in ArcGIS and tree points that fell within the mega-polygons from the KBA were selected. Erroneous points were manually removed and buffers (based on tree radius from the TreeVaw result file) were created to outline each individual tree with overlapping canopies.

Both KBA and LMA initially required a canopy height model (CHM) to extract each individual tree, its height, and canopy diameter (see Figure 3.2

for details). However, their differences in algorithms produced different results. In particular, the KBA accurately identified individual trees but failed to separate grouped trees with overlapping canopies. In contrast, the LMA was capable of separating grouped trees into individual trees and calculated their canopy diameters based on their maximum heights. In urban areas, both single and grouped trees are associated with/among building structures; and for accurate assessments of tree damage, the canopy outlines of both individual and grouped trees should be identified accurately. Hence, a merger of the two methods were necessary and a hybrid of KB-LM method was used in this study to measure tree heights and canopy diameters for individual and grouped trees in the study area.

c) *Calculation of Height and Crown Damage*

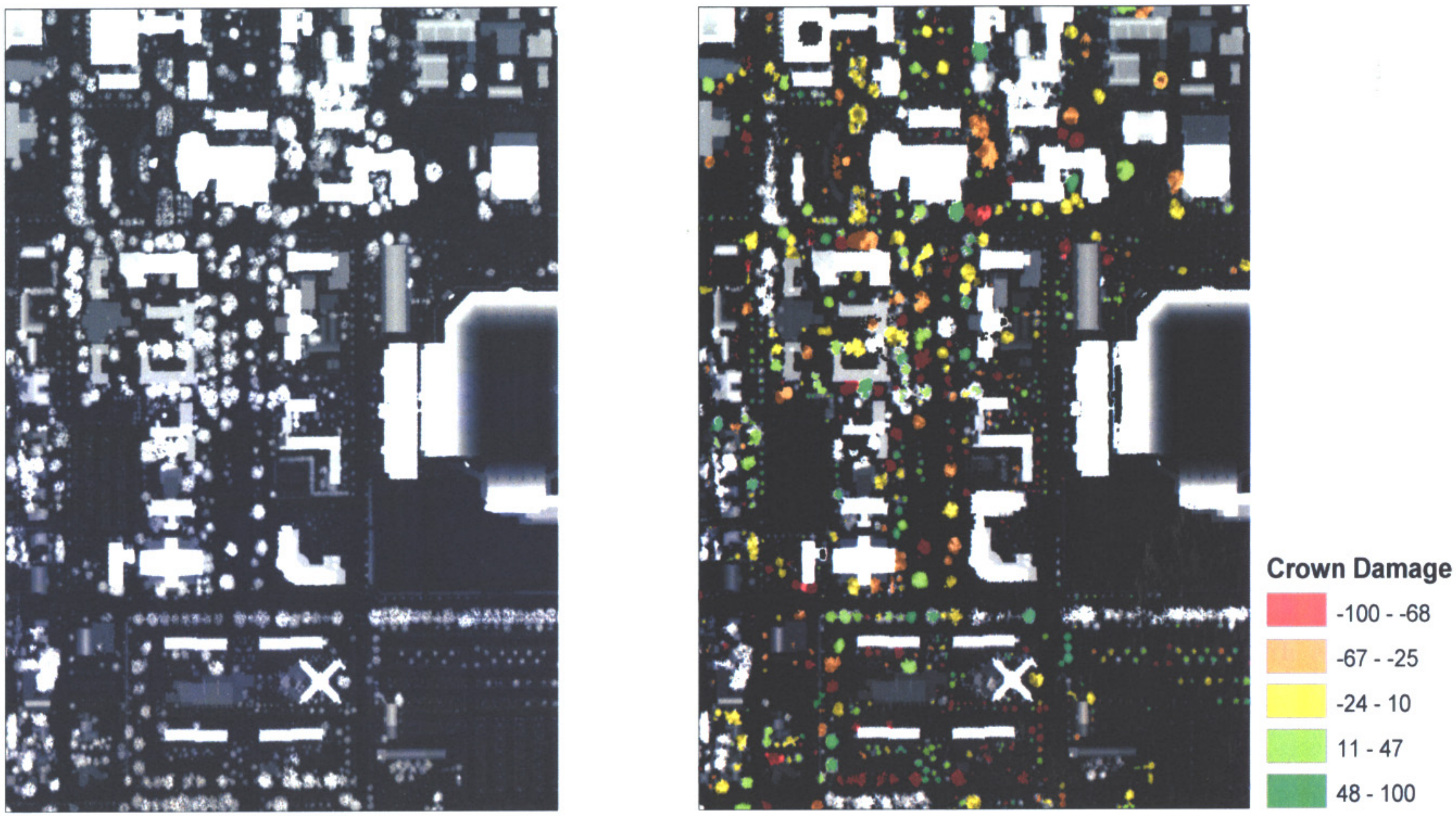
The polygons extracted from the KBA and LMA were used to measure the damage each tree suffered during the storm. Within each individual KBA and LMA buffered polygons, the zonal statistics function of ArcGIS was used to calculate the maximum value (assumed to represent the heights of the tree stems) and the sum of all the pixel values (representing canopy coverage) from the pre and post-storm CHMs. Their differences were calculated which indicated the amount of damage each tree sustained: negative change in maximum heights indicated tree stem damage while no change and positive changes in tree heights indicated its growth, sustainability, and resilience to the ice storm. Similarly, the change in pre and post-storm sums of pixel values indicated tree canopy damage due to the storm (Figure 2.3). The changes were converted into percentages and interpreted in the following scenarios:

- *Scenario A: Decrease in tree height, but no change in canopy diameter would indicate damage of tree stems;*
- *Scenario B: No change in tree height, but decrease in canopy diameter would indicate only canopy damage;*
- *Scenario C: Decrease in both tree height and canopy diameter would refer to both stem and canopy damage;*
- *Scenario D: Unchanged height and canopy diameter would indicate no tree damage;*
- *Scenario E. 100% decrease in height and canopy diameter: total tree damage by uprooting or manual removal of the damaged tree.*

d) Accuracy Assessment via Field Sampling

The accuracy of the tree damage estimation depends on two factors: extraction of accurate crown outlines (diameters) and their heights. The accuracies of these two factors were tested through field surveys conducted between August of 2008 and September of 2009 in the following manner. First, a sample of 524 trees was randomly selected within the study area and their species types were recorded. The sampled trees contained both grouped and single trees. Their pre and post-storm heights and canopy diameters were

Figure 2.3: Canopy Height Models (CHM) showing the amount of crown damage for extracted trees within a section of the study area.



Pre-storm CHM

Post-storm CHM showing the amount of % of crown damage for each tree measured from the LiDAR data using both the KBA and LMA to obtain the *test data*; and percent changes in tree heights and canopy diameters were computed to obtain *test tree damage* data. Because the LMA results showed the radius of the crowns, it was doubled to calculate the tree diameters. For KBA, It was assumed the outline of the tree canopies were in the shape of a circle. Therefore, with their known perimeters, their diameters were calculated using the equation

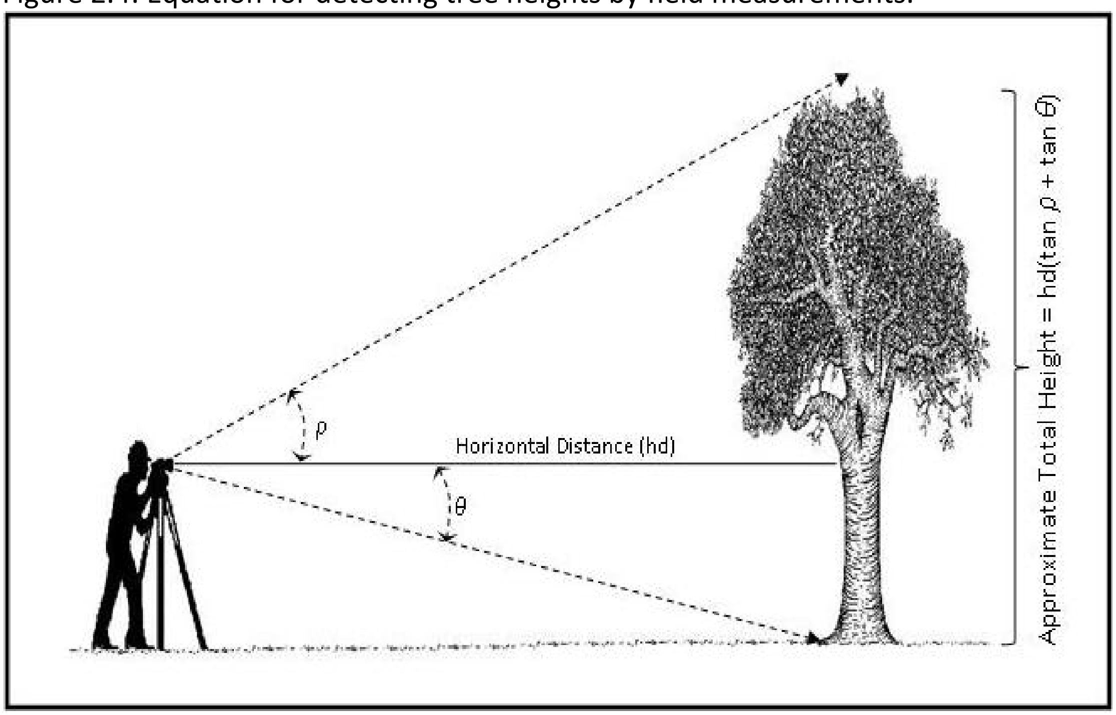
$$D = P / \pi$$

Where D is the diameter of the tree crown and P is the calculated perimeter.

Second, the post-storm heights and canopy diameters of the sampled trees were manually measured in the field using a Brunton compass and a measuring tape to obtain the *reference data*. Due to financial restrictions and unavailability of laser hypsometers, tree heights were calculated by conventional method of measuring distance and angle to the top of trees and then using geometric equation (see Figure 2.4). RMSEs were calculated based on the test and reference data. Third, the post-storm *reference* tree heights and canopy diameters were separately subtracted from the LiDAR extracted pre-storm *test* heights and canopy diameters; and their percentage changes were computed to obtain the *reference tree damage* data. Finally, the *reference tree damage* data were correlated with *test damage data* to test the accuracy of the latter. High degree of positive correlation between the test and reference damage data and high R^2 value indicated high degree of accuracy of the LiDAR estimates.

The accuracy of LMA in detecting the number of trees within a group was evaluated by manually counting the standing trees in the field within 40 mega-polygons from the KBA. The accuracy of the delineated tree tops (or tree trunks) for the sampled trees were tested by determining the locations of the stems with a Trimble GeoExplorer 2005 GPS unit during the winter season when trees were in leaf-off conditions (in order to reduce the errors in the GPS measurements).

Figure 2.4: Equation for detecting tree heights by field measurements.



The distances between the tree-top center coordinates obtained by the LMA and the actual trunk coordinates obtained by the GPS unit were measured and the

RMSE was calculated. Finally, hot spot analysis was performed to isolate areas where large number of trees was completely destroyed.

Results and Discussion

a) Individual Tree Extraction

The combination of KBA and LMA outlined a total of 31,976 trees. Among them, the KBA extracted and classified 14,143 as bushes and small trees (BST) and 6,790 as medium to big trees (MBT). Very smaller BSTs were not considered significant in damage assessment and were manually removed. The BST species identified were Cypress, Callery and Bradford Pears with a pre-storm average height of 8.3 m and crown diameter of 9.0 m. The MBTs identified were large (≤ 25 m long) broadleaf trees including mature Shumard Oaks, Pin Oaks, Bur Oaks, Silver Maples, Sweetgums, American Elms, Hackberries, and Sycamores with an average height of 14 m and crown diameter of 21 m. About 73% of KBA extracted trees were accurately identified in the field samples as single trees. However, trees such as Loblolly Pines with small branches that often grow independently very close to each other were identified as one large tree by the KBA. Out of 47 Pine tree species sampled, 74% were identified accurately. Problems also arose when the canopies and branches of two medium to large size broadleaf trees (e.g., Silver Maples or Siberian Elms) grew within 1-2 m from each other, or when these larger trees had smaller understory trees nearby, they were identified as one single tree with very broad canopy coverage. It was found that the KBA identified 24% single trees that contained 2 to 3 individual trees; and 3% containing 4 to 5 individual trees.

The KBA has failed to extract some trees that were possibly removed during any of two steps in the method's algorithm. For example, when contours between 1.9 and 5.48 m were eliminated to remove residential houses, they also removed the trees whose canopy boundaries were outlined by these contours. Also, when large and group trees were extracted by selecting contours greater than 5.48 m with lengths greater than 153 m, trees whose heights and contour lengths did not meet those requirements were automatically removed. By manually counting the number of trees that were visible in the CHM taken over 5 random 300 x 300 m grids, it was seen that nearly 18% of the trees were not classified as either BSTs or MBTs.

The KBA extracted 1,189 large mega-group polygons. Field sampling indicated that each of these polygons contained groups of 7-13 trees mostly located in the backyards of the residential houses and along the sidewalks of city streets. The LMA was used to identify the individual trees within these large polygons. A total of 11,143 trees were extracted by the LMA and 69% of them were accurately counted and identified. Of the remaining trees, 4% were completely unrecognized; 16% contained two trees in each single large canopy; and 11% contained three or more trees in a single large canopy. On an average, these trees were 17 m tall; however, with overlapping branches, their average canopy diameter was 11 m with RMSE of 8.27 m. The position of the tree stems identified in the LMA had a RMSE of 2.4 m. Shumard Oaks, Silver Maples, Sycamores, and Sweetgums were main species identified by the LMA.

b) Tree Damage Estimation: Changing Tree Height and Canopy Coverage

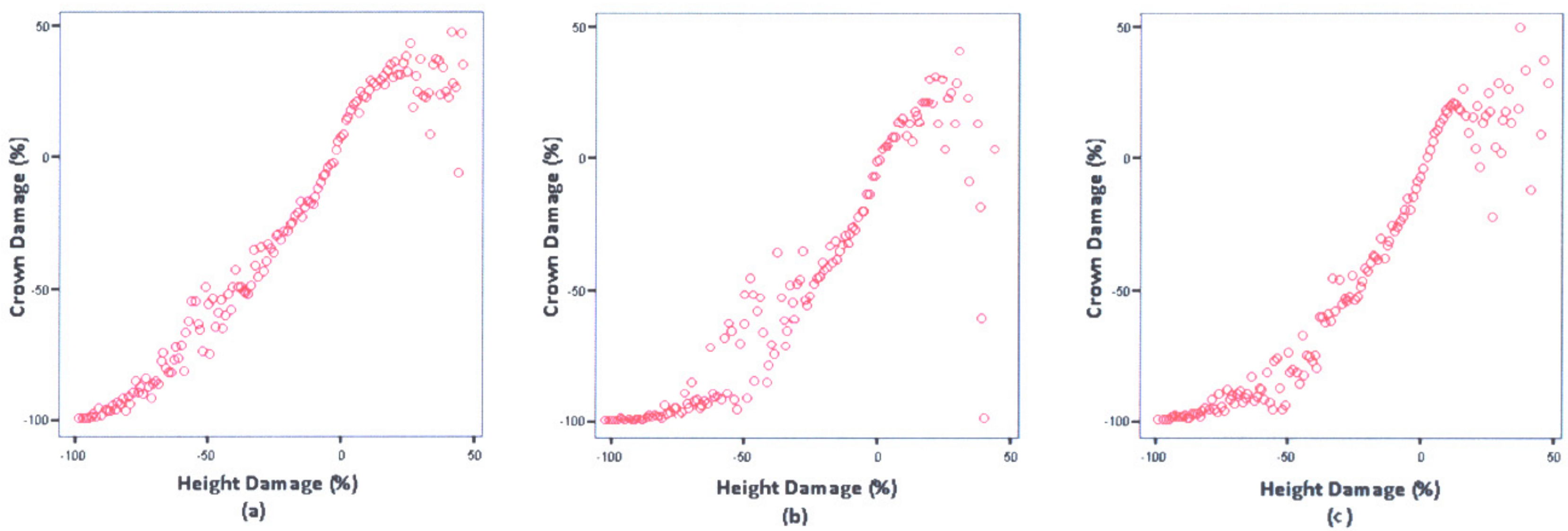
Once the outlines of all the trees were extracted for the pre-storm period any changes in their height and canopy coverage were calculated by measuring the difference between pre- and post-storm CHMs within the individual tree outlines. Of the total 31,976 trees that were extracted, 2,871 (9%) were completely damaged or uprooted by the storm, and later on cleared by the city or its residents. Among the totally damaged trees, 1945 (6%) were BSTs, 519 (1.6%) were MBTs, and 371 (1.2%) were grouped trees (Table 2.3 and Figure 2.5).

Of the total 14,043 BSTs, 3,249 (23%) were found to have a decreased height (hence stem damage) and canopy damage. Nearly 31% of the damaged trees had experienced severe (>67% decrease) canopy and stem damage (CSD); 34% experienced moderate (26-67%) damage; and 36% experienced minor canopy and stem damage (<25%). Less than 2% of the BSTs had experienced stem damage but no canopy damage; almost 11% had suffered canopy damage but no stem damage; and 5% did not suffer any canopy or stem damage at all.

Table 2.3: Damage characteristics among the three groups of trees.

Scenario	BSTs N= 14,043 (44%)	MBTs N= 6,790 (21%)	Grouped Trees N=11,143 (35%)	Total 31,976 (100%)
Complete tree damage, or cleared	1,945 (13.9)	519 (7.6)	407 (3.7)	2,871 (9)
Decrease in only tree height (stem)	194 (1.4)	55 (0.8)	183 (1.6)	432 (1.4)
Decrease in only tree canopy	1,535 (10.9)	1,813 (26.7)	2001 (18)	5,349 (16.7)
No Damage	657 (4.7)	572 (8.4)	653 (5.9)	1,882 (5.9)
Decrease in both canopy and height	3,249 (23.1)	1,580 (23.3)	2,039 (18.3)	6,868 (21.5)
Increase in either height or canopy, or both	5,205 (37.1)	1,740 (25.6)	5,114 (45.9)	12,059 (37.7)
Increase in height, decrease in canopy	878 (6.3)	413 (6.1)	488 (4.4)	1,779 (5.6)
Increase in canopy, decrease in height	380 (2.7)	98 (1.4)	258 (2.3)	736 (2.3)

Figure 2.5: Distribution of tree damage among BSTs (a), MBTs (b), and grouped trees (c).



During this ice storm, about 8% MBTs suffered minor (<1%) stem damage but major (27%) canopy damage. The latter is attributed to the fact that the larger trees have wider canopy coverage or surface area that increases their risk of exposure to ice. The percentage of trees without any damage (8.4%) was also highest in this group. Similar to trees in the BSTs, 23% of the MBTs had experienced CSD due to the storm. Among them, 36% had severe (>67%), 37% had moderate (26-66%), and 27% had minor (<25%) damage. About 6% of MBTs had suffered only canopy damage while their stem sustained the storm and grew since then; and about 2% of the trees had experienced canopy growth after the storm although their stem height declined during the storm. It appeared that MBTs had larger and stronger stems that were more storm resilient than the BSTs. However, their branches are very susceptible to breakage since their larger branches have greater surface areas resulting in the accumulation of more ice loadings.

When identified by the LMA, the grouped trees were found to suffer least damage due to the ice storm: only 2% of all grouped trees had experienced decrease in heights; 18% had a decrease in canopy; and another 18% had a decrease in both canopy and height. This significantly lower (compared to individual trees) magnitude of damage among grouped trees may be attributed to at least three situations: first, within the grouped trees, understory BSTs were well protected by the strong MBTs and suffered comparatively less damage; second, few stems and branches of MBTs were broken and fell on understory BSTs to cause their canopy damage; and finally, lesser degree of accuracy in extracting tree heights and canopy diameters among grouped trees by the LMA. This last possibility was also noted by Koukoulas and Blackburn (2005).

The extracted data also revealed that 38% of BSTs has gained either height or canopy size or both. Of these, 22% trees gained <15%; 7% gained between 15-20%; 8% gained 20-40%; and 2% gained >40% in height and canopy size. On the other hand, 26% of MBTs had experienced up to 8% increase in height, and 11% increase in canopy size during the 16 months between the pre and post-storm LiDAR data collection. Such increment in tree height and canopy size can be attributed to biological characteristics and the tree extraction algorithms. First, as found in the study area, the BSTs were young trees that were approximately 8m tall and 9 m in canopy diameters; and the MBTs were around 14 m tall and 21 m in canopy diameters. From biological growth view point, 1-2 m height and canopy growth in 16 months, which results in 13-26% increase, is very natural for young plants among the BSTs. Similar 1-2 m growth in height and canopy diameter in 15 months, which results in 7-15% growth, which is less common but possible among the MBTs if they are not severely damaged by the storm. Growth difference among the BSTs vs. MBTs mentioned above well articulates this fact. Second, the young healthy BSTs are more resilient to ice storm damage than older disease infected MBTs. Hence, growth among the former is more harmonic than the latter.

Finally, from a technical viewpoint, the LMA used in this study assumes that the maximum height is the location of main tree stem and based on individual tree heights, tree canopy diameters are extracted. For coniferous trees, this assumption fits well. However, for deciduous trees, the LMA extracted maximum height may be simply a high branch growing away from the actual tree trunk creating major distortions in post-storm heights and canopy diameter measurements indicating their staggering increases. Such distortions may also occur due to variation in the data collection times. The pre-storm data were collected in February and March of 2007, when trees were in leaf-off conditions. Previous studies have shown that high degree of accuracy may be achieved when LiDAR data is used to determine maximum tree heights in leaf-off conditions (Brandtberg et al. 2003; Brandtberg 2007). However, Næsset found that while maximum canopy height determined from LiDAR data is not affected by tree being in leaf-off or leaf-on condition, the canopy height measures in the lower and intermediate parts of the canopy were significantly different in two conditions (Næsset 2005). This factor can also affect the staggering increase in canopy diameters as shown by the results.

In assessing the magnitude of tree damage by ice storm in the study area, the analysis of sample data provided much clearer picture. Of the sampled 524 trees, 6% suffered severe (>67% decrease) stem damage; 13% experienced moderate (26-67%) stem damage; and 54% suffered minor (<25%) damage of them stem. Only 1% of the trees showed no change in stem heights while 27% showed an increase in heights. Thus, 28% of the sample trees sustained the ice storm damage and achieved growth in tree height in seven months (December, 2007 - July, 2008) and can be identified as resilient to ice storms. On the other hand, 15% of the sampled trees had experienced severe (>67%) canopy damage; 36% had moderate (26-67%) damage; and 30% suffered minor (<25%) damage of their canopies due to the storm. Another 15% sampled trees had experienced up to 25% increase; and 4% achieved over 25% growth in their canopy diameter after the storm. Approximately 11 % of the sampled trees had complete damage of their stem and canopy. The pre-storm CHM showed the existence of these trees with full blown individual branches whereas the post-storm CHM showed their location as empty spots; and when verified during field study, it was found that these trees were either uprooted or severely damaged during the ice storm and were cleared by the city or the owners of the residential properties. Personal interviews with the residential owners revealed that about 35% were cleared because they felt the trees were not attractive enough or they wanted to plant a new species of tree. The remaining 47% believed the trees were not capable of surviving and needed to be cleared. Within the city and government properties such as schools, hospitals, and parks and recreational areas, much care were taken to preserve the trees. Between 5% and 10% of the trees in these areas were completely destroyed. About 16% of the sampled trees experienced height increase but canopy damage; 8% experienced stem damage but canopy growth; about 20% of trees suffered minor height and canopy damage by <25%; 10% experienced both height and canopy damage between 26-67%; 8% suffered severe stem and canopy damage by >67%; 17% experienced minor (<25%) stem height damage but moderate (26-67%) canopy damage; 8% experienced moderate (26-67%) height damage but severe (>67%) canopy damage; and 10% experienced growth in both stem height and canopy diameter. The latter growth in height and canopy diameter among the sample trees may be attributed to tree spacing, biological characteristics, time and technical algorithmic issues discussed earlier.

There were several limitations that were found in both the KBA and LMA in detecting tree damage. For instance, both methods were incapable of detecting damage of very small or understory trees next to bigger trees. They were also incapable of measuring damage when the bottom branches of the tree near the ground were broken but the top branches were left intact.

c) Ice Storm Tree Damage and Resilience among Species

There were 31 species identified in the sample of 524 trees. Of those, 10 species were prominent and had at least 30 trees in the randomly chosen sample (Table 2.4). Comparison of the pre- and post-storm LiDAR data

Table 2.4: Characteristics of sampled trees in the study area.

Species (Common Name)	**Scientific Name**	Number of Trees	Mean Pre-Storm Height (m)	Mean Height Damage (%)	Mean Pre-storm Crown Diameter (m)	Mean Crown Damage (%)
American Elm	Ulmus americana L.	37	11.58	20	19	45
Hackberry	Celtis occidentalis L.	30	12.19	11	18.6	36
Pine	Pinus Family	37	11.58	21	11	36
Pin Oak	Quercus palustris M.	47	14.33	7	14.5	24
Shumard Oak	Quercus shumardii Buckl.	82	13.72	13	19	28
Siberian Elm	Ulmus pumila L.	35	10.97	20	15	36
Silver Maple	Acer saccarinum L.	62	14.63	10	17.5	33
Sugar Maple	Acer saccharum Marsh.	30	11.28	21	18	35
Sweetgum	Liquidambar styraciflua L.	32	13.41	12	17.4	26
Sycamore	Plantanus occidentalis L.	52	14.94	5	15.8	11

revealed that species such as Pin Oaks, Sycamores, and Silver Maples with stem heights ranging between 13-17 m, and canopy diameters ranging between 13-17 m suffered minor (stem damage <10%, and canopy damage <25%) and appeared to be the most ice storm resistant trees in the city. Several Pin Oak trees gained height by 10%, and canopy diameter by 30%; while several others had suffered severe stem and canopy damage by >80%. Hackberries, Shumard Oaks, and Sweetgums had average stem heights ranging between 9-13 m and canopy diameters between 12-21 m. They suffered between 11-19% stem damage and 19-36% canopy damage. Among each of these species, several trees had gained some height after the storm while several others were severely damaged in both stem and canopy. American Elms, Pines, Siberian Elms, and Sugar Maples with average height <12 m and canopy diameter ranging between 18 to 23 m suffered most severe stem damage (20-36%) and severe canopy damage (36-45%) among the sampled trees and thus these species appeared to be the most vulnerable to ice storm. Analyzing the species wise variations in the magnitude of both stem heights and canopy damage, it is revealed that the magnitude of damage depends on individual tree characteristics, and other spatial characteristics of individual tree locations.

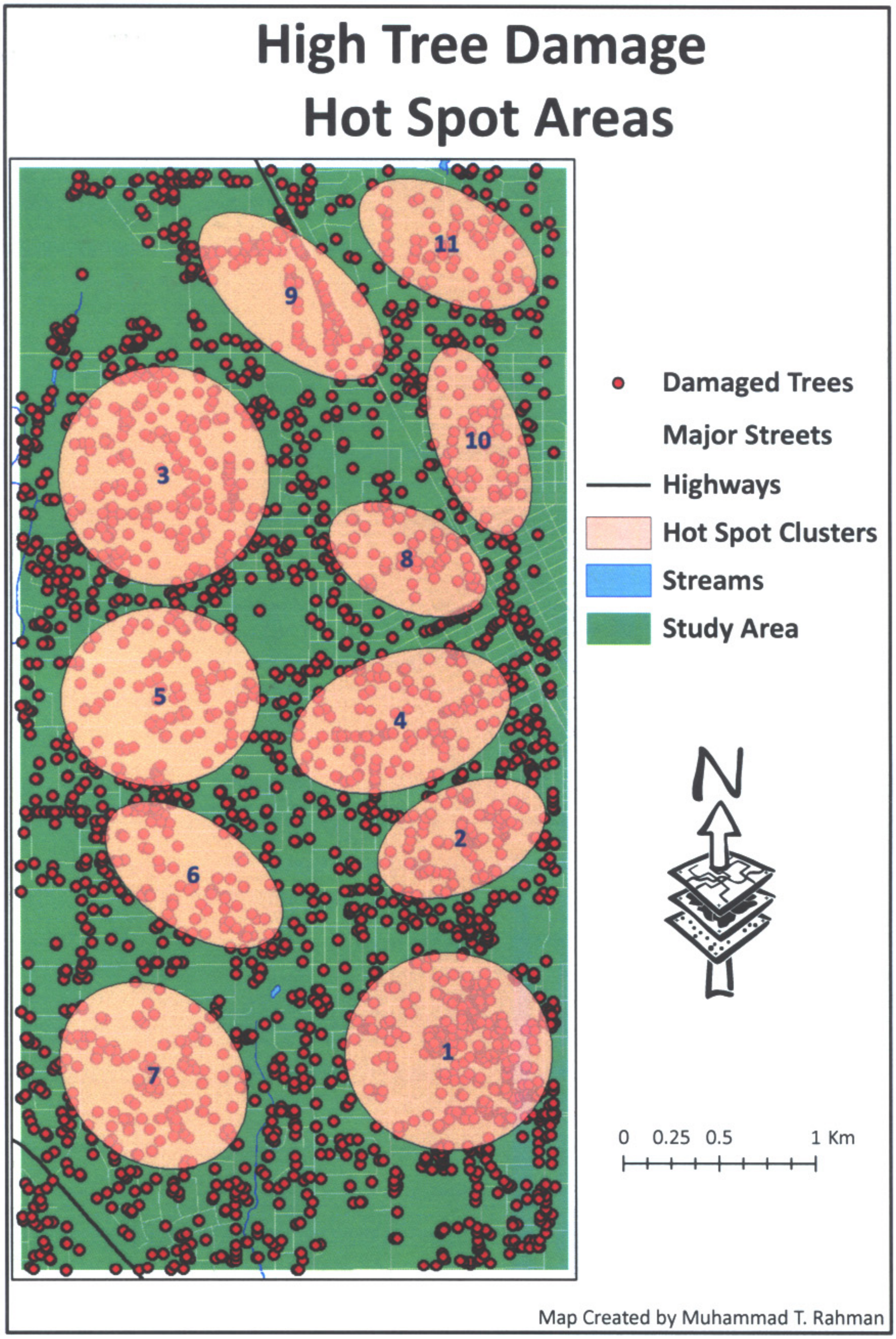
Hot Spot Analysis

Hot spot analysis was performed for all the trees that had high (>66%) amount of trunk and canopy damage (Figure 2.6). A total of 11 clusters were found when the criteria for selecting each cluster were 100 trees within 0.8 km. The number of trees that were damaged within each hotspot is given in Table 2.5. The hot spot analysis indicates that the highest number of trees was damaged in the northern part (clusters 3, 8, 9, 10, & 11) of the study area while the central and southern (clusters 1 & 7) and the central parts (clusters 2, 4, 5, & 6) had the similar amount of total damage. This could be attributed to the spatial variation of ice amounts, wind speed, slope and local edaphic conditions, and tree characteristics that all contribute to tree damage.

Table 2.5: Number of trees damaged within each hot spot cluster.

Cluster Number	Number of Trees
1	558
2	185
3	429
4	226
5	186
6	163
7	240
8	115
9	177
10 & 11	114

Figure 2.6: Hot spots of the areas where trees were highly damaged due to the December, 2007 ice storm.



Test of Accuracy of LiDAR Aided Tree Damage Assessment

As previously mentioned, the accuracy of tree damage estimation via LiDAR data depends on accurate extraction of tree height and crown outline (diameter). Both KB and LM methods extracted the same maximum heights (r = 0.99) for individual trees. When correlated with the post storm *reference* tree heights, both the KBA and LMA extracted *test* heights showed very strong positive correlations (r=0.90 for KB; r=0.92 for LM) indicating >81% (R^2) degree of accuracy of height measurement by the LiDAR. In the second step, percentage changes were computed separately for (i) the KBA extracted pre- and post-storm *test* tree heights to estimate *test* tree height damages using the KBA; and (ii) the KBA extracted pre-storm *test* tree heights and manually measured post-storm *reference* tree heights to the estimate *reference* tree height damages; and finally, the percent change data on test tree heights was correlated with the percent change data on the reference tree heights. The KBA extracted *test* tree height change estimates showed very strong positive correlation with KBA-manual estimates of *reference* tree height change indicating high degree (r=0.93; R^2= 0.86; RMSE=1.08m) of accuracy of KB method in measuring tree height damage from ice storm in urban areas. Similar operation was repeated for the tree height damage assessment using LMA.

The LMA extracted test tree height change estimate also showed very strong positive correlation (r=0.90; R^2 = 0.81; RMSE= 1.3m) with LMA-manual estimate of reference tree height change indicating high degree (>81%) of accuracy of LMA in measuring tree height damage from ice storm in urban areas. In the third step, pre- and post-storm canopy diameters for reference trees were extracted by KBA and LMA for single and grouped trees; and their post-storm canopy diameters were measured manually during field survey. As expected, the KBA had failed to extract canopy diameters for grouped trees. Percent change in single tree canopy diameters were computed separately for (i) the KBA extracted pre- and post-storm *test* tree canopy diameters to estimate the *test* tree canopy change using the KBA; and (ii) the KBA extracted pre-storm canopy diameters and manually measured post-storm *reference* canopy diameters to obtain the reference canopy diameters change data; and finally, the *test* canopy diameters change data was correlated with the reference canopy diameters change data. The *test* canopy diameters change data showed strong positive correlations with the *reference* canopy diameters change data (r=0.85; R^2=0.721; and RMSE=2.05m) indicating the fact that the KBA provides 72% accurate assessment of tree canopy damage during the ice storm. Once again, the above operation was repeated for the LMA of canopy diameter measurement. The percent change in *test* canopy diameter (LMA extracted pre- and post-storm canopy diameter of grouped trees) showed moderately positive correlation with the percent change in *reference* canopy diameter data obtained from LMA extracted pre-storm and manually measured post-storm canopy diameter (r= 0.65; R^2=0.42;

and RMSE=3.65m) indicating the fact that the LMA is capable of estimating canopy damage of grouped tree with only 42% level of accuracy. Similar results were also reported by Popescu et al. (2007) who used LM method and separate polynomial equations to extract height and canopy diameters of coniferous, deciduous, and mixed tree stands in Texas forest; and achieved higher degree of accuracy in measuring tree heights than crown diameters. This variation in accuracy level may be attributed to two factors. First, the circular search window used in this study to identify maximum points and tree diameters is based on a regressed equation representing a single tree height and canopy diameter ration. However, in this urban study area, there are 25 species each with different height to canopy diameter ration. They are also not spatially correlated (Moran's I = 0.001864 and Geary's C = 0.992170) indicating the different species of trees are randomly grouped together in different parts of the city. Hence, a single regression equation would not be suitable to outline canopy diameters for all of the species. Second, the locations of tree stems extracted by the LMA were also somewhat distorted (RMSE= of 2.4 m) due to the method's inherent assumption that the maximum height is the location of the stem. Although this may usually be true for coniferous species, it may not be so for deciduous tree species where the maximum height may be the height of a branch that is very far from the stem. Therefore, it was noticed that among the sampled trees, the accuracy level for damage assessment for coniferous trees were higher than deciduous trees. Despite somewhat lesser degree of accuracy in crown damage assessment, the present study results showed that both the KBA and LMA separately and in hybrid form provided over 85% accurate estimation of ice storm height/stem damage; and 42% accurate estimation of crown damage for wide range of urban tree species in the City of Norman. These findings provided strong support to accept the proposed hypothesis underlying this study.

Conclusion

This study has assessed tree damage caused by December 8-11, 2007 ice storm in the city of Norman, Oklahoma. Instead of using traditional methods of tree damage assessment which requires more time and man-power, the study attempted to examine the utility of an integrated approach of using active remote sensing and GIS in tree damage assessment in an urban setting. The study used pre- and post-ice storm LiDAR data to extract pre and post-storm tree heights and canopy diameters using a hybrid of KB and LM approaches. The study was conducted based on assumptions that both KBA and LMA would accurately extract the height and canopy outlines for a given time; and that computation and analyses of change (negative or positive) between pre- and post-ice storm tree heights and canopy diameters would provide a scope of estimation of tree damage and/or growth in relatively less time and effort. The results have indicated that both KBA and

LMA methods are unique in accurately estimating tree heights; however, the KBA method is not capable of extracting the outlines of canopies for group trees with overlapping branches. Since the vegetation of this study area (usually as well as other urban areas) are mixed in species composition and contains both individual and the group trees, a hybrid of KBA and LMA is necessary for height and canopy damage assessment for the entire city.

The study has yielded some significant results. First, the uses of LiDAR data allowed the classification of the City trees into BSTs and MBTs and into individual and grouped trees. Second, the study results show that an integrated LiDAR aided RS and GIS platform can effectively measure and map urban tree damages due to ice storm and other natural hazards. It also quantifies the amount of damage that the City of Norman suffered during the ice storm hazard under study. Third, when tested for accuracy of tree damage assessment, the study results show that both KB and LM methods assessed tree height damages with very high (>85%) level of accuracy; and tree canopy damage with moderate (42%) degree of accuracy. Such difference and variability in the level of accuracy between height and canopy damage is attributed to changing tree characteristics during the pre- and post-ice storm periods as well as the species wise variability of tree height-canopy diameter ratio which has significantly affected the accuracy level of canopy damage assessment by the LMA. Fourth, methodologically, the study results have identified some weaknesses in both the KB and LM approaches of using of

LiDAR data for measuring tree heights and canopy sizes. For example, in the original study, the KBA used LiDAR data with 2 m pixel size which was capable of extracting tree heights of individual trees with 80% accuracy while that for highly dense grouped trees with less than 50% accuracy (Koukoulas and Blackburn, 2005). Koukoulas and Blackburn suggested that using higher resolution data may improve the accuracy level. In the present study, 0.3m pixel sized data was used and much higher accuracy level was achieved, suggesting that increment in pixel size and higher resolution data may increase the accuracy level. However, detecting small groups of 3-4 individual trees that are very close to each other were still problematic. Therefore, the KBA is suitable for extracting tree heights and canopy diameter of individual trees and not for grouped trees; whereas, the LMA method is capable of detecting canopy diameter of both individual and grouped trees, with the latter being done with less accuracy level. Finally, the study results revealed that an extraction of individual tree boundaries depends on the selection of contour length and area/perimeter, and spatial resolution/grid size of the LiDAR data. It also depends on the parameters underlining the regression equation used for selecting search radius in the CHM by the LMA.

In conclusion, this study is an attempt to examine the utility of LiDAR data in the assessment of tree damage due to ice storm and other natural hazards. The study has successfully established the fact that the LiDAR technology is very much useful in estimating tree damage. It is yet to be examined whether it can be used for assessing changes in other tree parameters such as tree volume, biomass, and LAI. It is also yet to be determined whether a leaf-off or leaf-on condition of the trees does in fact affect the accuracy of the damage assessment results. This requires further research and hence forms the foundation for future research.

CHAPTER III

MODELLING FACTORS AFFECTING TREE DAMAGE IN NORMAN, OKLAHOMA

One of the most essential impacts of natural hazards on environment is the damage they cause to tree species composition, tree structure, and plant succession through uprooting, breaking branches and stems, and destroying flowers, fruits, seeds, and pollens. Natural hazards are commonly exogenous and directly affect the exposed trees. However, there are numerous endogenous factors that transform a tree into vulnerable or resilient to damage even before the occurrence of the hazard event. And the degree of tree damage depends upon the *dynamic pressures* from local geography (soil, elevation, and slope) and biological characteristics of trees that form *unsafe conditions* under which the hazard will cause substantial damage. Factors that make trees vulnerable to damage vary with species and place.

This study examines the factors that influence tree damage from ice storms. It will review the existing literature on the topic to identify: "*What factors affect tree damage and make urban trees vulnerable to ice storms?"* Once the factors are identified, the study will attempt to formulate and test ice storm tree height and canopy damage models based on field data collected within the City of Norman, Oklahoma. The study will highlight the factors that make trees vulnerable to ice storm damage.

Determinants of Ice Storm Tree Damage

Studies dealing with ice storm tree damage can be grouped into three categories: those focusing on climatic drivers; those emphasizing biological and structural characteristics of trees; and those identifying edaphic (land elevation, slope, soil composition, thickness, and moisture content) conditions of ecosystems that contribute to damage of trees. Ice storm tree damage research began in the early 20th century as qualitative assessment of the nature and severity of damage caused by wind and ice accumulation during two specific ice storms (Harshberger 1904; Illick 1916). Harshberger (1904), who was the pioneer in ice storm research, compared the catastrophic ice storms of 1902 and 1904 that severely affected the vegetation in Philadelphia. He reported that strong wind caused more tree damage during the first ice storm while weak wind speed and more ice accumulation caused less damage to trees and vegetation in the second ice storm.

The first quantitative assessment of ice storm tree damage began in the early 1920s. Since then, a series of related studies explored the impacts of ice accumulations on specific tree species in various geographic regions within the United States (Rogers 1923; Croxton 1939; Deuber 1940). Several studies had focused on the impact of various characteristics of glaze on the severity, nature and spatial variation of tree damage. Ice accumulation, direction and speed of wind, and wood strength to resist the combined effects of wind and glaze were identified as factors affecting tree damage. Lemon (1961) noted that in deciduous forest environments, where annual glaze is a recurring feature, damage occurs in a successive manner in accordance with the amount of ice accumulation which is directly proportional to the tree surface area produced by numerous small twigs and branches. He observed that accumulation of 0.6 - 1.3 cm causes "conspicuous" breakage in the faulty limbs of small branches and heavier accumulation (>2.5 cm) with gentle wind or low to moderate accumulation (1.3-2.5 cm) with strong wind causes "conspicuous" breakage of larger branches. Lemon also noted that the burden of falling broken branches of large trees on their younger or shorter under story trees can break off their stems (Lemon 1961). If the ground temperature at tree breast height (1.37 m) is above freezing and the tree tops are covered with heavy load of accumulated freezing ice, the trees cannot stand the load and becomes uprooted (Giuliano 2008). Review of the existing literature suggests that greater ice accumulations increase the weight of ice, which causes breakage of their branches when wood strength is exceeded. Strong wind during ice storms can also break tree stems and branches, and uproot trees. In order to examine the impact of wind speed and ice accumulation on damage to trees, it is hypothesized that (H_1): *the magnitude of tree damage* *(percent change in tree height and crown diameter) of tree damage is positively related to the wind speed (WIND) and thickness of ice accumulation (ICE) during the storm.*

Several studies have noted that *tree species and characteristics* such as stem diameter, branch diameter, and branch angle influence the extent of their damage from ice storms. Among species, Black Cherry, suffered the most damage while Eastern Hemlock was found to be the most resistant to ice storms. McKeller (1942), from his examination of pine trees in the Georgia Piedmont region, observed that heavy foliage intercepts and holds large amount of ice and causes tree damage, and that there is a marked difference among Longleaf (*Pinus palustris Mill*), Loblolly (*Pinus taeda L.*) and Slash pines (*Pinus elliottii Engelm*) in terms of breaking trunks and limbs, bending and uprooting. He also noted that Loblolly Pines are most resistant to ice storms followed by Slash Pines and Longleaf Pines; and that the Slash Pines suffer the most broken limbs and bending; and Longleaf Pines are mostly uprooted.

Abell (1934) examined the impacts of ice storms upon the hardwood forests in the Appalachian region. He reported that tree damage varied by tree sizes: larger trees lost branches within the crown. On the other hand, smaller trees were broken off below the crown; open grown shade trees suffered greater damage than fruit trees; and even crown canopies were more damaged than the irregular canopies. He found that White Pine and Hemlock were highly resistant to ice storms and suffered much less damage than

Scarlet Oak; and Red Maple and Black Locust were least resistant to ice storm damage.

Tree age also affects the degree of tree damage. Downs (1938) studied the impacts of ice storm on softwood tree species (Birch-Beech-Hemlock) in Pennsylvania and New York. He found that secondary growth (21-40 years) and older growth trees (>40 years) with larger crown size suffered the greatest percentage of damage (21-39 %) because of presence of decay and decrease in flexibility of stem and limbs. Much less tree damage (7%) in young growth trees (<20 years) was attributed to lack of decay. Damages on smaller trees were due to "falling upon them of ice-weighted branches and tops of larger trees" (Downs 1938). Croxton (1939) who studied tree damage from ice storm in Central Illinois also reported that growth habit of trees in terms of the amount surface occupied by the branches determined the degree of damage from ice storms. The larger branched trees suffered greater damage due to accumulation of more ice than the smaller branched trees (Croxton 1939).

Crown form (shape, surface area, and angle of branching) also influences the extent of tree damage by ice storms. Trees with cylindrical crown suffer less stem injury than those with conical crowns while long symmetrical crowns suffer less injury than short one-sided crowns (Croxton 1939). Crown surface area, which determines the amount of ice accumulation, influences the degree of tree damage from ice storm. Bruderle and Stearns

(1985) noted that gymnosperm conifers with cone shaped crown and smaller surface area suffered less damage from ice storms. However, as a group, coniferous softwood species are highly susceptible to ice damage than hardwood trees (Whitney and Johnson 1984; Warrillow and Mou 1999). The broad crown angiosperms with larger surface area suffered greater damage from ice storms (Hauer et al. 1993).

The angle of branching by determining the crown surface area, also determines the amount of glaze exposure. Branching at 90^{o} angle (horizontal branching), which facilitates the growth of numerous small twigs and branches, produces large surface area that increases the glaze exposure and ice accumulation and thus, increases the ice damage (Bruederle and Stearn 1985). Wherein the horizontal branching is suppressed, branches tend to grow perpendicular with acute angles creating less crown surface area that hinders ice deposits and cause less tree damage (Lemon 1961; Bruederle and Stearn 1985).

Physical resistance, the ability of an individual tree to withstand bending before collapse under ice loading, affects the degree of tree damage from ice storm. The resistance capacity is related to wood specific gravity and moisture content and any change in either of these two parameters can reduce the resistance capacity of tree (Panshin and de Zeeuw 1970; Bragg et al. 2003). Within the same species, wood specific gravity varies with tree age and along the dimension of an individual tree: young tree and bole wood in the crown have lesser specific gravity than mature tree and bole wood at the tree base (Gibson et al. 1986). Tree damage occurs when the weight of the accumulated ice exceeds the maximum bending capacity (or resilience) of the branches, boles, and roots (Hauer et al. 1993; Petty and Worrell 1981; Peltola et al. 1999; Bragg et al. 2003). Tree growth form also affects the tree's maximum bending capacity and thus determines the degree of damage from ice storm. Heavy accumulation of ice on faulty, disease affected weak limbs increases the degree of tree damage from ice storms. The older insect affected decayed trees, with less wood specific gravity and more moisture content, suffer severe damages than younger and healthy trees (Bruederle and Stearn 1985; Hauer et al. 1993). From the above literature, it is revealed that biological characteristics of trees such as species, tree age, crown shape, angle of branching affect the extent of tree damage from ice storm. To observe the effect of tree characteristics on ice storm tree damage, it is hypothesized here that (H_2): *the magnitude of tree damage is positively related to main stem/trunk diameter (SDBH), branch diameter (BRANCH), pre-ice storm crown diameter (CROWN), and angle of branching (BANGLE) of trees.*

Several local edaphic conditions such as elevation, slope, soil depth, soil texture, and soil moisture content contribute to uprooting while tree spacing and distance from forest edge also significantly affect the magnitude of understory tree damage during ice storms. Trees located at the lower elevation of the wind-ward side suffer greater ice damage because of stronger wind and larger ice accumulation compared to those located at higher elevation particularly on the lee-ward side of mountain slopes (Nicholas and Zedaker 1989).

Trees on steep slopes are more susceptible to ice storm damage than those on the plains (Bruederle and Stearn 1985; Seischab et al. 1993). Thin soil layers on steep slope support only shallow-rooted trees that are more vulnerable to ice damage (Warrillow and Mou 1999). In contrast, thick soil layers at the foot hills support deep rooted more ice resistant trees that suffer less tree damage. The canopy exposure to ice storm is greater on steep slopes. Trees on steep slopes develop asymmetrical crowns that receive unbalanced ice loads which causes more damage to them. Trees on top of slopes and valley bottoms receive balanced ice loads and suffer less damage (Warrillow and Mou 1999). In the wind-ward side of mountains, where wind speed is stronger, trees suffer more glaze damage than those in the lee-ward side with weaker wind speed. In order to examine the effect of slope and elevation of land on ice storm tree damage, it is hypothesized here that (H3): *the magnitude of tree damage is positively related to slope at the tree locations.*

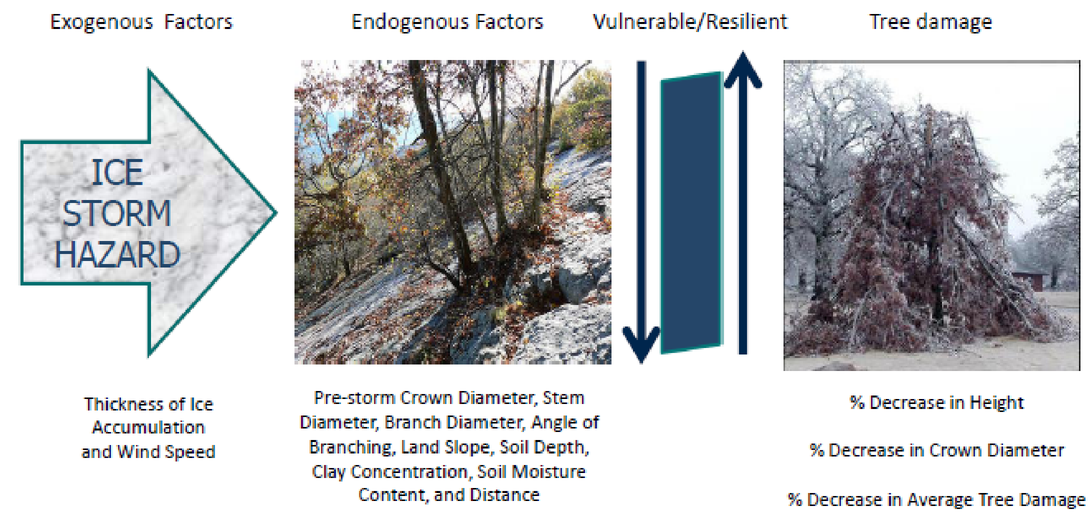
Several soil characteristics such as soil depth, texture and moisture directly affect root area and contribute to tree uprooting during natural hazards. Thin clay rich soil, which often gets hard when dry, hinder penetration of tree roots making trees vulnerable to uprooting during windy storms (Lindemann and Baker 2002; Gratkowski 1956; Everham and Brokaw

1996). During ice storms, if the ground temperature is above freezing, the freezing rain droplets melt as they touch the ground; and the ice melt water percolates through the top soil increasing soil moisture content that decreases soil shear strength. Decreasing shear strength contributes to uprooting of ice loaded trees (Bromley 1939; Putz et al. 1983). To examine this relationship between soil depths, texture and moisture content, it is hypothesized here that (H4): *the magnitude of tree damage is negatively related to soil depth and positively related to soil clay and moisture contents.*

Distance between two trees in urban neighborhoods determines the risk of falling of larger and higher trees on understory short young trees causing their damage during ice storms. Closely spaced trees suffer more damage than widely spaced trees located individually away from other trees (Whitney and Johnson 1984). To examine the effect of distance on the magnitude of tree damage, it is hypothesized that (H5): *the magnitude of tree damage is inversely related to distance between trees in an urban neighborhood.*

For this study, an ice storm tree damage model is proposed for the City of Norman to examine the above hypotheses. The proposed model is a causal one that is based on *input, status* and *output* variables (Figure 3.1). The model specifies the maximum speed of wind (WIND) and the thickness of ice accumulation on trees (ICE) as two *input* variable directly representing the ice storm hazard. Variables representing tree biological characteristics, edaphic conditions, and human induced location and spacing of trees are considered

Figure 3.1: Ice storm tree damage model for the City of Norman, Oklahoma.



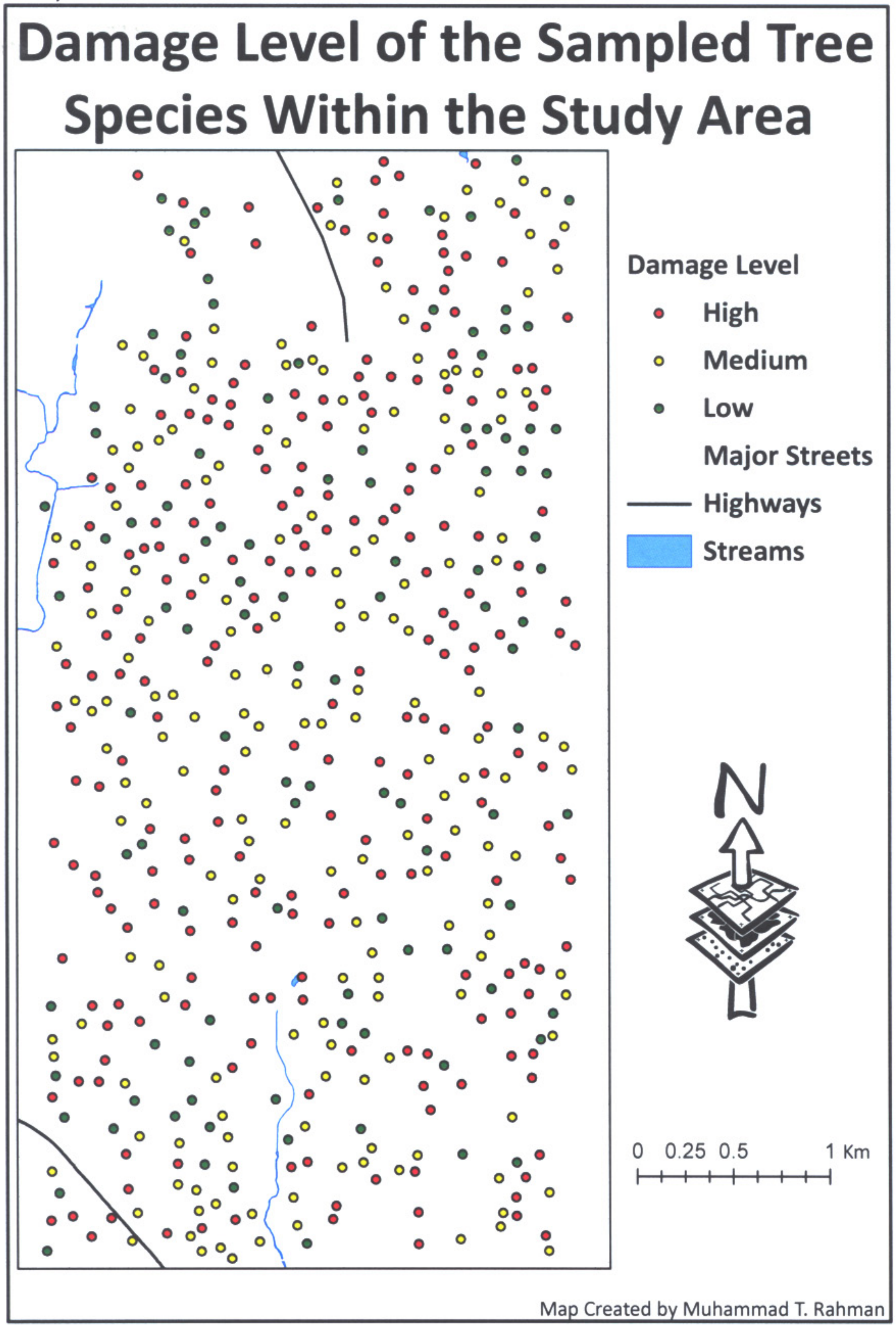
as *status* variables that are endogenous and create *unsafe conditions* for trees and make them vulnerable to damage during ice storms. Tree biological characteristics included in the model are: pre-storm crown diameter (CROWN) which determines the amount of ice that could have accumulated on a tree; stem diameter at breast height (SDBH); branch diameter above breast height (BRANCH) which also determines the amount of ice accumulation on branches; and the angle of branching (BANGLE) indicating tree crown shape. Land slope (SLOPE), soil depth (SDEPTH), soil texture in terms of average percentage of clay content (CLAY), and soil moisture content (MOISTURE) will be included in the model to represent edaphic conditions of the tree locations. The last status variable to be included in the proposed model is the distance between the sample trees and their neighboring trees in an urban setting (DISTANCE). The magnitude of tree damage is the *output* of ice storm and the dependent variable in the model. Three separate dependent damage variables were created to represent percent change (-) or damage: in tree height (HEIGHT); in crown diameter (CROWN), and in average tree damage (AVERAGE).

The model assumes that the city is covered with large number of trees representing different species, ages, heights, stem and branch diameters, canopy shapes and branching patterns. The city has several types of soils and undulated terrains that form variable slopes of land. The trees are located around urban dwellings, and near and above the natural creeks that traversed the city, and on an undulated surface. Thin, moist clay rich soil on steeper slopes near the creeks, municipal sewage drains, as well as on undulated surface may have accelerated the process of tree bending and uprooting. Among the closely spaced urban trees, breakage of older large tree stems and branches would have broken understory young trees.

Study Area, Data, and Methodology

A total of 524 randomly sampled trees were selected by dividing the study area into 200 grid blocks. The grid blocks measured 290 x 290 m and within each block, 3 to 4 random tree samples (with a minimum distance of 60 m) were taken (Figure 3.2). The approximate location of each tree was recorded using a Trimble GeoExplorer 2005 series GPS unit. Data on two separate dependent damage variables (HEIGHT, CROWN) were extracted

Figures 3.2: Major tree species that were sampled and their damage level within the study area.



through comparison of pre- and post-storm LiDAR data of the study area (as discussed in Chapter III). And average tree damage (TREE) was computed by calculating the average of percentage of height and canopy damage. Data on wind speed was recorded by Oklahoma Mesonet for December 8 (beginning day) and December 11 (ending day) for Norman and surrounding cities and counties within 250 km in all directions from the city; and for those two days, the maximum wind speeds for the nearest 15 counties were used and interpolated to estimate the variation of wind speed within the study area. Thus, the maximum wind speed ranged from 32 to 56 kmh from northeast to southwest corner of the area. The data on ice accumulation were also not recorded at the time of storm because all the instruments were frozen during the storm. However, data on the amount of freezing rain that occurred on December 8-11, 2007 in the City of Norman and its surrounding cities/counties within 250 km in all directions were available and used to interpolate the thickness of accumulate ice on sample trees. Also, the Touring Video Network reported 6.22 cm of freezing rain in Norman during December 8-11, with temperature of -6.67^{O}C which caused 2.54 cm of ice accumulations on trees. Reporters of NSW and Norman MESONET reported that 0.635 to 1.27 cm accumulation caused breakage of small branches and weak limbs; 1.27 to 2.54 cm accumulation caused breakage of large branches; and several large trees were uprooted after bending under the weight of accumulated ice. The ice storm approached the city from the northeast side where heavy accumulation (about 2.54 cm) caused uprooting of large number of trees. Ice accumulation declined toward the southwest end of the city, where about 0.635 to 1.27 cm ice accumulation resulted in moderate to severe tree damage. Each of the sampled trees located in the north and northeastern part of the study area was assigned 2.54 cm of ice accumulations. Trees located in the central part of the study area were assigned 1.27 cm of accumulations and those in the southern part were assigned 0.635 cm of ice accumulation. During field surveying, branch angles, and branch sizes were also recorded for the sampled trees.

Data on pre-storm crown diameter (CROWN) were extracted from the pre-storm LiDAR data. Stem diameter (SDBH), branch diameter (BRANCH), angle of branching (BANGLE) measured using a Brunton compass, and distance (DISTANCE) was measured during the field survey. The digital elevation model (DEM) for the study area was obtained from the City of Norman's GIS Department. The DEM was used to calculate the slope (SLOPE) of the study area in ENVI v. 4.4 software platform and were recorded for each sampled tree. Soil depth (SDEPTH), clay content (CLAY), and moisture content (MOISTURE) were extracted from the USDA's SSURGO database for the county. The database was created based on 1 soil sample for every 10 acres of land (Oklahoma Soil Scientist). All the data were entered into ArcGIS v. 9.3 software platform as well as SPSS software to create the model.

Bi-variate correlation statistics were computed by taking percent tree height and canopy damage as dependent variables against 10 independent variables identified in the review of literature. Based on the directions and magnitude of correlations as indicated by the correlation coefficients, the proposed five hypotheses underlying the study were tested.

The proposed models are assumed to be linear in which the variation in the degree of ice storm tree damage (Y) is influenced by the independent variables. A multiple regression model was used to examine the models. The model is represented as follows:

$$Y = a + b_1X_1 + b_2X_2 + \ldots\ldots.. + \xi$$

The models were tested and key factors affecting tree damage during the December 8-11, 2007 ice storm were identified. The models were created (for the entire study area samples as well as for each of the 10 predominant tree species) to find out what conditions make trees more vulnerable or resilient to ice storm damage.

Results

a) Determinants of Tree Damage during Ice Storms

Determinants of tree damage during ice storms in Norman, Oklahoma fall into three categories: climatic, biotic, and edaphic and locational characteristics. In this section, each factors affecting the magnitude of tree damage during and after ice storms are examined individually and based upon the findings of field research, hypotheses relating to climatic, biotic, edaphic and location factors are tested.

i) <u>Climatic Factor</u>

The maximum speed of wind (WIND) and the thickness of ice accumulation (ICE) were taken as two climatic factors inducing tree damage during the December ice storm in Norman. The interpolated maximum wind speed data showed that trees in the northeastern section of the study area experienced 34 kmh wind; and the wind speed increased gradually to 42 kmh toward the south and southwest section. The interpolated data also showed 2.54 cm of ice accumulation on sample trees located in the northeastern part of the study area and the thickness decreased gradually toward southwest and southern part of the city.

The maximum wind speed showed significant but moderate positive correlation (r =0.47) with the percent change in tree heights (HEIGHTS); and moderate positive correlation (r =0.51) with the percent change in tree crown diameter (CROWN). This relationship is expected because the wind speed was not stronger like a hurricane to cause more damage. Relationships between wind speed and tree height and canopy damage varied among tree species. The sample data contained 10 species of trees that were predominant in the study area. Among those, both height and canopy damage of American Elms, Pines, Hackberry, Pin Oak, Siberian Elms, Silver Maples, Sweetgums, and Sycamores showed significant and moderate positive relationships with the wind accompanying the ice storm indicating the fact that these species suffered much damage due to the combined effect of wind and ice accumulation. Shumard Oak and Sugar Maple trees showed weak positive correlations with the wind speed indicating that these species were stronger trees that suffered less damage due to wind effect.

The thickness of ICE showed significant strong positive correlation (r= 0.61) with the percent change in tree heights (HEIGHT); and strong positive correlation (r=0.60) with the percent change in tree canopy diameter (Table 3.1). Relationships between the thickness of ice accumulation and tree height and canopy damage varied among tree species. Among those, both height and canopy damage of American Elms, Pines, Shumard Oaks, Siberian Elms, Silver Maples, Sweetgums, Sycamores, and Sugar Maples showed significant and very strong positive relationship with the thickness of ice accumulation. In contrast, height and canopy damage of Hackberries and Pin Oak trees showed significant but moderate positive correlation with the thickness of ice accumulations (Table 3.1).

It is to be noted here that during an ice storm, tree height can be damaged in two ways: first, strong wind and associated freezing rain during the storm can bend and break the top part of the tree stem causing decrease in their height; and second, accumulations of ice on top tree branches can break those branches and thereby reduces the tree height. The extent of canopy damage is directly caused by strong wind and greater among of ice

Table 3.1: Correlation coefficients between the percent of tree height and canopy damage and 11 determinants.

SPECIES		WIND	ICE	CROWN	SDBH	BRANCH	BANGLE	SLOPE	SDEPTH	CLAY	MOISTURE	DISTANCE
All Species N=524	HEIGHT	0.48	0.61	0.50	0.56	0.44	0.62	0.49	-0.41	0.43	0.25	-0.50
	CANOPY	0.51	0.60	0.47	0.54	0.42	0.61	0.47	-0.40	0.41	0.28	-0.51
American Elm	HEIGHT	0.65	0.60	0.73	0.65	0.48	0.64	0.26	-0.05	0.31	0.45	-0.40
	CANOPY	0.62	0.45	0.67	0.70	0.48	0.73	0.37	-0.33	0.22	0.27	-0.49
Pine	HEIGHT	0.52	0.64	0.33*	0.11*	0.28	0.64	0.46	-0.53	0.72	0.40	-0.42
	CANOPY	0.69	0.68	0.33*	0.08*	0.37	0.58	0.51	-0.54	0.63	0.53	-0.50
Hackberry	HEIGHT	0.47	0.52	0.50	0.48	0.56	0.70	0.57	-0.21	0.65	0.03*	-0.78
	CANOPY	0.52	0.48	0.73	0.58	0.60	0.79	0.61	-0.35	0.54	-0.14*	-0.58
Pin Oak	HEIGHT	0.52	0.49	0.56	0.84	0.79	0.85	0.82	-0.46*	0.09*	0.06*	-0.67
	CANOPY	0.48	0.57	0.57	0.76	0.68	0.74	0.66	-0.42*	-0.09*	0.21*	-0.51
Shumard Oak	HEIGHT	0.33	0.51	0.44	0.75	0.51	0.72	0.57	-0.62	0.53	0.25*	-0.59
	CANOPY	0.30	0.60	0.46	0.63	0.38	0.77	0.51	-0.47	0.51	0.23*	-0.57
Siberian Elm	HEIGHT	0.54	0.86	0.60	0.52	0.49	0.78	0.81	-0.64	0.23*	0.19*	-0.71
	CANOPY	0.47	0.86	0.54	0.54	0.36	0.79	0.77	-0.69	0.22*	0.26*	-0.79
Silver Maple	HEIGHT	0.52	0.64	0.33	0.43	0.20	0.71	0.41	-0.32	0.54	0.35	-0.50
	CANOPY	0.52	0.60	0.39	0.48	0.20	0.69	0.43	-0.37	0.41	0.31	-0.59
Sweetgum	HEIGHT	0.55	0.75	0.78	0.68	0.71	0.87	0.68	-0.76	0.60	0.10*	-0.51
	CANOPY	0.52	0.76	0.75	0.74	0.71	0.83	0.70	-0.20	0.31	0.28	-0.48
Sycamore	HEIGHT	0.57	0.69	0.82	0.65	0.40	0.65	0.61	-0.21	0.11*	0.25*	-0.56
	CANOPY	0.45	0.59	0.74	0.77	0.48	0.70	0.12*	-0.34	-0.04*	0.32	-0.46
Sugar Maple	HEIGHT	0.24	0.61	0.47	0.46	0.29*	0.76	0.33	-0.66	0.24*	-0.31*	-0.61
	CANOPY	0.23	0.68	0.33	0.37	0.30*	0.69	0.38	-0.66	0.38*	-0.47*	-0.63

*Not significant at 0.05 level.

accumulated on it. In this regard, the pre-storm canopy diameter (size of tree surface area) plays an important role. Large size canopy allows more wind exposure and ice accumulations which in turn cause breakage of limbs and branches that reduce the canopy size. Considering the magnitude and direction of relationships (correlation coefficients), the first hypothesis is accepted.

ii) <u>Biotic Factors</u>

Pre-storm crown diameter (CROWN), stem diameter at breast height (SDBH), branch diameter (BRANCH), and angle of branching (BANGLE) were the biotic factors examined in this study. These factors represent several fundamental tree characteristics that indicate tree age (crown, stem and branch diameter), and shape of crown (angle of branching) and surface area (crown diameter). While individual tree crown, branch diameter, and branch angle determines the amount of ice loading and accumulations during the storm, stem diameter controls the tree bending elasticity under ice loading. Older insect infected faulty stems would facilitate ice storm tree damage.

The sample data collected from LiDAR and during the field study in Norman showed significant relationships between tree characteristics and tree height and canopy damages. In particular, crown diameters (CROWN) showed significant but moderately strong positive correlations with both tree heights (r=0.47) and canopy damages (r=0.45). Stem diameters showed strong positive correlations with tree heights (r=0.55), and canopy damages (r=0.55). Branch diameters showed significant moderate positive correlations with tree heights (r=0.44), and canopy damages (r=0.42). However, branch angles showed significant strong positive correlations with both tree heights (r=0.67) and canopy damage (r=0.66). Such relationships between tree biotic characteristics and height and canopy damage were also observed among all 10 species in the study area except for Pine trees for which the crowns and stem diameters did not show any significant correlations with heights and canopy damages (Table 3.1). These relationships were expected because, larger crown area, larger stem, branch thickness, and branch angle actually facilitates the accumulations of larger amount of ice on trees; and larger loads of ice causes breakage of branches and limbs on both tree tops and canopies. Based on the magnitude and direction of relationships expressed by the correlation coefficients, second hypothesis is accepted in this study.

iii) Edaphic Factors

Land slope gradient (SLOPE), soil depth (SDEPTH), soil clay content (CLAY), and soil moisture content (MOISTURE) at sample tree locations were selected as key edaphic factors that influences tree damage during ice storms. These factors showed variable degree of impacts on tree height and canopy damage. Steeper slope of land, which accelerates soil erosion at tree locations, make trees more vulnerable to damage during ice storms because trees on slope are usually tilted (inclined) and accumulation of ice on branches and stems creates an unbalanced weight on one side which increases the chance of uprooting trees during and after the storm. This impact of slope on tree height and canopy damage is reflected in significant but moderately positive correlations between slope and tree height (r=0.49) and canopy (r=0.47) damage. Among species, height and canopy damage of American Elms, Pines, Silver Maples, and Sugar Maples showed significant but weak to moderate (r = 0.30 to 0.50) correlations with slope; while those of Hackberries, Pin Oaks, Shumard Oaks, Siberian Elms and Sweetgums showed strong positive (r >0.50) correlations with the slope. This variability in relationship is expected because of the near flatness and slightly undulated topography of the study area. Several sample trees, located near the small creeks and on top of undulated surfaces with somewhat minor to moderate steep slopes, coincidentally suffered major damage and uprooting; and hence yielded such moderate positive correlations with height and canopy damage.

The study area is comprised of six types of soil, each with variable thickness of top soil layer. Each soil type has a uniform depth throughout the study area unless, as evidenced in numerous sample tree locations, the soil thickness is modified by human activities and decreased due to rainfall erosion since the last SSURGO soil survey was undertaken by the USDA. Soil depth (SDEPTH) had inversely affected tree damage in the study area. Depth of soil showed significantly but moderate inverse correlation with both decreased tree height (r=-0.49), and canopy diameter (r=-0.47). It is to be noted here that shallow soil layers make trees more unstable and vulnerable to uprooting during ice storms and contributes to both tree height and canopy damages. Thickness of soil layer had significantly and inversely affected all 10 tree species in study area.

Percent of clay content in soils also depends on and varied with soil type. Each soil type has a specific clay content which is consistent throughout the area occupied by that soil, and may occasionally vary due to local changes in slope and level of erosion. In the study area, soils are variably rich in clay (13-64%) content soil clay content and had some minor impact on tree damage during ice storm. In this study, in order to account for the effect of variability of range between the minimum and maximum clay content, an average percent of clay content (CLAY) was computed. The average percent of clay content of soil showed moderate positive correlation with the tree height damage ($r=0.42$) and canopy damage ($r = 0.46$) from ice storm. Among species, in cases of Pine, Hackberry, Shumard Oak, and Sweetgum trees, soil clay content showed strong positive correlations with tree height damage and canopy damage ($r \geq 0.60$); whereas in American Elms, Siberian Elms, Silver Maples, Pin Oaks, Sycamores, and Sugar Maples, it showed weak to moderate positive correlations ($r \leq 0.50$) with tree height and canopy damage. The extent of height and canopy damage in Pin Oak trees are not related to soil clay content. These variable relationships between clay content and tree damages may be attributed to root systems and tolerance of each species to clay and soil drainage system. For example, roots of American Elms are greater in radius, and shallow in depth, and can have tap roots in dry areas; they grow better on moist but well drained soil and do not favor clay soil. Similarly, Hackberry, Shumard Oak, Sweetgum species do not thrive well on poorly drained clay rich or mud soils. It appears that trees that do not thrive well on poorly drained soils would not thrive well on clay soils which are poorly drained. Poorly drained clay soils gets hard when dry, and hinder penetration of tree roots into deeper soils, and make tree roots shallow and wide spread and vulnerable to uprooting during windy ice storms (Lindemann and Baker 2002; Gratkowski 1956; Everham and Brokaw 1996).

During the ice storm, if the ground temperature rises above freezing, the freezing rain droplets melt as they touch the ground; and the ice-melt water percolates through the top soil increasing soil moisture content that decreases soil shear strength. Decreasing shear strength induces uprooting of ice loaded trees (Putz et al. 1983). In the study area, there were five soil types each with variable pre-storm soil moisture contents. During the ice storm they became wet, and thin, moist clay soils induced tree uprooting. Soil moisture content (MOISTURE) also showed significant weak positive correlations with both tree height ($r = 0.28$) and canopy ($r = 0.32$) damage. Such weak relationships were also evident in all 10 tree species which was expected because the soil moisture content for each soil type was uniform for all sample trees located in that soil category and the magnitude of tree height and canopy damage varied among the sample trees within that soil.

The correlation results suggest that four edaphic factors significantly contributed to tree height and canopy damage caused by the ice storm under consideration. However, the magnitude of relationships indicated by the correlation coefficients varied because of variation in tree species, and their adaptive capability with the edaphic conditions examined here. Based upon the direction and magnitude of relationships between land slope, soil depth, soil texture, and soil moisture content with tree height and canopy damage, the third and the fourth hypotheses are accepted.

iv) Location Factor

The average distance between a sampled tree and its nearest neighboring trees is the single locational factor examined in this study that may have contributed to tree damage during the ice storm under consideration. Once loaded with large quantity of freezing ice, that exceeds the tree's wood resistance capacity, the branches and stems of taller trees break down and fall on nearest understory shorter trees, and damage their stems and branches. In this study, the average distance between the sample tree and its nearest neighbors showed significant moderately negative correlations with tree height ($r = -0.50$) and canopy ($r = -0.51$) damage indicating that lower the distance between trees, higher the percent of tree damages during ice storm. All major tree species showed moderate to strong negative correlations with distance factor (Table 3.1). In an urban area like the City of Norman, such relationship is expected because residents have planted individual trees in their yards and along the boundary fences for ornamental purposes and those trees may not always be damaged by their nearest trees. However, among group trees in the study area, breakage of ice loaded branches of some larger trees damaged the trunks and canopies of their closest under story trees. Hence, based on the direction and magnitude of correlation of distance with tree height and canopy damage, the hypothesis 5 is accepted.

b) Modeling Tree Damages during an Ice Storm

i) <u>Test of Multi-collinearity & Selection of Final Independent Variables</u>

Using the SPSS program, three sets of multiple regressions were computed taking the percent change in tree height (HEIGHT), tree crown (CROWN) and total tree damage (TREE), computed as an average of height and canopy damage of 524 sample trees, as three separate dependent variables against 11 independent variables identified in priori model (Figure 3.1). The independent variables were tested for multi-collinearity using simple bi-variate correlation statistics and strongly correlated ($r >= \pm 0.50$) variables were excluded from modeling.

The maximum speed of wind (WIND) and the accumulation of ice (ICE) was weakly correlated among themselves and with all other independent variables and hence, included in the models (Table 3.2). Tree crown diameter (CROWN) was weakly correlated with branch angle, and

Table 3.2: Correlation Coefficients between 11 independent variables: a test of multi-collinearity.

	WIND	ICE	CROWN	SDBH	BRANCH	BANGLE	SLOPE	SDEPTH	CLAY	MOISTURE	DISTANCE
WIND	1.0										
ICE	0.29	1.0									
CROWN	0.29	0.29	1.0								
SDBH	0.32	0.31	0.69	1.00							
BRANCH	0.31	0.21	0.47	0.52	1.00						
BANGLE	0.31	0.40	0.26	0.35	0.24	1.00					
SLOPE	0.29	0.32	0.24	0.31	0.33	0.42	1.00				
SDEPTH	-0.16	-0.20	-0.09	-0.18	-0.16	-0.39	-0.30	1.00			
CLAY	0.15	0.45	0.18	0.21	0.15	0.29	0.22	-0.04	1.00		
MOISTURE	0.18	0.32	0.14	0.15	0.08	0.15	0.08	0.12	0.42	1.00	
DISTANCE	-0.28	-0.30	-0.32	-0.41	-0.28	-0.36	-0.26	-0.21	-0.15	-0.07	1.00

strongly correlated with stem diameter (SDBH), and branch diameter (BRANCH); the latter two were also strongly correlated, and hence, excluded from the models. Both crown diameter and branch angle would indicate the total surface area for ice accumulation and they were not strongly correlated. Hence, they were included in the models. Land slope (SLOPE) and soil depth (SDEPTH) were weakly correlated with all other variables, and therefore, included in the models. Soil average clay content (CLAY) was strongly correlated with the soil moisture content (MOISTURE). Since clay soils are generally moist, average clay content alone would account for any impact that soil moisture may have on tree damage. Therefore, soil moisture content was eliminated from the models. The distance (DISTANCE) variable was weakly correlated with all other independent variables and it was included in the models. Thus, a set of eight independent variables were finally selected for modeling

ii) Tree Height Damage Model

Stepwise multiple regression analysis of eight independent variables representing the climatic, biotic, edaphic and location factors have explained 72% of the total variation in the percent of tree height change due to the ice storm. Among the independent variables, the thickness of ice accumulation has emerged as the most important predictor (based on standardized β value) of tree height damage and was followed by branch angle, pre-storm tree crown diameter, and maximum wind speed. Among the edaphic factors, soil depth has emerged as the most important predictor with negative influence on tree height damage; both soil clay content and slope contributed positively to tree height damage. Finally, the distance from the nearest neighboring trees also exerted negative influence to tree height damage model (Table 3.3, Col. 1).

Stepwise, the biotic variable, the branch angle (BANGLE) entered the model first and explained 38% of the total variance of tree height damage due to ice storm. In the next two steps, the thickness of ice accumulation (ICE) and the pre-storm crown diameter entered the model and explained respectively 15% and 7% of the total variance. In the fourth step, the second climatic variable, maximum wind speed (WIND) entered the model and explained an additional 5% of the variance. In the next four steps, soil depth (SDEPTH), distance from the nearest tree (DISTANCE), average of clay content of soil (CLAY), and land slope (SLOPE) entered the model and explained respectively 3%, 2%, 2%, and 1% of the total variance in tree height damage.

In the next stage of data processing, multiple regression analyses were employed separately for each of the 10 species included in the tree samples. The tree height damage model (Table 3.3) for American Elms has explained 80% (adjusted R^2) of the total variance; tree crown diameter, maximum wind speed, thickness of ice accumulation, and distance emerged as the most important predictors that explained respectively 67%, 6%, 4%, and 3% of the

Table 3.3: Standardized regression coefficients (β) and coefficient of determination (R^2) resulting from the multiple regression of tree height damage on 8 independent variables for all sampled trees (N= 524), and 10 major tree species.

Independent Variables	All trees R^2= 0.72; N=524	American Elm R^2=0.80 N=37	Hackberry R^2 =0.81 N=30	Pine R^2 =0.72 N=37	Pin Oak R^2 =0.84 N=47	Shumard Oak R^2 =0.74 N=82	Siberian Elm R^2 =0.83 N=35	Silver Maple R^2 =0.66 N=62	Sugar Maple R^2 =0.66 N=30	Sweetgum R^2 =0.90 N=32	Sycamore R^2 =0.79 N=52
WIND	0.19	0.23*	0.12*	0.20	0.22	0.12	-0.12	0.17	0.05	-0.01	0.16
ICE	0.24	0.24	0.11*	0.18	0.07*	0.19	0.41	0.28	0.04*	0.25	0.21
CROWN	0.20	0.48	0.36	-0.11*	-0.06*	0.18	0.22*	-0.07*	0.32	0.03*	0.41
BANGLE	0.21	0.09*	0.13*	0.27	0.52	0.22	0.34	0.25	0.47	0.53	0.13*
SLOPE	0.10	0.02*	0.04*	0.11*	0.30	0.16	0.20*	0.197	0.07*	-0.05*	0.20
SDEPTH	-0.17	-0.03*	-0.03*	-0.23	-0.01*	-0.16	-0.25*	-0.15	-0.23*	-0.19*	-0.03*
CLAY	0.14	-0.01*	-0.15*	0.40	0.07*	0.19	0.11*	0.20	-0.06*	0.12*	-0.08*
DISTANCE	-0.16	-0.17*	-0.42	-.06*	-0.09*	-0.23	-0.17*	-0.23	-0.25*	-0.23	-0.12*
Constant	-84.41	-129.40	-97.6	-144.18	-150.11	-56.76	47.98	-83.36	-7.41	-41.34	-93.06
St. Error Est.	13.24	46.47	56.70	63.07	40.15	32.24	77.50	57.31	88.47	61.62	34.33

Maximum wind speed in mph (WIND); Thickness (in cm) of accumulated ice (ICE); Pre-storm tree crown diameter in m (CROWN); Pre-storm tree branch angle in degrees (BANGLE); Slope of land at tree location in degrees (SLOPE); Depth of soil at tree location in cm (SDEPTH); Percent of clay content in soil at tree location (CLAY); Distance between the sample tree and its nearest neighboring tree in m (DISTANCE). All standardized coefficients are significant at 0.01 levels unless marked with asterisk.

total variance in tree height damage. For Pine trees, the multiple regression analysis explained 70% (adjusted R^2) of the total variance; average soil clay content, branch angle, and wind speed appeared as the most important predictors contributing respectively 51%, 12% and 7% of the total variation in tree height damage. For Hackberry trees, the model explained 78% of the total variance in their height damage due to ice storm; and distance from the nearest tree, crown diameter, and branch angle appeared as important predictors contributing respectively 58%, 21% and 2% of the total explained variance. For Pin Oak trees, the multiple regression analysis explained about 84% of the total variation; and branch angle, maximum wind speed, and slope, emerged as important predictors contributing respectively 72%, 8%, and 4% of the total variation in their height damage during the ice storm. For Shumard Oak trees, the model explained 74% of the total variance; and sequentially, independent variables such as branch angle, distance, soil depth, crown diameter, slope, thickness of ice accumulation, and average clay content of soil entered the model and explained respectively, 52%, 10%, 4%, 3%, 2%, 2% and 1% of the total variance of tree height damage. Thickness of ice accumulation, branch angle and soil depth, contributing respectively 62%, 13% and 3% of the total variance (adjusted R^2 =0.78) emerged as the principal causes height damage among Siberian Elms trees.

The thickness of ice accumulation, branch angle, maximum wind speed, distance from the nearest trees, slope and average clay content contributed respectively, 42%, 16%, 5%, 3%,, 3% and 2% of the total variance in ice storm height damage among the Silver Maple trees. Again, the branch angle, distance, and thickness of ice accumulation, explaining respectively 75%, 8% and 5% of the total variance (adjusted of $R^2 = 0.88$), appeared as the major contributors to height damage among Sweetgum trees during the ice storm. The pre-storm crown diameter, slope and thickness of ice accumulation contributed respectively 65%, 9% and 3% of the total variance explaining the ice storm height damage among Sycamore trees. Finally, the branch angle, crown diameter, distance, and soil depth appeared to be best predictors of ice storm height damage among the Sugar Maple trees. These variables respectively explained 64%, 16%, 5% and 2% of the total variance.

iii) <u>Tree Canopy Damage Model</u>

Multiple regression analysis of eight independent variables have explained 71 percent of the total variation in the percent of tree canopy damage due to the ice storm. Among the independent variables, thickness of ice accumulation has emerged as the most important predictor (based on standardized β value) of canopy damage, followed by branch angle, maximum wind speed, pre-storm, crown diameter, average clay content of soil, and slope. Likewise in tree height damage assessment, soil depth and distance variables have exerted negative influence while average soil clay content, and land slope exerted positive influence on the tree canopy damage during the ice storm (Table 3.4, Col. 1).

Table 3.4: Standardized regression coefficients (β) and coefficient of determination (R^2) resulting from the multiple regression of tree canopy damage on 8 independent variables for all sampled trees (N= 524), and 10 major tree species.

Independent Variables	All Trees R^2= 0.71; N=524	American Elm R^2 =0.77 N=37	Hackberry R^2 =0.91 N=30	Pine R^2 =0.77 N=37	Pin Oak R^2 =0.72 N=47	Shumard Oak R^2 =0.71 N=82	Siberian Elm R^2 =0.83 N=35	Silver Maple R^2 =0.69 N=62	Sugar Maple R^2 =0.77 N=30	Sweetgum R^2 =0.84 N=32	Sycamore R^2 =0.70 N=52
WIND	0.24	0.10*	0.19	0.40	0.18*	0.10*	-0.01*	0.23	0.08*	0.03	0.06
ICE	0.27	0.33	0.07*	0.20*	0.25	0.30	0.43	0.26	0.13*	0.36	0.13*
CROWN	0.16	0.31	0.44	-0.03*	0.29	0.14	0.19*	-0.03*	-0.06*	-0.08*	0.40
BANGLE	0.20	0.28	0.25	0.16*	0.29*	0.37	0.26	0.14*	0.55	0.62	0.22
SLOPE	0.09	0.12	-0.01*	0.24	0.09*	0.04*	-0.25	0.24	0.04*	0.10*	0.12*
SDEPTH	-0.15	-0.07*	-0.15	-0.26	0.01*	-0.03*	-0.28	-0.17	-0.22	0.16*	-0.10*
CLAY	0.12	0.05*	0.18	0.28	-0.04*	0.10*	0.05*	0.03*	-0.07*	-0.09*	-0.21*
DISTANCE	-0.17	-0.12	-0.12*	-0.05*	-0.05*	-0.26	-0.24	-0.33	-0.29	-0.21*	-0.26*
Constant	-112.18	-84.76	-150.071	-174.15	-175.90	-111.49	42.61	-83.64	-1.09	175.32	-21.30
St. Error Est.	14.66	45.42	41.60	58.10	65.75	37.29	72.9	55.77	109.02	80.70	46.38

*Not significant at 0.05 level.

When employed a stepwise multiple regression, the climatic variable, thickness of ice accumulation (ICE) entered the model first and explained 37% of the total variance of tree canopy damage due to the storm. In the next three steps, branch angle (BANGLE), maximum wind speed (WIND), and distance from the nearest trees (DISTANCE) entered the model and explained respectively 15% 9% and 4% of the total variance. In the fifth step, the pre-storm crown diameter (CROWN) entered the model and explained an additional 2% of the variance. In the next three steps, soil depth (SDEPTH), average clay content (CLAY), and slope (SLOPE) entered and explained another 4% of the total variance in tree canopy damage.

Multiple regression analyses of 10 tree species data on canopy damage also revealed some important comparative results. The tree canopy damage model for American Elms has explained 77% (adjusted R^2) of the total variance; pre-storm crown diameter, branch angle and the thickness of ice accumulation emerged as important predictors explaining respectively 55%, 15%, 7% of the total variance in canopy damage. For Pine trees, the model explained 77% (adjusted R^2) of the total variance; the maximum wind speed, average clay content of soil, soil depth, and slope appeared as the most important predictors contributing respectively 46%, 22%, 7%, and 3% of the total variation in tree canopy damage. For Hackberry trees, the model explained 92% of the total variance in canopy damage due to ice storm; and the branch angle, pre-storm crown diameter, average clay content of soil, soil depth, and maximum wind speed explained respectively 62%, 18%, 7%, 2% and 2% of the total variation.

For Pin Oak trees, the multiple regression analysis explained 72% of the total variation, and branch angle, maximum wind speed, crown diameter and the thickness of ice accumulation emerged as important predictors contributing respectively 54%, 9%, 4%, and 5% of the total variation in their canopy damage. For Shumard Oak trees, the model explained 77% of the total variance; sequentially, variables such as the tree branch angle, distance, thickness of ice accumulation, and crown diameter entered the model, and explained respectively, 59%, 10%, 6%, and 2% of the total variance of tree canopy damage. The thickness of ice accumulation on trees, soil depth, and the tree branch angle are three most important predictors of canopy damage among the Siberian Elms trees as they contributed respectively 67%, 12% and 4% of the total variance (adjusted $R^2 = 0.83$). The branch angle, thickness of ice accumulation, distance from nearest trees, land slope, and maximum wind speed contributing respectively, 35%, 13%, 8%, 7%, 4%, and 2% of the total variance in ice storm canopy damage among the Silver Maple trees. The tree branch angle, thickness of ice accumulation, and distance from nearest trees respectively explained 69%, 10% and 5% of the total variance (adjusted $R^2 = 0.84$), and thus, appeared as major contributors to canopy damage among Sweetgum trees during the ice storm. Pre-storm crown diameter, slope, distance, average clay content of soil, and branch angle contributed respectively 56%, 6%, 3% , 3%, and 2% of the total variance explaining the ice storm canopy damage among Sycamore trees. Finally, the branch angle, and distance emerged as the best predictors of ice storm canopy damage among the Sugar Maple trees as these variables explained respectively 67% and 10% of the total variance.

iv) <u>Tree Damage Model</u>

The sampled trees have suffered variable magnitude of damage during the ice storm in the study area. While some trees suffered major height damage with much less canopy damage, others suffered minor height damage and major canopy damage, and yet some others did not suffer any damage at all and even experienced both height and canopy increase. In order to assess an overall tree damage during the ice storm under consideration, an average of tree height and canopy damage was computed and regressed against the eight independent variables (factors) affecting tree damage (Table 3.5). The model explained 76% of the variation in average tree damage during the ice storm; the thickness of ice accumulation and tree branch angle emerged as two most important predictors contributing about 40% and 16% of tree damages during the ice storm. In the next six steps, maximum wind speed, pre-storm crown diameter, depth of soil, distance, average clay content of soil, and slope entered in the model and explained respectively about 8%, 4%, 3%, 2%, 1% and 1% of the tree damage. Both the depth of soil and distance variables exerted negative influence whereas tree

Table 3.5: Standardized regression coefficients (β) and coefficient of determination (R^2) resulting from the multiple regression of average tree damage on 8 independent variables for all sampled trees (N= 524), and 10 major tree species.

Independent Variables	R^2= 0.76; N=524	American Elm R^2 =0.86 N=37	Hackberry R^2 =0.89 N=30	Pine R^2 =0.77 N=37	Pin Oak R^2 =0.83 N=47	Shumard Oak R^2 =0.81 N=82	Siberian Elm R^2 =0.87 N=35	Silver Maple R^2 =0.76 N=62	Sugar Maple R^2 =0.71 N=30	Sweetgum R^2 =0.90 N=32	Sycamore R^2 =0.80 N=52
WIND	0.22	0.17*	0.11*	0.31	0.21	0.11	-0.07*	0.21	0.07*	0.01	0.11*
ICE	0.26	0.32	0.04*	0.19	0.18	0.26	0.43	0.28	0.07*	0.32	0.18
CROWN	0.19	0.44	0.36	-0.07*	0.14	0.16	0.21	-0.03*	0.18*	-0.03*	0.43
BANGLE	0.21	0.14*	0.31	0.22	0.41	0.31	0.31	0.21	0.53	0.59	0.19
SLOPE	0.10	0.08*	0.04*	0.12*	0.20	0.09*	-0.23*	0.22	-0.05*	0.03*	0.16
SDEPTH	-0.17	-0.01*	-0.03*	-0.25	0.01*	-0.09*	-0.28*	-0.17	-0.23	-0.05*	-0.07*
CLAY	0.13	-0.03*	0.16*	0.29	-0.06*	0.14	0.08*	0.12	0.07*	0.11*	-0.15
DISTANCE	-0.17	-0.16*	-0.26	-0.01*	-0.06*	-0.26	-0.21*	-0.29	-0.28	-0.22	-0.20
Constant	-98.90	-110.29	-86.35	158.31	-163.66	-84.12	45.30	-83.50	-4.25	108.33	-57.18
St. Error Est.	12.13	35.42	58.44	55.99	43.08	28.42	58.15	48.23	79.04	59.69	32.40

*Not significant at 0.05 level.

crown diameter, slope, soil clay content have had their positive influence on the tree damage during the ice storm.

Among species, pre-storm crown diameter, thickness of ice accumulation, branch angle, wind speed, and distance from the nearest trees contributed respectively 68%, 10%, 4%, 2% and 2% (adjusted R^2 = 0.86) to the explained variance of ice storm damage of American Elms trees in the study area. Average clay content of soil, maximum wind speed, soil depth and tree branch angle explained about 46%, 22%, 6%, and 3% respectively of the total variation (adjusted R^2 = 0. 77) in ice storm damage of Pine trees in the study area. Among the Hackberry species, branch angle, pre-storm crown diameter, distance from neighboring trees, and average clay content of soil explained about 63%, 13%, 12% and 2% of the total variation (adjusted R^2 = 0.89) of tree damage during the ice storm. The branch angle, maximum wind speed, thickness of ice accumulation, and slope explained about 69%, 10%, 2%, and 2% of the total variance (adjusted R^2 = 0.83) of ice storm damage of Pin Oak trees. For Shumard Oak trees, variables such as branch angle, distance, thickness of ice accumulation, crown diameter, and slope sequentially entered the model and explained respectively about 61%, 11%, 5%, 2%, and 2% of the explained variance (adjusted R^2 = 0.81%) of tree damage. The thickness of ice accumulation, branch angle and soil depth were responsible for the damage of Siberian Elms trees during the ice storm as these variables explained respectively 69%, 13% and 4% of total variance (adjusted R^2 = 0.87). For the

Silver Maple species, thickness of ice accumulation, branch angle, maximum wind speed, distance from the neighboring trees, slope, and soil depth have contributed respectively 42%, 17%, 6%, 5%, 5% and 2% of the total variation (adjusted $R^2 = 0.77$) in tree damage. Branch angle (75%), average clay content of soil, (10%) distance (2%), and thickness of ice accumulation (3%) were the key factors that have accounted for 90% (adjusted R^2) of the damage of Sweetgum trees. Pre-storm crown diameter, slope, thickness of ice accumulation, average clay content of soil, distance and branch angle accounted for about 82% of the variation in damage of Sycamore trees during the ice storm. Finally, branch angle, distance from neighboring trees, soil depth, and crown diameter by explaining respectively 71%, 12%, 4% and 2% of the total variation (adjusted $R^2 = 0.71$), have caused most of damages of Sugar Maple trees during the ice storm.

c) Testing the Predictability of the Models

The coefficients of the tree *height* damage model yielded the following equation:

$$\hat{Y} = -84.41 + (0.19*WIND) + (0.24*ICE) + (0.20*CROWN) + (0.21*BANGLE) + (0.10*SLOPE) - (0.17*SDEPTH) + (0.14*CLAY) - (0.16*DISTANCE) + 13.24$$

The equation generated an estimated value of tree height damage ($\hat{Y}_{est}$), which was strongly and positively correlated with the observed (Y_{obs}) height damage (r=0.57). Also the multiple regression of tree height damage against 8 independent variables also generated the predicted tree height damage (Y_{pred}) which correlated very strongly with the observed value (r=0.85).

The coefficients of the tree *canopy* damage model yielded the following equation:

$$\hat{Y} = -112.18 + (0.24*WIND) + (0.27*ICE) + (0.16*CROWN) + (0.20*BANGLE) + (0.09*SLOPE) - (0.15*SDEPTH) + (0.12*CLAY) - (0.17*DISTANCE) + 14.66$$

The equation also generated an estimated value of tree canopy damage ($\hat{Y}_{est}$), which was strongly and positively correlated with the observed (Y_{obs}) value of the canopy damage (r=0.56). Also, the multiple regression of tree canopy damage against 8 independent variables also generated the predicted tree canopy damage (Y_{pred}) which correlated very strongly with the observed value (r=0.84).

The average tree damage model also resulted in better explained variance (adjusted R^2 = 0.76) and its parameters yielded the following equation:

$$\hat{Y} = -98.90 + (0.22*WIND) + (0.26*ICE) + (0.19*CROWN) + (0.21*BANGLE) + (0.10*SLOPE) - (0.17*SDEPTH) + (0.13*CLAY) - (0.17*DISTANCE) + 12.13$$

The equation generated an estimated value of average tree damage ($\hat{Y}_{est}$), which was strongly and positively correlated with the observed (Y_{obs}) value of the average tree damage (r=0.58). The multiple regression of average tree damage against 8 independent variables also generated the predicted value of average tree damage (Y_{pred}) which was correlated very strongly with its observed value (r=0.88).

These findings indicated that the multiple regression analyses and the variables specified in the models and tested here adequately demonstrated the processes of tree damage during the ice storm.

Discussion

This study has revealed the causes and processes of tree damage during the ice storm of December 8-11, 2007 in the City of Norman, Oklahoma. The bi-variate correlation results suggest that among the independent variables representing climatic, biotic, edaphic, and locational factors, the thickness of ice accumulation has emerged as the most important predictor of tree damage during the ice storm. It was followed by the pre-storm tree biotic characteristics especially the angle of branching which had exerted strong positive influence on both height and canopy damage. Somewhat moderate wind speed also exerted some positive influence on tree height and canopy damage. Other tree characteristics, such as crown diameters, stem, and branch diameters also exerted significant positive influence on ice storm tree damage. The edaphic factors namely, the surface slope, clay, and moisture contents, had weak to moderate correlation; and soil depth and location of trees in relation to their nearest neighbor (distance) had significant negative impacts on tree height and canopy damage. These relationships were almost uniform among the 10 major tree species that dominated the study area. These relationships have supported the hypotheses underlying this study. Hence, all 11 independent variables initially selected contributed significantly to tree damage during ice storm and were initially included in modeling ice storm tree damage in the study area.

Prior to modeling tree damage, 11 independent variables were tested for multi-collinearty. Variables such as pre-storm tree branch thickness, stem diameter, and soil moisture content were excluded because of their higher correlation with other independent variables. Finally, the three multiple regression models employed in the study revealed that 72% of tree height, 71% of tree canopy, and 76% of average tree damages were explained by the 8 independent variables selected in the model. In all three models, the thickness of ice accumulation emerged as the most important predictor and it was successively followed by the tree branch angle, crown diameter and wind speed. The land slope and soil characteristics exerted low to moderate influence on the magnitude of tree damage. All the coefficients of independent variable were significant at 0.001 levels.

The nature and magnitude of influence of independent variables on tree damage were also evidenced separately for each of the 10 species. Although ice accumulation was the main factor causing height and canopy damages among all species, each species were influenced differently by different independent variable those induced the magnitude and damaging process. For example, for trees with larger crown and near-perpendicular branches, such as American Elms, Hackberries, Siberian Elms, Shumard Oaks, and Sycamore trees, ice loading was primarily responsible for their damage; however, and ice loading was facilitated by larger tree crown and almost right angular branches that provided more surface area for greater loading. For narrow canopy tall conifers such as Pines, Pin Oaks, and Silver Maples, the magnitude of tree damage is product of joint effect of ice loading and strong wind that destroys the stems and cause tree damage. Pines are shallow rooted and weak trees and their ice storm damage and uprooting is facilitated by wind, and shallow clay rich soil. Those species located on steeper clay rich shallow soils are greatly affected by wind which causes their uprooting once they are loaded with ice.

Both correlation and multiple regression results highlighted the process of tree damage during the ice storm. The strong positive influence of the thickness of ice accumulation suggested that higher amount of ice accumulated during the ice storm had created higher loading on tree canopies and branches. Wind speed may reduce the amount of ice accumulation. However, stronger winds easily break the ice loaded branches and causes uprooting of trees. When ice loading exceeded the load bearing and bending capacity of individual tree stem and branches, it caused the breakage of both stem and branches. Thus, higher amount of ice accumulation had caused greater percentage of height and canopy damage of trees. In the process of ice accumulation, tree branch angles played the most important role: branches that are near right angles to the tree stems hindered ice from falling on the ground, and allowed more ice to accumulate on tree branches. Therefore, trees with right angle branches suffered more ice storm damage. Tree trunk, branch, and crown diameters, contribute to tree height and canopy damage in two ways. First, older trees with bigger stems, branches and crowns often suffer damage from disease and insect infestation which make larger trees more vulnerable to breakage under ice loading. Second, bigger crown, perpendicular branches provide larger surface area to allow more ice accumulation that also induces their breakage. Thus, larger trees with bigger stem, branches, and crown sizes suffer more damage due to large quantity of ice loading as evidenced in this study. Strong positive correlations shown by the percentage of tree height and canopy damage with the pre-storm tree crown diameter, stem diameter, and branch diameter as evidenced in this study simply validates that fact.

The edaphic factors such as surface slope, soil depth, soil clay and moisture contents also play important mediating roles in the process of ice storm tree damage. A moderate correlation between surface slope and the percent of tree height and canopy damages, as evidenced in this study, suggested that trees located on steeper slope suffered greater damages during the storm than those located on a flat surface. Trees that are located on slightly undulated surface incidentally suffered greater damage during the ice storm. Trees located on steep slope grow as inclined toward the slope and these trees when loaded with ice easily become uprooted, and their stems and branches break from ice loading.

Soil depth showed negative correlations and regression coefficients with the percent damage in tree height and canopy size suggesting the fact that sampled trees located on shallower soil suffered greater damage from the ice storm. Also, the sampled trees located on soils with higher percentage of clay and moisture content suffered greater damage from ice storm as indicated by their significant moderate positive correlations with tree height and canopy damages. Clay rich soils, in general, are hard and compact when dry; they prevent trees from going deep into the surface and force them to spread horizontally. During an ice storm, as the freezing rain water percolates through soil, the clay rich soil suddenly loses greater amount of shearing strength and compactness which facilitates ice loaded trees to be uprooted. These impacts of soil depth, clay and moisture content on tree damage were supported in this study area where trees located on thinner, clay rich, wet soils suffered greater damage due to uprooting during the ice storm.

In this study, it was observed that the distance between trees exerted strong negative impact on tree damage indicating the fact that the sample trees located nearest to another tree suffered greater damage during the ice storm. This was due to the falling of ice loaded broken stems and branches of one tree on its neighboring ice loaded tree leading to the breakage of the latter.

The correlation and regression results allow an identification of climatic, biotic, edaphic and locational factors or conditions those make trees vulnerable or resilient to ice storm damage. Amongst all predictors, the amount of ice accumulation certainly remains the key factor making trees vulnerable to damage: trees located in areas of thicker ice accumulation are more vulnerable than those located in thinner accumulation areas. Older trees with big canopy and perpendicular (right angle) branches are more vulnerable than smaller trees with acute angled branches. Trees located on steeper slope with shallow clay rich moist soils are more vulnerable than those located on flat plain land with deeper soil with less clay content. Also, grouped trees are more vulnerable than the individual trees.

Similarly, the coefficients of regression and determination yielded by the average tree damage models dealing with individual tree species suggest that American Elm, Siberian Elm, Pine, Sugar Maple trees would be most vulnerable to ice storm damage because of their wide spread very large crown and horizontal branching that allowed larger accumulation of ice as well as their location on shallow clay rich soils as evidenced by larger coefficient of determination on independent variables such as crown diameter, angle of branching, soil depth, and soil clay contents (Figure 3.1; Table 3.5). In contrast, Pin Oaks, Pecans, Hackberries, Sweetgums, Sycamores, Silver Maples, and Shumard Oaks are least to moderately vulnerable to ice storm damage because of their larger and stronger stem and branch, and acute to wide branching and their preference of flat land, deep, moist, and clay rich soils that were characteristics of the study area.

Conclusion: Toward an Ice Storm Tree Damage Model

This study has taken much interest in examining the factors affecting the incidence of tree damage during the hazardous ice storm of December 8-11, 2007 in the City of Norman, Oklahoma. Based upon LiDAR aided data on tree height and canopy damage, and field data on ice accumulation, tree biotic characteristics, edaphic, and location conditions, this study examined a priori model of ice storm tree damage in the study area. While the data supported the acceptance of five hypotheses of relationships between tree height and canopy damage and 8 contributing independent variables, it also allowed examining three models taken separately: the percent change in tree heights, canopy diameters, and average of the two as dependant variables. The three models explained high percentage of variance (adjusted R^2) of tree height, canopy and average damage. Based on the magnitude, direction and significance of influence of the independent variables on the dependent variables, the study results allowed the formulation of ice storm tree damage models for the study area. The models state that the accumulation of ice on trees during the storm was responsible for massive breakage of tree stems and branches leading to decreases in both tree heights and canopy diameters. The degree of tree height and canopy damage, which varied with trees species, was modified by a number of mediating status variables in the following manner: that older trees with larger crown, stem, and branch diameter, and those with wider right angular branches were loaded greater amount of ice and they suffered greater percentage of stem and branch damage; that those trees located on steeper slope were inclined and bended more as the freezing rain precipitated and crystallized and finally uprooted under pressure of ice loading and strong effect of wind; those trees located on shallower, wet and clay rich soils were easily uprooted under ice loading and under moderate wind speed; that those trees located in close proximity to others suffered more damage due falling of broken branches and stems of the neighboring trees on them. In this process, young trees with smaller crown, stem, and nearly acute angular branches located on thicker sand and silt rich well drained soils on plain surface suffered less height and canopy damage during the ice storm. Some of these latter trees even experienced some growth in their stem height and canopy indicating that they are less vulnerable and more resilient to ice storms than the older and larger trees.

The model tested here is a linear one and is in the initial stage of formulation. In a small area such as that under study, where the spatial variation in freezing rain, wind speed, surface slope, soil depth, soil clay and moisture content were not much, the model explained about 76% of the variation in tree damage. If tested in a larger area with much more variability in slope, soil depth, clay and moisture contents, these status variables should have more prominent influence on the dependent variables. The study results suggest that tree crown, stem, branch size, and branch angle, as well as surface slope, soil depth, clay and moisture content and location of trees in respect to other neighboring tree jointly determined the degree and magnitude of tree damage during the ice storm in the study area. Hence, these variables can be taken as determinants and indicators of vulnerability of tree damage due to ice storms.

CHAPTER IV

MAPPING THE VULNERABILITY OF TREE DAMAGE FROM ICE STORMS

Every year, natural hazards such as hurricanes, floods, tornadoes, and ice storms causes substantial damage to trees in orchards, natural vegetations, and urban areas around the country. They not only cause economic losses by damaging the branches and trunks of trees, but also change the species composition and structure of individual trees and affect their capabilities to cope with diseases and form resilience to disasters. Sheer volume of existing literature has estimated the degree of tree damage due to various natural hazards. However, they have not explored whether trees are vulnerable to a specific hazard and whether there are variations among tree species in terms of their vulnerability to natural hazards. The present study aims to meet this gap. Precisely, it reviews the literature on ice storm hazard and its impact on trees in the United States to identify the conditions that make trees vulnerable to ice storm damage. It also performs an inventory of the City of Norman's bio-physical conditions such as distribution of trees, individual tree characteristics such as trunk diameter at breast height (DBH), canopy diameter, branch diameter, angle of branching, proximity to other trees, local soil conditions (depth and moisture content), and land topography (e.g. slope). Based on the existing knowledge and exploratory data, the study addresses the question: *"Which parts of the study area within the City of Norman are vulnerable to ice storm trees damage?"* Using the data on the area's bio-physical and ice storm conditions (based on the December 8-11, 2007 ice storm), an index of vulnerability was computed and mapped using the GIS techniques to identify the parts of the study area that are more vulnerable to tree damage during the ice storm.

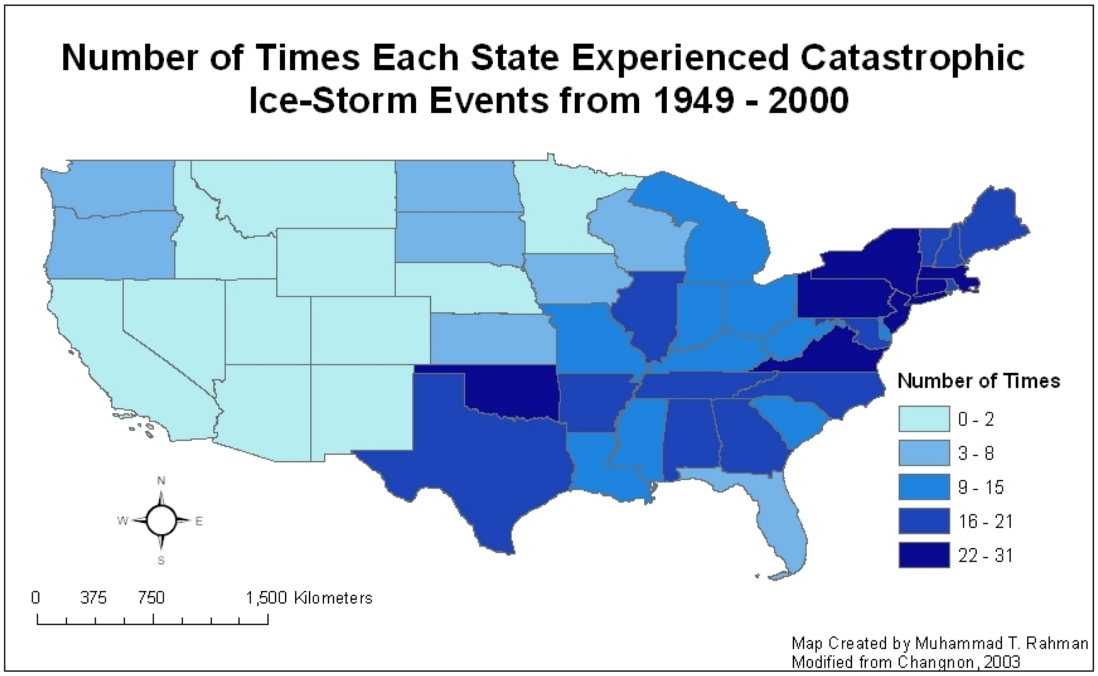
Ice Storm Hazard and Tree Damage

Ice storms occur between November and March with average peak season being December in the west and January in the eastern part of the country. Known as glaze, ice storms forms when super-cooled rain drops fall on the ground surface with below freezing temperatures (-4^{o}C to 0^{o}C), and freeze (hence the term freezing rain) on contact with ground objects such as trees and power lines embedding all exposed surface with an accumulation of a thick layer of ice (Bennet 1959; Lemon 1961). The thick layer of ice adds extra weight on the power lines and branches of the trees, causing them to tear and break apart. A 12 hour long ice storm can produce several centimeters thick ice accumulation; and a 15 m tall conifer tree can accumulate 45,000 kg of ice during a severe storm (Heidorn 2001). Presence of strong winds during the ice storm can also breaks branches and trunks, and uproots trees (Changnon and Karl 2003).

Both the frequency of ice storm and its severity of damage vary over geographic regions. The Northeastern US receives 5-7 days of freezing rains per year (highly frequent); Midwestern states receive 4-5 days (moderate high); Northwestern states receive 3-4 days (moderate); Central, Southeast and Southern states receive 1-3 days (low frequent) of freezing rain every year. The Northeastern US receives the most frequent catastrophic ice storms followed by the Southeast; the Central, Southwest, and Southern states received less frequent catastrophic ice storms (Changnon 2003). Severity of ice storm is determined by the total value of damage it causes. According to American Insurance Company standards, ice storm becomes catastrophic when the total value of damage exceeds $25 million per event (NRC 1999). In the United States, ice storms destroy over $375 million worth of building structures, trees and power lines annually (Changnon 2003). During 1949-2000, there were 87 catastrophic ice storms that caused over $16 billion loss of property (Figure 4.1).

Studies dealing with the nature and impacts of major ice storms on trees in the United States and Canada are numerous and they follow a geographic pattern. There were 24 studies published in between 1936-2000 (Bragg et al. 2003). Of them, 6 (25%) dealt with the Northeastern US and Southeast Canada; 6 with the Midwestern states; 2 (8%) with the Western US, and 10 (42%) with the Southern US; 2 with Texas; and only one study dealt with Oklahoma.

Figure 4.1: Distribution of catastrophic ice storm events in the US from 1949-2000.



Despite the lack of studies, the occurrence of ice storms in Oklahoma is in no way insignificant. During 1949-2000, there were 30 catastrophic ice storms in the State that damaged trees, building structures, property and power lines (Changnon and Karl 2003). Since the year 2000, major ice storm occurred in Oklahoma in every two to three years. They generally lasted for several hours to several days and the large quantity of ice accumulated on tree branches during the storm caused them to break and fall on the surrounding understory tree tops, rooftops and power lines causing their destruction and power loss. These storms generally caused damage in the central, north-central and north-eastern part of the state killing close to hundred people; leaving millions people without power for several days, and damaging large number of trees including close to 30,000 acres of pecan trees (Smith and Rohla 2009).

Oklahoma's natural vegetation can be divided into 15 regions with Oak, Hickory, Blackjack, and Pine trees being dominant tree species**.** These tree species have different biological characteristics and variable adaptive capability with soil and moisture contents. Over the years, these trees have been exposed to multiple ice storms and experienced variable degrees of damage; sustained growth and survived if not uprooted or totally destroyed by the storm or by urban clearing. Considering their biodiversity as well as the frequent occurrence of ice storm as a major natural hazard, it was hypothesized that: *the trees in the study area are vulnerable to ice storm damage and the degree of tree damage varies spatially within the area.* What makes the trees vulnerable to ice storm is a research question that was explored in this study.

Indicators of Vulnerability of Ice Storm Tree Damage

Vulnerability of trees to ice storm damage varies over geographic regions. While the storms directly damage trees by breaking their trunk and branches, the magnitude of damage is significantly modified by the glaze characteristics, tree biological characteristics, and local edaphic conditions.

The conditions that increases or decreases the degree of tree damages during ice storms are the *indicators* that make trees *vulnerable* to the hazard.

Sheer volume of existing studies has identified a number of indicators that make trees vulnerable to damage during ice storms. Among *climatic conditions*, the thickness of ice accumulation and direction of wind are two important indicators of tree damage. Tree damage occurs when the weight of an accumulated ice exceeds the wood strength of the tree and causes breakages of trunks and branches, and sometimes uprooting. The burden of falling ice loaded broken branches on the understory trees also damage younger or shorter trees across. Strong wind during ice storms can also break tree trunks and branches, and uproot trees to cause tree damage (Lemon 1961; Giuliano 2008).

Several *tree characteristics* such as tree species, wood strengths, trunk and canopy diameters, branch diameters, growth patterns, and the ability of physical resistance influence the extent of tree damage from ice storms and hence are important indicators of tree vulnerability. Tree wood strength to resist the combined effects of wind and glaze is an important indicator of tree vulnerability to ice storm damage (Lemon 1961). Each tree species has different wood strength and resistance capacity to sustain ice storm damage. Tree species with low wood resistance are more vulnerable to ice storm damage. Among deciduous hardwood species, Box Elder *(Acer negundo)*, Eastern Cider trees with wood strength of <1.0 are most vulnerable while

Sycamore (*Platanus occidentalis*) with wood strength >1.6 are intermediate to most resistant to ice storm damage (Warrillow and Mou 1999). Among conifers, the Loblolly Pines (*Pinus taeda*) are most resistant to ice storm followed by Slash Pines (*Pinus elliottii)* and Longleaf Pines (*Pinus palustris*). Individual gymnosperm conifers are less vulnerable than group trees whereas softwood species are more vulnerable to ice damage than the hardwood species (Warrillow and Mou 1999; Bruederle and Stearn 1985; Whitney and Johnson 1984). Broadleaf trees with large surface areas such as Black Cherry, Scarlet Oak, Black Locust are most vulnerable while small crowned White Pine and Eastern Hemlocks are least vulnerable to ice storms (Abell 1934; Hauer et al. 1993).

Tree canopy size (diameter) is an important indicator of vulnerability of tree damage during ice storm (Abell 1934). Larger trees with larger canopy surface area experience greater amount of ice accumulation and suffer greater breakage of branches within the crown. Crown surface area, which determines the amount of ice accumulation, is also an indicator that affects the degree of tree damage from ice storms. Coniferous gymnosperms with smaller cone shaped crowns and smaller surface areas suffered less damage from ice storms than the broad crown angiosperms (Bruderle and Stearns 1985; Hauer et al. 1993; Whitney and Johnson 1984; Warrillow and Mou 1999).

Tree age also makes them vulnerable to ice storm damage. Downs (1938) noted that middle aged (21-40 years) and older trees (>40 years) with larger crowns suffered the greatest percentage damage (21.5-39.4%) because of presence of decayed boles and limbs. Tree growth habit is an important indicator of tree vulnerability to ice storm damage. Croxton (1939) found that the larger branched trees suffered greater damage due to accumulation of more ice than the smaller branched trees.

The angle of branching is an indicator of tree vulnerability as it determines the amount of glaze exposure. Horizontal branching at 90^0 angles produces large surface areas and allows large amount of ice accumulation that increases the vulnerability of tree damage than acute angle branching (Bruederle and Stearn 1985).

Wood specific gravity increases the maximum bending capacity which enables a tree to withstand bending before collapse under ice loading; hence, is an indicator of vulnerability of tree damage from ice storms (Panshin and de Zeeuw 1970; Bragg et al. 2003). Tree damage occurs when the weight of the accumulated ice exceeds the maximum bending capacity (or resilience) of the branches, boles, and roots (Hauer et al. 1993; Petty and Worrell 1981; Peltola et al. 1999; Bragg et al. 2003). Tree age and growth form determines the wood specific gravity and maximum bending capacity. The older insect affected decayed trees with less wood specific gravity and more moisture content are more vulnerable to ice storm damage than younger and healthy trees (Bruederle and Stearn 1985; Gibson et al. 1986; Hauer et al. 1993).

Several edaphic conditions such as slope, soil depth, soil texture, soil moisture content, and tree spacing (distance from the nearest tree) are also important indicators of tree vulnerability to ice storm. Shallow rooted trees grown on thin soils on steep slopes develop asymmetrical crowns that receive unbalanced ice loads and become more vulnerable to ice damage. Deep rooted trees grown on thicker plain soils develop symmetrical crowns, receive balanced ice loads; and hence remain less vulnerable (Bruederle and Stearn 1985; Seischab et al. 1993; Warrillow and Mou 1999).

Soil depth, clay and moisture contents directly affect root area and contribute to tree uprooting during ice storms. Thin clay rich soil, which gets hard when dry, hinder penetration of tree roots and make trees vulnerable to uprooting during windy ice storms (Lindemann and Baker 2002; Gratkowski 1956; Everham and Brokaw 1996). During an ice storm, if the ground temperature is above freezing, the freezing rain droplets melt as they touch the ground; and the ice melt water percolates through the top soil increasing soil moisture content that decreases soil shear strength. Decreasing shear strength causes uprooting of ice loaded trees (Putz et al. 1983).

Tree spacing is also an important indicator of vulnerability of tree damage during ice storms. Distance between two trees determines the risk of falling of higher trees on understory trees causing their damage during an ice storm. Closely spaced trees are more vulnerable to ice storm damage than widely spaced trees (Whitney and Johnson 1984).

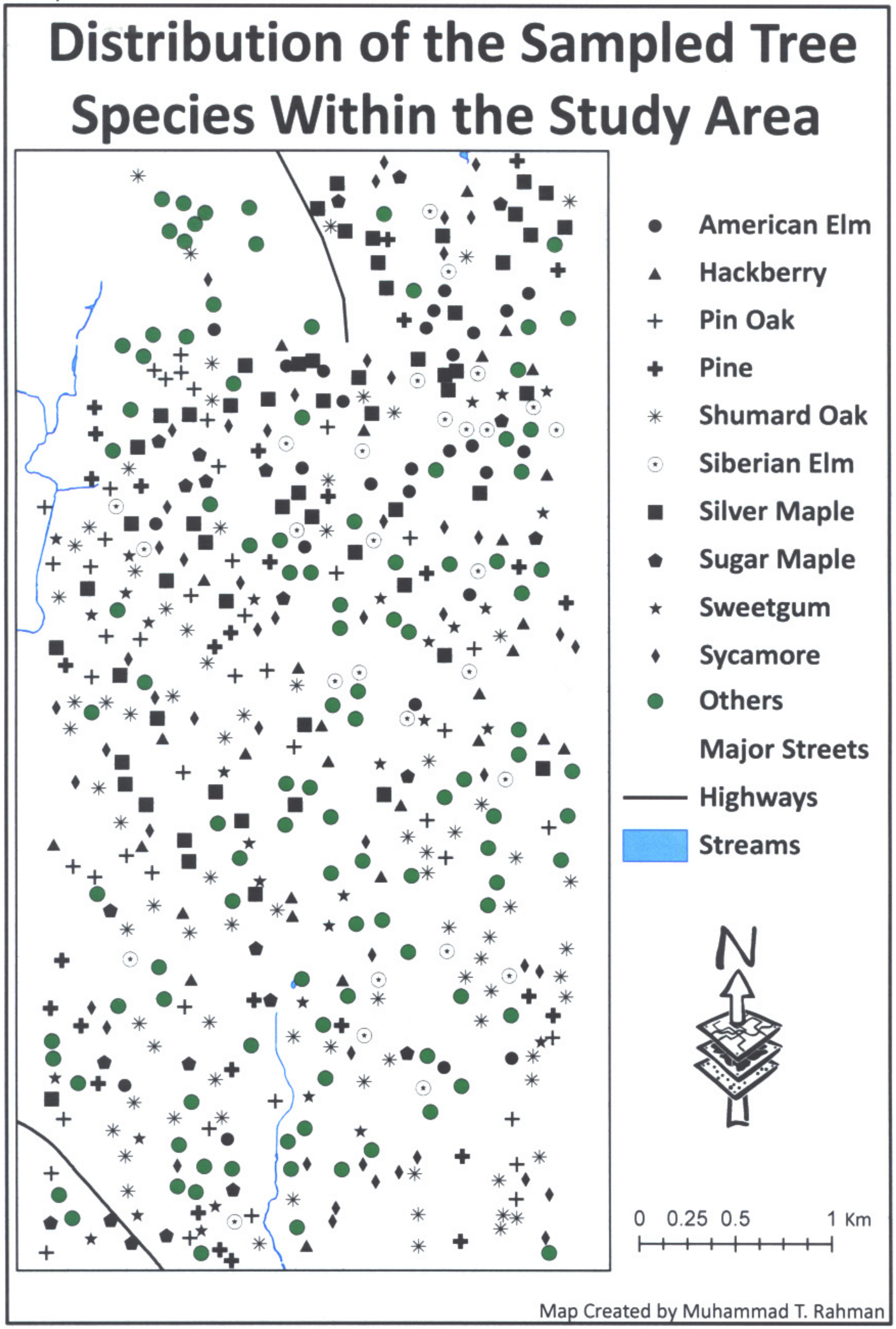
From the review of literature, 12 key indicators of vulnerability have been identified that directly and indirectly cause tree damage during an ice storm and thus make trees vulnerable. They are namely: thickness of ice accumulation, wind speed, wood strengths, crown diameters, tree trunk diameters, branch diameters, branch angles, surface slopes, soil depths, clay and moisture contents, and distances between trees.

Data and Methodology

The study was conducted in the central part of the City of Norman, Oklahoma. The study area has 31 species of trees scattered non-uniformly throughout (Figure 4.2). Field survey for this study involved collection of data on the tree characteristics by species, and topographic and soil quality data for the city. Since the city is only a small part of the State that was hit by the December, 2007 ice storm, the amount of ice thickness and the average wind speed were collected from the Oklahoma Climatological Survey (OCS), National Weather Service (NWS), and Oklahoma Mesonet Center located in the University of Oklahoma's Norman campus and were interpolated for the surrounding counties.

Data on tree characteristics were collected through direct field surveys within the study area. The study area was divided into 200 grid blocks with each block measuring approximately 290 x 290 m. Within each grid, 3 to 4 random tree samples (depending on their availability) with a minimum

Figures 4.2: Major tree species that were sampled and their locations within the study area.



distance of 60 m apart was selected. A total of 585 trees were sampled of which 61 were totally damaged by the ice storm of December 8-11, 2007 and were removed by the residents and the City. Therefore, only 524 trees were selected for field data collection. Using a handheld Trimble GeoExplorer 2005 series GPS unit, the location of each tree, their trunk diameter at breast height (tdbh), branch diameter, proximity of individual trees to the nearest tree, and angle of branching were measured and recorded during the field observations. Angle of branching was measured for the lowest five branches using Brunton compass, and the mean angle of branching was calculated for each sample tree. Pre-storm crown diameters were gathered from the pre-storm LiDAR data using ArcGIS v. 9.3 software.

Data on soil depth, clay, and moisture content for each sample tree location was obtained from the USDA's Database (SSURGO) for Cleveland County. The database had a high soil sample density (for every 10 acres, a soil sample was taken). Land slope for each sample tree base was gathered from the Digital Elevation Model (DEM) prepared at a spatial resolution of 0.3 m per pixel in 2007 by the City of Norman using the ENVI v. 4.4 remote sensing software.

Analytical Method

The ice thickness and wind speed data along with the field sample data were placed in tabular form and mapped using ArcGIS software. It was assumed that data on ice accumulation, wind speed, crown diameter, angle of branching, slope, and soil clay contents all have positive relationships with tree damage. Therefore, these values were ranked from 1 to 5 based on natural breaks among the data sets. On the other hand, soil depth, and distance among trees have inverse relationship so they were ranked from 5 to 1 with increasing values. All the rank scores were given a certain weight (based on the percentage of variance calculated in chapter 3) and were added to obtain a total rank score for each tree. There were 8 indicators of vulnerability considered in this study and the total rank score ranged between 0.72 and 5.0.

Based on damage data collected from pre- and post-storm LiDAR data over the study area, the total rank scores were grouped based on the amount of damage and the ranges of ranked scores were used as an *index of vulnerability* for ice storm tree damage. Trees with high rank scores were assumed to be *most vulnerable* to ice storm damage than those with low rank scores. The scores were mapped and a hot-spot analysis was performed using the CrimeStat software to identify highly vulnerable "hot spot" areas.

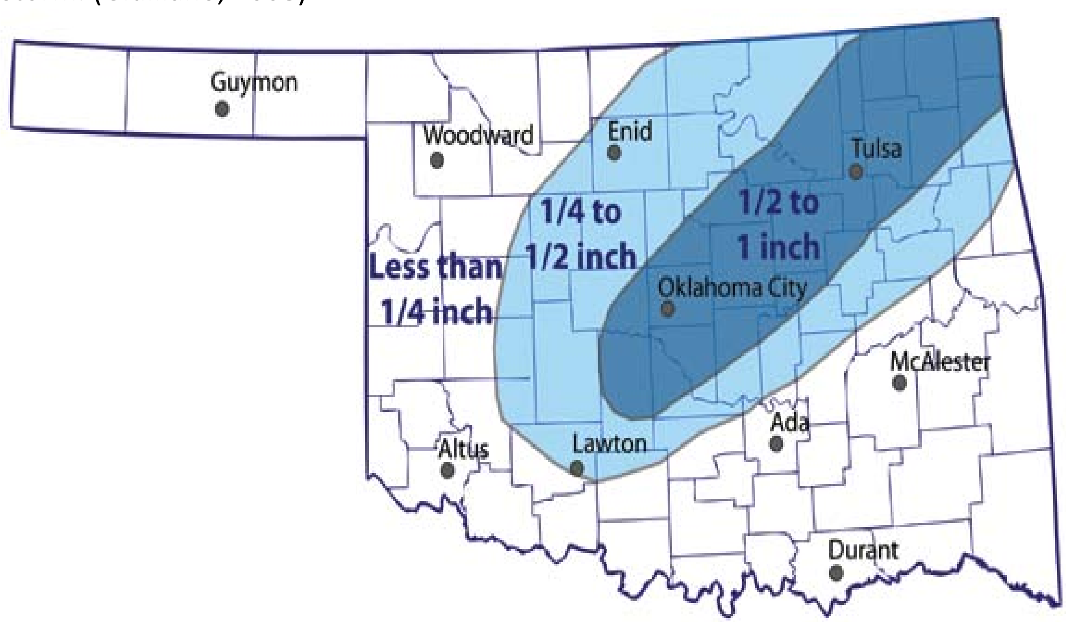
Results

a) Nature of Indicators of Vulnerability in the Study Area

i) __Thickness of Ice Accumulation__

Giulliano (2008) estimated the thickness of ice accumulation during December 8-11, 2007 for the State of Oklahoma and reported that the City of Norman received an accumulation of 1.27 - 2.54 cm of ice (Figure 4.3). Since the storm approached from the northeast, it is assumed that a 2.54 cm thick ice was accumulated in the northeast and 1.27 cm ice accumulated in the south southwest side of the city. Considering this aspect in the study area, sampled trees located in the north and northeast side were assumed to accumulate approximately 2.54 cm of thick ice; those in the central part were assigned around 1.90 cm; and those in the south and southwest side, about 1.27 cm of ice accumulation.

Figure 4.3: Thickness of ice in the State of Oklahoma during December 9-11, 2007 ice storm. (Giulliano, 2008)



ii) *Wind Speed*

Te average wind speed data collected on the 8th and the 11th of December shows that in the central part of the Oklahoma, wind was blowing between 32 and 56 kph. However, when interpolated based on the data of the Cleveland and surrounding counties, the wind speed for the study area varied between 34 and 42 kph. The wind speed increased from the north and northeastern part to the south western part of the study area.

iii) Crown Diameters

The crown diameters indicated tree age and growth form of the sampled trees. The crown diameters of the trees ranged between 11 m for Pines, to 15 m for Pin Oaks, Sycamores, Siberian Elms, to 17-19 m for American Elms, Hackberries, Shumard Oaks, Silver Maples, Sugar Maples, and Sweetgums. Because of their location on nearly flat topographic slope, the sampled trees were found to have symmetrical crown shapes. In an urban neighborhood, crown diameters may be shortened by trimming.

iv) Branch Angles

Some species spread out their branches more horizontally than others. Among the sample species, the average angle of branching varied from 33-39^{o} for American Elms and Sycamores; 40-45^{o} for Shumard Oaks and Pines; 46-49^{o} for Sweetgums and Pin Oaks; and >50^{o} for Silver and Sugar Maples, Siberian Elms, and Hackberries.

v) Surface Slopes

The study area consisted of almost flat plain land with minor inclines along several small creeks running through its west, south, and eastern parts. Most sample tree locations have slopes of <12°. However, those located nearby the creeks, have slopes between 12-33°.

vi) Soil Depth

The study area is dominated by six soil series, namely: the Kirkland in the north, Teller in the west central and southeast, Slaughterville in the southwest, Derby in the south, Bethany in the center, and Venos in the central and southern part. Average depth of soil varied from 175 cm for Venos, to 200 cm for Kirkland, Teller and Slaughterville to 210 cm for Derby and Bethany series.

vii) Average Soil Clay Content

The SSURGO soil database produced by USDA listed the minimum and maximum soil clay content of each soil type for the City of Norman. In this study, an average of the minimum and maximum clay content was computed for the study area and used to calculate the vulnerability index. The average clay content of Kirkland soil is 36%; and that of Bethany, Venos, Teller, Slaughterville ranged respectively from 32%, 22%, 15% and 10%. The Derby soil contains very little clay (<10%). The USDA did not test the clay content in the urban soils.

viii) <u>Tree Spacing/Distance</u>

The study area is covered by wide range of tree species. There were over 30,000 trees detected using LiDAR data for this study. The sampled trees were spaced at an average of 3.4 m apart although individual trees may have been more widely spaced.

b) Index of Vulnerability of Tree damage from Ice Storm

Raw values of the above described 8 indicators were ranked and individual rank scores were added by assigned weights to compute the *index of vulnerability* (IOV) of tree damage during ice storm. The distribution of the individual rank scores are given in Figure 4.4 and Table 4.1. Since the indicators would contribute to tree damage during an ice storm, high total rank scores would indicate high vulnerability and lower total rank scores would indicate low vulnerability. For the total of 524 sample trees, the total rank score ranged between 0.72 and 5.0. However, based on damage amount, trees that scored between 4.22 and 5.0 were identified as highly vulnerable and those scoring between 3.37 and 4.21 were marked as moderately vulnerable. The trees that scored between 2.38 and 3.36 were considered to have low vulnerability to be damaged by the ice storm. When mapped, most trees in the north central, northeastern and southeastern side of the study area were found to be highly vulnerable to ice storm damage; those in the central part were found to be moderately vulnerable; and those in the

Figures 4.4: Major tree species that were sampled and their weighted index scores within the study area.

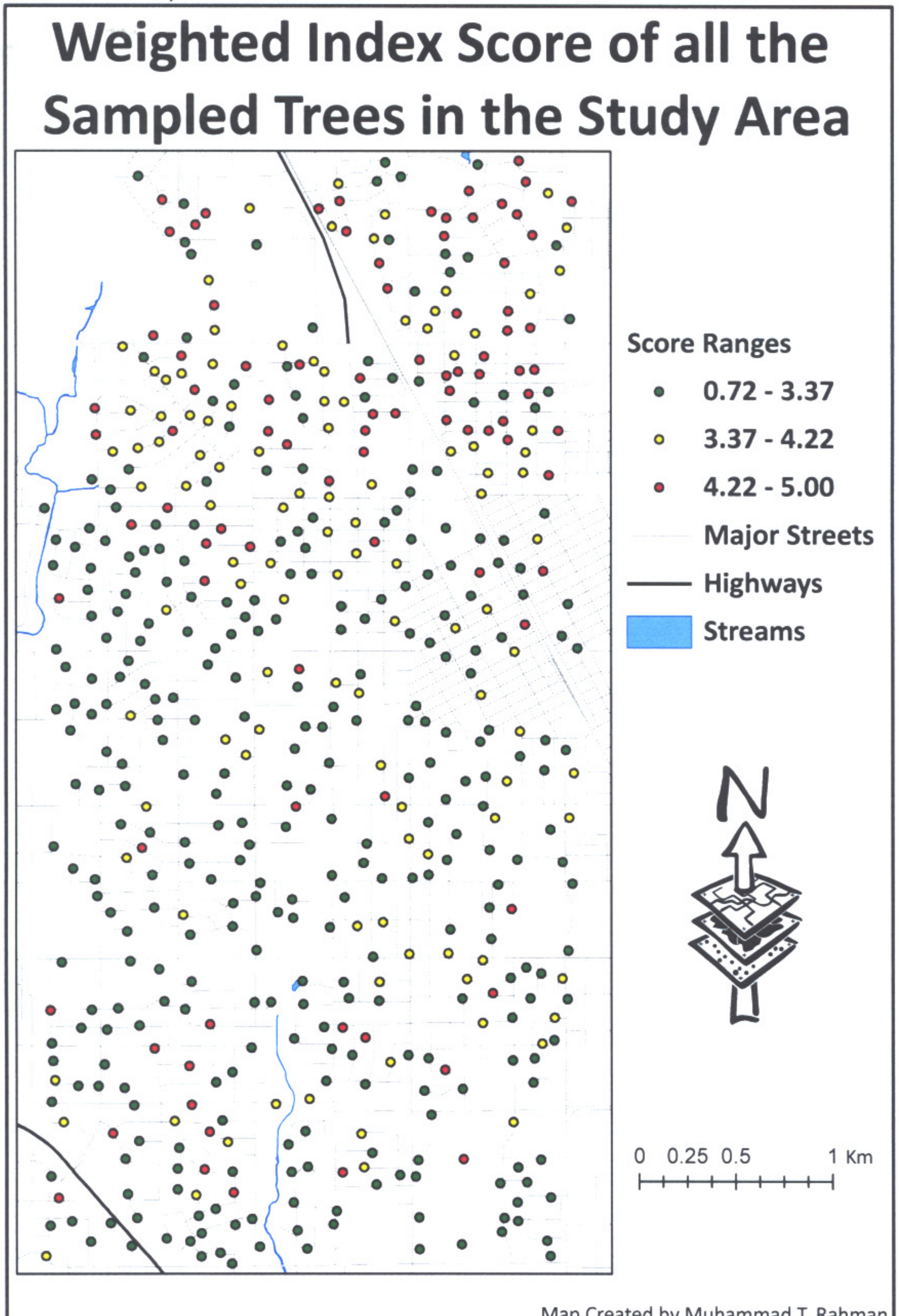


Table 4.1: Score ranges for high, moderate, and low vulnerability of trees.

	High Vulnerability			Moderate Vulnerability			Low Vulnerability		
Species	**Index Range**	**Avg. Damage Range (%)**	**Number of Trees**	**Index Range**	**Avg. Damage Range (%)**	**Number of Trees**	**Index Range**	**Avg. Damage Range (%)**	**Number of Trees**
American Elm	4.23-4.28	70-92	7	3.40-4.16	28-56	8	2.43-2.85	7-20	12
Eastern Cedar	4.66-4.87	98-100	6	3.27-3.78	30-53	3	1.4-1.72	6-13	6
Hackberry	4.20-4.98	71-90	8	3.39-3.91	28-63	13	2.33-3.03	3-11	5
Pin Oak	4.20-4.85	70-81	10	3.35-3.53	32-57	13	1.97-3.50	3-25	10
Pine	4.27-4.81	72-100	7	3.03-3.97	26-55	6	2.09-3.05	4-21	15
Shumard Oak	4.26-4.94	71-100	14	3.38-3.89	24-68	35	2.37-2.94	4-20	17
Siberian Elm	3.54-4.95	73-90	4	3.31-4.09	29-65	13	1.90-2.39	3-23	8
Silver Maple	4.65-4.91	74-82	2	3.60-4.20	26-59	17	2.44-3.57	3-21	36
Sugar Maple	4.92-4.95	76-100	5	4.10-4.81	31-66	7	2.36-4.00	5-20	15
Sweetgum	3.57-3.89	75-100	5	3.03-3.35	28-55	7	2.06-2.87	2-20	8
Sycamore	3.90-5.00	70-100	2	3.33-3.86	29-59	12	2.0-3.15	4-21	23
All the Sample	**4.22-5.00**	**>68**	**70**	**3.37-4.21**	**23-68**	**134**	**2.38-3.36**	**2-22**	**155**

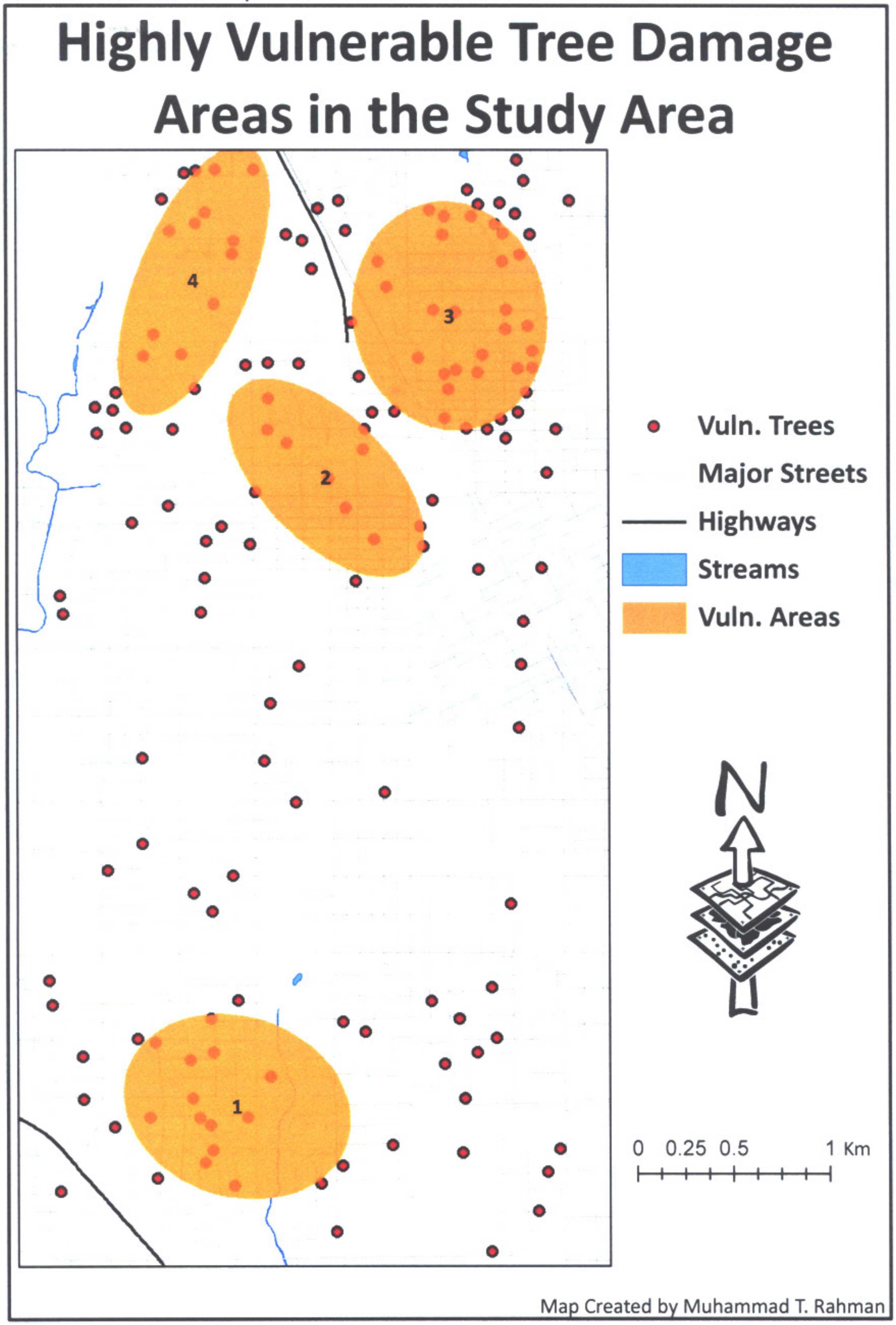
southwestern part were identified to have low vulnerability.

Among individual tree species, Silver Maple, Sycamore, Sugar Maple, and Pine trees were found to have low vulnerability; Shumard Oaks, and Siberian Elms would be low to moderately vulnerable; and American Elms, Sweetgums, Hackberries, and Pin Oaks are expected to be moderate to highly vulnerable tree species. While some Eastern Cedars were categorized as highly vulnerable, some were found to be low to moderately susceptible to tree trunk and canopy breakage depending on their individual locations and tree characteristic. The distribution of the total rank scores indicated that the vulnerability of tree damage from ice storm did indeed vary spatially within the study area. Therefore, the proposed hypothesis was accepted.

c) Hot Spot Analysis

Hot spot analysis was performed using 155 tree samples in the CrimeStat software platform. These samples included trees that had high IOV scores (4.22-5.0). Trees that were cleared due to the storm were also included in the analysis since the biophysical conditions of the individual tree locations and characteristics met the conditions that made those areas highly vulnerable. The hot spot results indicated that there are four main clusters (regions) within the study area where trees are highly vulnerable to damage from ice storms (Figure 4.5). For simple understanding and visualizations, the

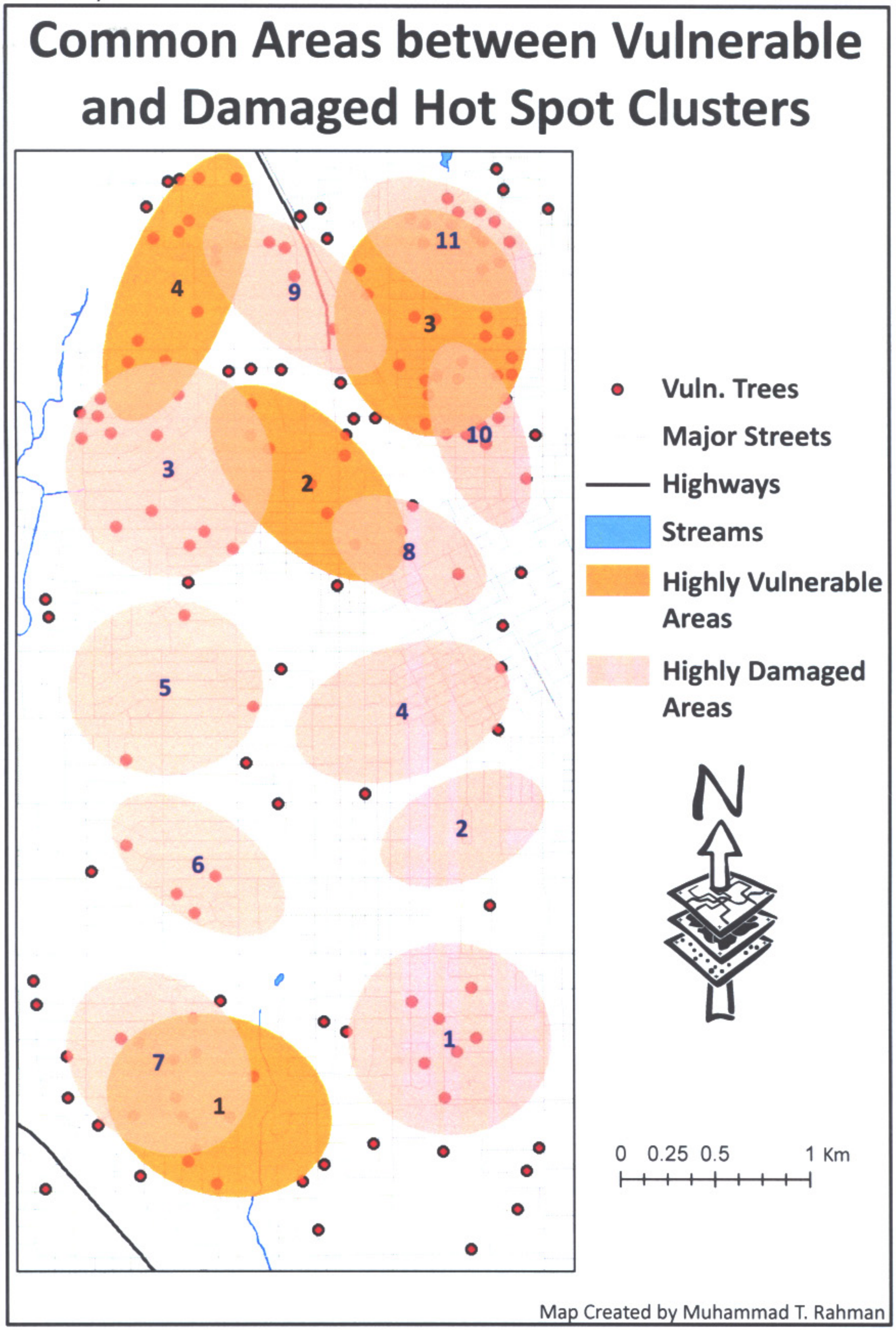
Figures 4.5: Hot spot areas that are highly vulnerable to tree damage from ice storms within the study area.



hot spots are indicated by 1x standard deviation ellipses. The ellipses only show general areas (rather than include all the samples) where trees are highly vulnerable. These were the areas where there were at least 15 trees within a radius of 0.80 km, which seemed to be the optimal parameters for the hot spot analysis. Fewer trees within small search radius produced many clusters, whereas many trees within large search area produced only one large region. Region 1 had 23 trees that are highly vulnerable and they mostly belonged to Sugar Maple, and Shumard Oak species. Almost half of the trees were completely cleared in this region. Although the slope was typically very low and soil was quite deep for this area, the clay concentration within this area was quite high. These trees had large canopy sizes, trunk diameters, and branch angles. They also grew very close to each other and had high ice accumulations. It is this latter factor that gave the trees in this region a very high index scores.

In regions 2 and 3, a total of 61 trees were found to be highly vulnerable to damage. Within these areas, Silver Maples, Shumard Oaks, and American Elms are the major species found. Similar to region 1, these trees are also very close to each other and have very high canopy diameter. However, the slope in this area and the branch thicknesses of the trees are fairly low, while the branch angles are quite high. While the soil depth is quite low, the average soil clay percentages are very high for these sections of the study area.

Figures 4.6: Comparison between damaged and vulnerable hot spot areas within the study area.



In region 4, 21 Eastern Cedars and Pin Oaks were found to be highly vulnerable. Although they are very distant from each other, the major cause of their high vulnerability is the high clay content of the soil, high angle of branching, and the young age of the trees (based on their branch and crown diameters). Also, majority of the trees within this region were cleared due to the storm causing this region to be a hot spot for tree vulnerability.

When compared the hotspots for tree vulnerability and tree damage, it was observed that all four hotspot regions of the VI share common areas between regions 3, 7, 8, 9, 10, and 11 on the damage hotspot areas (Figure 4.6). This suggests that the method used to create the VI can indeed identify areas that are likely to have tree damage from ice storms based on the local biological and edaphic conditions. It can be seen that no commonality is found for damage regions 1, 2, 4, 5, and 6. This can be attributed to several possibilities. First, accuracy level of damage data can influence the number of trees that were considered to be highly damaged. Second, the index values are based on 8 variables and any variations within these variables can also change the vulnerability level of a tree. Finally the four regions have diverse trees species with different physical characteristics and it would not be possible to take into account all their physical conditions that caused them to be damaged.

Conclusion

This study has taken much interest in searching for and constructing an index of vulnerability of tree damage during ice storms. Based on an extensive review of literature, this study has identified 11 key indicators of vulnerability. They represent climate, tree characteristics, local edaphic conditions and tree spacing of a region. The study area within the City of Norman is characterized by wide range of tree biological, and soil characteristics. While the city received only 1.27 to 2.54 cm of ice and 34-42 kmh wind gusts during the ice storm under consideration, the amount of ice accumulation varied over space. Along with ice accumulations, individual tree characteristics, surface slope, soil depth, clay, and moisture content, as tree spacing all have made a tree less or more vulnerable to damage. The proposed methodology for creating the index would not allow city planners and foresters of other states to find areas where trees are vulnerable to ice storms, but would also allow finding vulnerable areas for other types of natural hazards as well.

CHAPTER V

SUMMARY AND CONCLUSIONS

This study purported to fulfill a gap in research on the study of vulnerability and assessment of tree damage due to ice storms in an urban area. For that purpose, it assessed the magnitude of tree damage during the ice storm that occurred on December 8-11, 2007 in the City of Norman, Oklahoma by developing an integrated LiDAR aided remote sensing and GIS methodology (component I); explored the factors responsible for tree damage during ice storms and developed models tree damage during ice storms (component II) for the study area; and based upon the weights, it created an index of vulnerability of ice storm tree damage (component III).

The first component has assessed tree damage within the study area. It examined the utility of an integrated active remote sensing and GIS approach to tree damage assessment in an urban setting. Using the pre- and post-ice storm LiDAR data to extract pre and post-storm tree heights and canopy diameters, this section of the study was conducted based on assumptions that both the Koukulas and Blackburn Approach (KBA) and the Local Maxima Approach (LMA) would accurately extract the height and canopy outlines for a given time; and that the computation and analyses of change (negative or positive) between pre- and post-ice storm tree heights and canopy diameters would provide a scope of estimation of tree damage and/or growth in relatively less time and effort. The results have indicated that both KBA and LMA methods are unique in accurately estimating tree heights; however, the KBA method is not capable of extracting the outlines of canopies for group trees with overlapping branches. Since the vegetation of this study area (possibly in other urban areas as well) are mixed in species composition and contains both individual and the group trees, a hybrid of KBA and LMA was necessary for height and canopy damage assessment for the study area. The study shows that species such as Bald Cypresses, Pin Oaks, Sycamores, Silver Maples suffered minor stem and canopy damages; Hackberries, Pecans, Shumard Oaks, and Sweetgums suffered moderate damage; American Elms, Pines, Siberian Elms, Sugar Maples, and Eastern Cedars suffered most severe damage from the ice storm. Mapping the extracted damage data revealed that trees in the northern and northeastern part of the study area were more damaged than those in the southern part. The results of this component are significant in several ways. First, by using the LiDAR data, it is possible to classify the trees in the study area into bushes and small trees (BSTs), medium and big trees (MBTs), and into individual and grouped trees. Second, the proposed integrated LiDAR aided RS and GIS platform can effectively measure, quantify, and map urban tree damage due to ice storms and other natural hazards. Third, a hybrid of KB and LM methods can assess tree height damages with very high (>85%) level of accuracy and tree canopy damage with moderate (42%) degree of accuracy. Changing tree characteristics during the pre- and post-ice storm periods as well as the species wise variability of tree height-canopy diameter ratio were some of the factors that can affect the level of accuracy between height and canopy damage estimation.

The second component of this study has examined the factors affecting the incidence of tree damage during the hazardous ice storm. Based upon the LiDAR aided data on tree height and canopy damage, and field data on ice accumulation, tree biotic characteristics, edaphic and location conditions, this section has examined priori models of ice storm tree damage in the study area. Based on the relationships between tree height and canopy damage and 11 contributing independent variables, five hypotheses underlying the study were accepted. The section also examined three models taken separately: the percent change in tree height, canopy diameter, and average of the two as dependant variables and eight independent variables; independent variables such as tree stem diameter, branch diameter, and soil moisture content were eliminated from the models because of their multi-collinearity. The three models explained higher percentage of variance (adjusted R^2) of height, canopy and average tree damage. Based on the magnitude, direction and significance of influence of the independent variables on the dependent variables, the study results allowed the formulation of ice storm tree damage models for the study area. The model indicates that greater accumulation of ice on trees during the occurrence of hazardous ice storm was the primary factor responsible for the massive breakage of stems and branches of trees in the study area. The magnitude of tree damage, however, was mediated through a set of *status* variables such as pre-storm tree crown, branch angle, surface slope, soil depth and clay content, and distance of trees in respect to other neighboring trees. Multiple regression coefficients suggest that ice accumulation amount, branch angle, wind speed, distance, crown diameter, soil depth and clay content, and distance contributed significantly to height, canopy and average trees damage during the ice storm. This result indicate that trees with larger crowns, perpendicular branches and growing in groups on undulated slope and thin clay rich moist soils were severely damaged during the ice storm; and hence, tree species with these biotic, edaphic, and location characteristics would be the most vulnerable to ice storm damage.

In the third component, an index of vulnerability of ice storm tree damage was created based on climatic, tree biotic characteristics, and local edaphic and locational conditions of the study area. Mapping of the index revealed that despite the existence of large variety of tree species in the southern part of the study area, the "hotspot" of vulnerability lies in its northern section where trees would be more vulnerable due to the occurrence of greater amount of freezing rain and ice accumulation, slightly varied biophysical characteristics, and the presence of more larger and grouped trees in that section. The index also suggests that species such as Silver Maple, Sycamore, Sugar Maple, and Pine trees would be less vulnerable; Shumard Oaks and Siberian Elms low to moderately vulnerable; and American Elms, Sweetgums, Hackberries, and Pin Oaks would be moderate to highly vulnerable to ice storm damage.

The results of the three components suggest that they have several theoretical, methodological and policy implications. Theoretically, the study results revealed that like the humans, trees are also vulnerable to natural hazard damage; and that the formulation and mapping of an index of vulnerability would help researchers and policy makers to identify the hotspots and species susceptible natural hazard damage. Methodologically, it was found that an integrated approach combining an active LiDAR aided remote sensing and GIS platform can be effectively used to measure the tree damage in urban areas; and that modeling tree damage can help identification of factors contributing to tree damage during ice storms. Finally, the study results (combining three components) have significant policy implications for the City of Norman. It was revealed that hotspots of vulnerability, i.e., the areas with predicted high vulnerability are located in the northern section of the city; and that those hotspots indeed experienced high degree of tree damage during the ice storm of December 8-11, 2007; and that species such as Bald Cypresses, Pin Oaks, Sycamores, Silver Maples appeared to be the most ice storm resistant trees in the city; Hackberries, Pecans, Shumard Oaks, Sweetgums, and Callery Pears are moderately vulnerable; and American Elms, Pines, Siberian Elms, Sugar Maples, and Eastern Cedars with large crown and perpendicular branching are most vulnerable to ice storm. Trees in the northern section of the City are more vulnerable than those in the south. It is expected that these findings will help the City of Norman to plan their land use and urban forest coverage to reduce the future tree damage from frequently occurring ice storms.

Suggestions for Future Research

Several areas of future research relating to tree damage from natural hazards and their assessments can be conducted. First, the factors incorporated in the priori models and the index may vary depending on the nature of hazards. For example, in the case hurricane and tornadoes, wind (rather than the ice loadings) are the primary causes of tree damage. The factors may also vary spatially as in the case of the ice storm tree damage occurring in the Great Plains versus that of the New England States where there are variations in the landscape and soil characteristics. It would therefore, be important to explore all the factors and their variations that may cause tree damage from ice storms and other disasters; and how they vary spatially across the State of Oklahoma, and other parts of the World. The timing of the ice storm and the amount of present leaves may play a role in the amount of damage trees sustain. Therefore, this factor should be explored as well. Also, the effectiveness of the priori models in predicting tree canopy and height damage from ice storms should also need to be examined.

Third, in the case of utilizing GIS and RS technologies for tree damage assessment, this study has shown that the LiDAR data are capable of accurately quantifying and estimating tree damage from ice storms. However, whether similar accuracy levels are possible for damage assessment from other types of disasters are needed to be explored. Improvements in LiDAR data as well as newer and better algorithms and methods that are currently being proposed for accurately extracting tree outlines should be examined further for assessing tree damage.

Appendix I

Distribution of Major Tree Species within the City of Norman

Species (Common Name)	Scientific Name	Frequency of Trees (Total = 1141)	Percent of Total
Hackberry	Celtis occidentalis L.	245	21.5
Shumard Oak	Quercus shumardii Buckl.	146	12.8
Silver Maple	Acer saccarinum L.	91	7.9
Sycamore	Plantanus occidentalis L.	82	7.2
Siberian Elm	Ulmus pumila L.	75	6.6
American Elm	Ulmus americana L.	68	5.9
Sweetgum	Liquidambar styraciflua L.	62	5.4
Sugar Maple	Acer saccharum Marsh.	60	5.3
Pin Oak	Quercus palustris M.	41	3.6
Redbud	Cercis canadensis L.	30	2.6
Pecan	Carya illinoensis	29	2.5
Bradford pear	Pyrus calleryana ‘var’	20	1.8
Red Maple	Acer rubrum L.	17	1.5

(Source: Hennessey 2000)

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