SPATIAL PATTERNS OF ICE STORM DISTURBANCE IN THE FORESTED LANDSCAPE OF OUACHITA MOUNTAINS, ARKANSAS AND OKLAHOMA

A Thesis

by

RACHEL E. ISAACS

Submitted to the Office of Graduate Studies of
Texas A&M University
in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE

August 2007

Major Subject: Geography

SPATIAL PATTERNS OF ICE STORM DISTURBANCE IN THE FORESTED LANDSCAPE OF OUACHITA MOUNTAINS, ARKANSAS AND OKLAHOMA

A Thesis

by

RACHEL E. ISAACS

Submitted to the Office of Graduate Studies of
Texas A&M University
in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE

Approved by:

Chair of Committee,	Charles W. Lafon
Committee Members,	Andrew Millington
	Sorin Popescu
Head of Department,	Douglas J. Sherman

August 2007

Major Subject: Geography

ABSTRACT

Spatial Patterns of Ice Storm Disturbance in the Forested Landscape of Ouachita Mountains, Arkansas and Oklahoma. (August 2007)

Rachel E. Isaacs, B.A., University of Hawai'i – Hilo

Chair of Advisory Committee: Dr. Charles W. Lafon

Large-extent ice storms have received relatively little attention from researchers. This research investigates the effects of abiotic and biotic factors on the spatial patterns of ice storm disturbance on a forested landscape. This investigation provides a landscape-level perspective on the impacts of ice storm disturbance, clarifies the effects on ecosystem dynamics, and will aid future forest management plans.

The study was conducted in Ouachita National Forest (ONF) in west-central Arkansas and southeastern Oklahoma and examined approximately 6000 km^2 of forest between 150 and 800 m elevation.

Normalized Difference Vegeation Index (NDVI) difference values were calculated using two Landsat 7 ETM+ scenes to identify NDVI changes that potentially were associated with ice storm damage to the forests. Forty-six geolocated field sites were used to determine the relationship of NDVI difference to actual forest damage caused by the ice storm by counting the number of downed tree boles intersecting a 100 m transect. These field sites encompassed a broad range of each of the physical variables (i.e. elevation, slope, and aspect), forest type, and degree of damage. The linear regression model determined the relationship between NDVI difference and ice storm damage. Elevation, slope, and aspect were calculated based on individual pixels from the

DEM. Categories of forest damage were based on NDVI difference values. A chi-square test of correspondence and Cramer's V test were then used to analyze relationships of damage to abiotic and biotic variables.

The strong, negative relationship observed in the linear regression model suggested that NDVI was representative of ice storm damage in the study area. The chi-square test of correspondence indicated the abiotic and biotic variables all had associations with NDVI difference results ($p<0.001$). The Cramer's V test established that elevation had the strongest influence on the degree of ice storm damage followed closely by slope and aspect. Moderate elevations, moderate slopes, and windward aspects received the highest percentage of major storm damage. Forest type displayed a weak relationship with the extent of damage.

The topographic patterns of ice storm damage are similar to patterns found in previous research. Topography influenced spatial patterns of ice storm damage. Elevation, slope, and aspect were all found to be important variables influencing the degree of ice storm damage. Knowledge concerning these spatial patterns is critical for future studies of ecosystem dynamics and forest management practices.

DEDICATION

This thesis is dedicated to family and friends who have supported me through this entire process… you know who you are.

ACKNOWLEDGEMENTS

I would first like to thank my committee members, Drs. Charles Lafon, Andrew Millington, and Sorin Popescu, for your advice, expertise, and edits throughout the thesis process.

I will be forever grateful to Kirk Stueve who provided assistance throughout this entire project. Your willingness to bushwhack throughout the back woods of Ouachita National Forest coping with summer temperatures, receiving multitudes of cuts from brambles, and losing count of the number of wood ticks found on your body, will be a debt difficult to repay. Without your assistance with the data collection and methodology, I would never have been able to complete this project. Finally, I would like to thank you and your wife, Mary Stueve, for inviting me into your home while I completed the final stages of the thesis. Without your support, I would not be graduating with a Master’s degree.

I would like to thank Chris Graff who also suffered summer heat, brambles, and wood ticks to help me complete this research. Your willingness and eagerness in the field made tough conditions easier to bear and much more fun.

I am indebted to Drs. Vatche Tchakerian, Doug Sherman, Jonathan Smith, whose advice and support enabled me to work through the final stages of the Master’s process.

I would like to thank the multitude of U.S. Forest Service personnel who provided me with data and expertise to aid in the analyses and conclusions drawn throughout the project. These specialists took time out of their busy schedules and I am very grateful for their time, consideration, and speculation: Debbie Ugbade, Dennis Haugen, Dwight Scarbrough, Warren Montague, James Guldin, Vicki Metcalf, and James Hill.

I am very appreciative of all of the support the staff at EMS Global – AGIS Technology has provided me throughout the final stages of this work. You have withstood my mood swings and lack of sleep. You worked hard to keep me smiling while I was stressed and anxious. In particular, I would like to thank Mark Brandon and Matthew Clemonds. They provided me a full-time job when I had little money and have always encouraged both my professional and academic advancements and achievements.

Lastly, I would like to thank family and friends who helped me throughout graduate school, assisted in the completion of this research, and otherwise kept me sane throughout this entire process. You know who you are and why words cannot express my gratitude.

TABLE OF CONTENTS

	Page
ABSTRACT	iii
DEDICATION	v
ACKNOWLEDGEMENTS	vi
TABLE OF CONTENTS	viii
LIST OF FIGURES	x
LIST OF TABLES	xii
LIST OF EQUATIONS	xiv
INTRODUCTION	1
Disturbance	1
Ice Storms	3
Ice Storm Meteorology and Climatology	4
Types of Damage to Forests	5
Abiotic Influences	6
Biotic Influences	8
Research Objectives	10
STUDY AREA	11
Study Area Description	11
December 2000 Ice Storms	16
METHODS	22
Data	22
Image Pre-Processing	24
Geometric Correction	24
Orthorectification	25
Image-to-Image Co-registration	26
Radiometric Correction	27
Normalized Difference Vegetation Index	30
Change Detection	30

Page

Field Verification and Calibration………………………………………….. 31
Analysis of Topographic Patterns………………………………………….. 40

RESULTS………………………………………………………………………….. 45

Elevation………………………………………………………………… 47
Slope……………………………………………………………………..… 49
Aspect…………………………………………………………………… 51
Species………………………………………………………………….... 53

DISCUSSION……………………………………………………………………… 55

Spatial Patterns of Ice Storm Damage…………………………………… 55
Conifer/Hardwood-Dominated Areas Patterns of Ice Storm Damage……... 58

CONCLUSION…………………………………………………………………….. 60

REFERENCES…………………………………………………………………….. 62

APPENDIX A: METADATA FOR THE SEPTEMBER 25, 2001 IMAGE.……… 69

APPENDIX B: DARK SUBTRACT HISTOGRAMS……………….…………. 70

APPENDIX C: STORM SEARCH INFORMATION FROM NCDC………..…… 83

VITA……………………………………………………………………………….. 89

LIST OF FIGURES

FIGURE Page

1 Study Area ……………….…………..…………………………….……………..... 12

2 Photograph taken May 25, 2006 overlooking Ouachita National Forest …………...………………………………………………………...... 14

3 Additional photograph taken May 25, 2006 overlooking Ouachita National Forest …………...……………………………………………………..…..... 15

4 December 12-13 ice storm accumulation …………………...……………..... 16

5 December 25-28 ice storm accumulation …………………...……………..... 17

6 Linear regression results corresponding to NDVI versus bole damage for the 46 geolocated sites …………………………….……………..... 33

7 Linear regression results corresponding to NDVI versus bole damage for the 23 hardwood-dominated sites ……………….…………….... 33

8 Linear regression results corresponding to NDVI versus bole damage for the 23 conifer-dominated sites …………………….…………….... 34

9 Average monthly temperature for Arkansas, Division 4……....…………….... 38

10 Average monthly precipitation for Arkansas, Division 4……...…………….... 39

11 Example of a minor ice storm damaged area ………..……...……………..... 41

12 Example of a moderate ice storm damaged area ……………....…………….... 42

13 Example of a major ice storm damaged area ………..……...……………..... 42

14 Ice storm damage for the Ouachita National Forest...…..……...…………….... 46

15 Spatial patterns of the categories of ice storm damage for elevation..........…. 48

16 Spatial patterns of the categories of ice storm damage for elevation in conifer-dominated areas ……………………………......…………... 48

17 Spatial patterns of the categories of ice storm damage for elevation in hardwood-dominated areas ……………………………......…………... 49

FIGURE | Page

18 Spatial patterns of the categories of ice storm damage for slope.............……. 50

19 Spatial patterns of the categories of ice storm damage for slope in conifer-dominated areas ……………………………….......…………... 50

20 Spatial patterns of the categories of ice storm damage for slope in hardwood-dominated areas ……………………..................…………... 51

21 Spatial patterns of the categories of ice storm damage for aspect …........….. 52

22 Spatial patterns of the categories of ice storm damage for aspect in conifer-dominated areas ……………………………….......………..…... 52

23 Spatial patterns of the categories of ice storm damage for aspect in hardwood-dominated areas ……………………......……………..…….. 53

24 Spatial patterns of the categories of ice storm damage for hardwood-dominated and conifer-dominated areas ……………………...………….. 54

LIST OF TABLES

TABLE		Page
1	Examples of damaging ice storm events in the southern United States………………………………………………………………..…………..	4
2	Wind speed, wind direction, and precipitation for Little Rock, AR during the December 12-13 ice storm……………………….…………..	18
3	Wind speed, wind direction, and precipitation for Fort Smith, AR during the December 12-13 ice storm……………………….…………..	18
4	Wind speed, wind direction, and precipitation for Little Rock, AR during the December 25-28 ice storm……………………….…………..	19
5	Wind speed, wind direction, and precipitation for Fort Smith, AR during the December 25-28 ice storm……………………….…………..	20
6	Landsat 7 ETM+ image parameters for the September 25, 2001 and October 6, 1999 scenes…………………………………..…….………..	23
7	Spectral radiance parameters for the September 25, 2001 Landsat ETM+ scene……………………………………………….…………..	28
8	Spectral radiance parameters for the October 6, 1999 Landsat ETM+ scene……………………………………………….…………..	28
9	Environmental factors assumed to have minor influence on the study area……………………………………………………….….…………....	35
10	The Palmer Drought Severity Index (PDSI) range as defined by the NCDC………………………………………..………….….…………..	37
11	Values in the table below represent monthly average PDSI from 1990 through 2001 obtained from NCDC……………......………….…………..	37
12	Categories of damage extracted from the NDVI difference range corresponding to total forest damage…….……………………………………..	43
13	Categories of damage extracted from the NDVI difference range corresponding to hardwood-dominated forest damage………………………	43

TABLE Page

14 Categories of damage extracted from the NDVI difference range corresponding to conifer-dominated forest damage……………….………… 43

15 Cramer's V results for total study area………………………………………. 45

16 Cramer's V results for total study area: conifer dominant..…………………. 47

17 Cramer's V results for total study area: hardwood dominant..……………… 47

LIST OF EQUATIONS

EQUATION		Page
1	Calibrated radiance units ………….……………………………..…………..	27
2	Rescaled gain units………………………………………………..…………..	28
3	At-satellite reflectance………………………………………………………..	29
4	Rescaled reflectance units……………………………………...………….	29
5	Normalized difference vegetation index (NDVI)………………...…………..	30

INTRODUCTION

Large, landscape-scale disturbance events infrequently impact forested landscapes, but they have long-lasting influences on subsequent vegetation development (Foster *et al.*, 1998; Turner & Dale, 1998). In the complex terrain of mountainous environments, spatially heterogeneous damage patterns generated by disturbance events have been found to be influenced by factors such as topography and stand composition (Turner & Dale, 1998). This research will investigate the affects of abiotic and biotic factors on the spatial patterns of ice storm disturbance on a forested landscape in the Ouachita Mountains, Arkansas and Oklahoma, which were affected recently by ice storms. Ice storms are major disturbance events that can damage extensive swaths of forest (Irland, 2000).

Disturbance

Understanding the general impacts of disturbances on species diversity and composition has become an important issue for researchers and forest managers alike (e.g. Turner, 2005a; Sousa, 1984; Romme *et al.*, 1998). Theory suggests that a community unaffected or infrequently affected by extreme conditions (e.g. desert environment) or disturbances will transition toward a state of equilibrium with low species diversity and composition (Huston, 1994). Communities experiencing disturbances at these extreme ends of the spectrum (low or high) have developed the ability to adapt and survive in these conditions.

This thesis follows the style of the *Journal of Biogeography*.

Alternatively, those areas experiencing a "middle-ground" of disturbance frequency and/or severity maintain maximum diversity and composition. This "middle-ground" of disturbance is known as the intermediate disturbance hypothesis (Connell, 1978; Fox & Connell, 1979; Huston, 1994).

Effects of disturbances on ecosystem dynamics, such as forest succession, have long been studied in relation to mitigating and examining their effects on species diversity (Turner *et al.*, 2001). The geographic setting and its influence on the landscape has been found to be an important factor affecting both the frequency and magnitude of the disturbance (Huston, 1994; Foster *et al.*, 1997; Wickham *et al.*, 2000). In many ecosystems, disturbances are necessary to maintain the structure, species diversity, and composition of the vegetation (Abrams & Scott, 1989; Romme *et al.*, 1998; Lafon & Kutac, 2003; Lafon, 2004; Turner, 2005).

Though there are many different types of disturbances, from climatic (i.e. hurricanes) to abiotic (i.e. fires), topography has been found to influence spatial patterns of disturbance severity. For example, forest vegetation dynamics are more severely impacted by windthrow on steep slopes, increasing the likelihood of the "domino effect" (trees falling into each other) to occur (Jacobs, 2000) on unprotected sites (Foster *et al.*, 1998; Turner, 2005). Windward slopes are commonly found to exacerbate the severity of fire disturbances as well. Likewise, fires tend to burn uphill as the hot air from the fire rises, and leeward slopes and more sheltered locations experience less disturbance impact (Turner *et al.*, 2001). Flooding has also been found to impact much larger areas in locations with little topographical variability, specifically flat areas or shallow slopes versus steeper slopes, which are more likely to limit the extent of the flood disturbance

(Macdonald, 2003). In general, the spatial heterogeneity of disturbances can produce discrete patches of vegetation across a landscape (Levin & Paine, 1974; Sousa, 1984; Sprugel, 1991)

Ice Storms

Large-extent ice storm events have received relatively little attention from researchers, compared with some other types of large-extent disturbances (e.g. fires, insect outbreaks). An ice storm event is defined as ice accumulation of at least 0.6 cm (Irland, 2000; Bragg *et al.*, 2003). The largest and most frequent of these storms have occurred in eastern North America (Bennett, 1959) restricting most research to be conducted in this area. Few studies of ice storm damage have focused on their effects in the southern United States (i.e. from Texas to Virginia) because these areas are impacted less frequently (Cool *et al.*, 1971). However, ice storms in these southern states are worrisome to forest managers because of the importance of timber in this region (Bragg *et al.*, 2003).

Historically, major ice storm events have been observed to be less frequent throughout the southern states, occurring once every two to five years as compared to the midwestern and the northeastern states, where these occur approximately every one or two years. Though sporadic incidences of ice storms of varying magnitudes have occurred historically, several severe, damaging, and costly ice storms have impacted the South (Table 1). Damage to timber alone has ranged from $60 million (Cool *et al.*, 1971) to $1.3 billion (Halverson & Guldin, 1995). These large-extent disturbances have frequently impacted over 7 million acres of forested land (Forgrave, 2001), and in some cases, an estimated two million acres were classified as severely damage (White, 1944).

Table 1 Examples of damaging ice storm events in the southern United States

Date	State(s)	Source
1905	Tennessee	Burton and Gwinner, 1960
January 13-14, 1944	East Texas through Louisiana	White, 1944 McNayr, 1944
1951	Mississippi	Halverson and Guldin, 1995
March 1-2, 1960	Tennessee, Georgia, Alabama	Burton and Gwinner, 1960
February 1969	South Carolina	Cool et al., 1971
January 1973	Louisiana	Shepard, 1975
January 1974	Louisiana	Shepard, 1975
1974	Arkansas	Fountain and Burnett, 1979
1978-1979	Arkansas	Fountain and Burnett, 1979
December 1986	North Carolina	Nicholas and Zedaker, 1989
February-March 1987	North Carolina	Nicholas and Zedaker, 1990
February 1994	Northeast Texas through South Carolina through Viriginia	Halverson and Guldin, 1995 Warrilow and Mou, 1999
December 22-27, 1998	Arkansas	Cain and Shelton, 2002
December 12-13, 2000	Texas, Oklahoma, and Arkansas	NCDC, 2006a
December 25-28, 2000	Texas, Oklahoma, and Arkansas	NCDC, 2006a

**Most sources of information for this table taken from Bragg et al., 2003*

Ice Storm Meteorology and Climatology

Ice storm events occur when warm air masses encounter cold air masses causing precipitation to freeze upon contact with a surface (Lemon, 1961; Irland, 2000). The cold air mass lowers ground temperatures to below freezing (<32° F) transforming liquid precipitation into ice once the precipitation comes into contact with objects on the ground (Rauber *et al.*, 2001; Bragg *et al.*, 2003). Additional freezing may occur at a micro-scale when variables such as elevation are taken into account (Nicholas & Zedaker, 1989; Jones & Mulherin, 1998). The temporal and spatial scales of a storm, along with further temperature considerations and other meteorological conditions (e.g. wind, snow, etc.) can also affect the long-term impacts of a storm (Bennett, 1959; Bragg *et al.*, 2003).

In January of 1951, over 100 million dollars in damage was caused by the most costly ice storm on record at the time. This storm spread out over 100 miles from Louisiana to West Virginia. Similar to the ice storm occurring January 2007 across much of the southern U.S., polar air from Canada pushed down throughout the central U.S. while warm, tropical air was rising from the Gulf of Mexico. As these two air masses collided, they combined to transform precipitation into freezing rain, sleet, and snow. Wind speeds in this ice storm were unusually high, and as much as 20.3 cm of ice accumulation (Harlin, 1952). The February 1994 ice storm developed in a similar manner spreading from east Texas to Washington, D.C. It was one of the most costly storms with over 20.3 cm of ice accumulation and over 1.3 billion dollars of damage to timber alone (Jacobs, 2000). On January 10, 1949, a severe ice storm impacted much of the southern U.S. spreading across Missouri, Arkansas, Oklahoma, and Kansas. Regions like the northeast U.S. are particularly susceptible to ice storms due to the more frequent collison of cold and warm air masses in these latitudes. Additionally, though wind speeds during storms on average have tended to be light, wind can reduce temperatures even a couple of degrees transforming what was once rain into freezing rain or sleet (Kiviat, 1949).

Types of Damage to Forests

On average, from 1982 to 2000, sixteen ice storms per year occurred in the United States (Ncdc, 2006b) and of these, the most frequent and intense of these storms were located in the eastern United States (Irland, 2000). Also known as ice loading or glaze events, ice accumulates on trees causing them to bend to such a degree that trees have been found with crowns touching the ground. This bending can also result in limb or bole breakage, or uprooting of trees that are less pliable (Abell, 1934).

Damage and mortality occur when there is an accumulation of at least 6.35 mm of freezing rain upon vegetation (Nws, 2005). Effects range from individual tree damage or mortality (due to limb breakage, bole damage, uprooted trees, and treefall gaps) to widespread vegetation mortality (Cannell & Morgan, 1989). Types of damage or potential mortality attributed to ice accumulation include basal area damage, limb breakage, or canopy loss (Jacobs, 2000). Additional types of damage observed are crown loss, a decrease in radial growth, and bent and broken boles (Shepard, 1975). Increasing the level of damage observed to these forests is the "edge effect," i.e., those trees on the boundary of the forest were more severely affected than those in the interior (Burton & Gwinner, 1960). As a result of the "edge effect," those trees at the edge are more exposed to fluctuations in the natural environment, which was found to play an important role in severity of damage to exposed trees (Jacobs, 2000).

Abiotic Influences

Topography has increasingly been shown to have a more significant influence on disturbance magnitude and impact than biotic factors at a broad spatial scale (Lafon *et al.*, 1999; Irland, 2000). Slope-angle, aspect, and soil type were all found to be physical factors contributing to the ice storm's impact (Cool *et al.*, 1971). Previous research has noted the effect of elevation and aspect in increasing the intensity of ice storm damage (Lafon *et al.*, 1999; Millward & Kraft, 2004).

Research has found conflicting patterns of ice storm damage over elevational gradients. Higher elevations and ridgetops were generally found to be more susceptible to damage (Abell, 1934; Nicholas & Zedaker, 1989). For example, in North Carolina, very little damage was found in a study of low elevation (1525 meters) forest, but higher amounts of damage were found at a higher elevation (1980 meters). This was thought to be due to colder temperatures and greater exposure to wind (Nicholas & Zedaker, 1989). However, recent studies have found more moderate elevations to have experienced more severe damage (Carvell *et al.*, 1957; Millward & Kraft, 2004; Stueve *et al.*, 2007). Exacerbating the degree of damage are below-freezing temperatures that can cause ice deposits to linger days after the ice storm event has passed through an area, particularly at higher elevations (Burton & Gwinner, 1960).

Aspect is an important topographical variable controlling the degree of ice storm damage. Windward aspects have been found to have experienced the most severe levels of damage as a result of an increase in ice deposition (Lafon *et al.*, 1999). It has also been noted that the location and degree of damage to tree crowns can be further exacerbated by the direction of wind flow (Cain and Shelton, 2002). In the Appalachian Mountains of Virginia, east-facing slopes suffered the most severe damage (Warrillow and Mou; 1999). Similarly, Lafon et al. (1999) and Stueve et al. (2007) found the most severe damage occurred on southeast and east-facing slopes. The least amount of damage was found to be on northwest-facing slopes. In the Adirondack forests of northern New York, northeast, north, and southeast-facing slopes received the highest percentage of forest damage (Millward & Kraft, 2004).

A weak relationship has been found with slope-steepness when attempting to predict the amount of ice storm damage to a location, though slope steepness has been thought to contribute to the severity of damage (Lafon, 2006). More often, the severity of ice storm damage has been found to increase as the slope angle increases (Lafon, 2004). For example, in southwestern Virginia, Warrillow and Mou (1999) found the most severe damage occurred on steep slopes. However, other studies have found the most severe damage occurring on moderate slopes (Millward & Kraft, 2004; Stueve *et al.*, 2007).

Biotic Influences

The severity of damage is influenced not only by the physical environment, but also by the physiological and morphological characteristics of the tree itself, and the surrounding vegetation (Warrillow & Mou, 1999). Trees that are less vulnerable are those that are able to bend under the weight of ice accumulation and have smaller surface areas. Older trees have a tendency to be the most severely impacted due to their lack of pliability, larger surface area, and heavier limbs. Hardwoods are typically less vulnerable due to their lack of canopy during winter (Bragg *et al.*, 2003). Areas where trees had been thinned have shown pronounced levels of damage (Fountain & Burnett, 1979). In Louisiana, when approximately fifty percent of trees in an area which had been thinned were damaged from the first storm, a second storm following soon after, caused as much as ninety percent damage in those trees not damaged from the first storm (Shepard, 1975).

Though results may vary within geographical regions (Carvell *et al.*, 1957), studies of species responses to ice storm damage have generally found conifers to be less susceptible to damage than hardwoods in the northeast United States due to their physical structure (Hopkin *et al.*, 2003). The reverse is found to be true in the southern United States with hardwoods frequently found to be less susceptible to damage than conifers (Halverson & Guldin, 1995). In a study in Mississippi, hardwoods were less affected by the ice storm with only approximately thirty-seven percent damage, while their pine counterparts experienced upwards of eighty-eight percent damage(Jacobs, 2000). In the southern states, hardwood species are typically late-successional species resulting in species with stouter physical structures better able to withstand ice storm damage, while conifers tend to have thinner boles and less dense wood, and are therefore more susceptible to snapping and therefore mortality (Lemon, 1961; Attiwill, 1994; Jacobs, 2000; Lafon, 2006).

Of the damaged pines, the most common damage was to the stems, whereas the hardwoods more commonly experienced branch damage. Trees with branch damage tend to survive more often than trees with stem damage (Halverson & Guldin, 1995). Jacobs (2000) found only infrequent damage was noted from a neighboring tree falling against adjacent trees indicating the “domino effect” to be a minor variable more dependent on species composition. In a study in Mississippi, southern pines tended to be more affected by the “domino effect” than hardwoods. A hardwood colliding with a conifer was found to more likely to cause major damage whereas the situation in reverse is much less likely (Jacobs, 2000). Additionally, homogenous tree stands of similar species composition and size were found to be less likely to experience the “domino effect.”

Research Objectives

This research studies the effects of two ice storm disturbances on the 12 - 13 and 25 - 27 of December 2000 in the Ouachita National Forest of Arkansas and Oklahoma (Ncdc, 2006b). Both abiotic and biotic factors (i.e. forest stand type) are thought to affect the intensity of damage and mortality.

The objectives of the research are to quantify and explain spatial patterns of ice storm damage and answer the following questions:

1) Do spatial patterns of ice storm disturbance correlate with the abiotic variables of elevation, aspect, or slope?
2) Do spatial patterns of ice storm disturbance correlate with the biotic variable, tree species?

This research will quantify those areas having the most severe damage due to the two ice storm events and determine whether heterogeneous patterns of damage exist. Much research has been conducted at plot-level investigating the influence of disturbances on stand dynamics (e.g. Cool et al., 1971; Lafon, 2006). Resulting research will provide a landscape-level perspective on the impacts of ice storm disturbance that can aid future forest management plans developed for Ouachita National Forest.

STUDY AREA

Study Area Description

Forest damage severity from a large-extent ice storm disturbance has been examined in Ouachita National Forest (ONF) in west-central Arkansas and southeastern Oklahoma. The study area consists of approximately 6000 km^2 of forested landscape in the Ouachita Mountains physiographic region (Figure 1). The Ouachita Mountains comprise east to west ridges with mesophytic forests dominated by oak (*Quercus spp.*) and hickory (*Carya spp.*) on the north-facing slopes and xerophytic shortleaf pine (*Pinus echinata*) -dominated forests on the south-facing slopes (James & Neal, 1986; Sealander & Heidt, 1990). In Arkansas, ONF stretches across portions of Sebastian, Logan, Yell, Perry, Scott, Polk, Montgomery, Garlands, and Saline counties. In Oklahoma, ONF only extends into LeFlore county. Elevation ranges from 150 m to 800 m and the topography consists of steep slopes (Graney, 1992). Average annual precipitation is approximately 125 cm (Ncdc, 2006a). Three major rivers flow through ONF, including the Arkansas River in the northwest, and the Red and Ouachita Rivers in the south (Robinson, 2000).

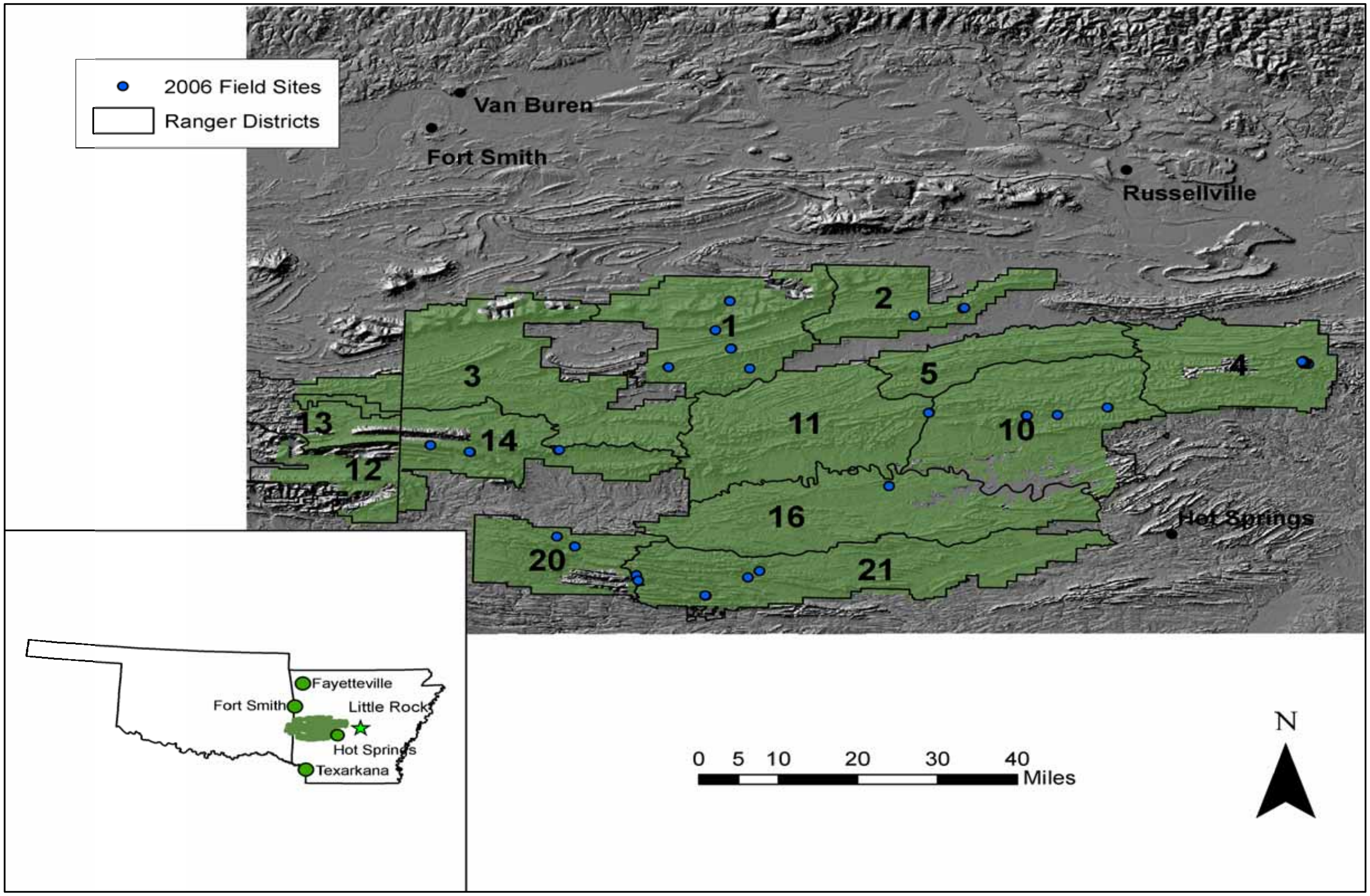


Figure 1 Study area. The green shaded area indicates national forest lands. Numbered areas represent forest ranger districts. The blue circles represent 46 forest damage field sites from which data were collected in May 2006.

Fire suppression practices initiated in the 1940s by the U.S. Forest Service have led to a shift in vegetation species composition from open woodlands, composed mainly of shortleaf pine (*Pinus echinata*) and bluestem grasses (*Andropogon spp.*), to a more dense pine and mixed hardwood forest system on south-facing slopes (Guldin *et al.*, 1994). In ONF, for more than half a century, the only fires that had occurred, burned small areas of the forest (less than 202 ha) (Usda, 1998). No major fire had occurred in the area for over fifty years due to fire suppression practices, until a wildfire spread (over 3237 ha) through ONF in the middle of March 2006 (Debbie Ugbade, Public Affairs Specialist, USFS, May 3, 2006, *personal communication*). Research suggests that southern pine species are shade-intolerant and therefore require intervention by forest managers or large-scale natural disturbances to cause a shift in species composition. Without interference, hardwood species are most likely to become the dominant species in a conifer-hardwood ecosystem (Cain & Shelton, 2002).

ONF predominately consists of hardwood species. Because of this, red oak borer (*Enaphalodes rufulus* Haldeman) outbreaks are of concern due to the possibility of them affecting forest vigor. Trees are most susceptible to the red oak borer after droughts (2001). Major infestations affect the Ozark Mountains to the north (2001 to present), but red oak borer has not been found to affect the Ouachita National Forest (Dennis Haugen, Entomologist, USFS, May 5, 2006, *personal communication*). Similar to the red oak borer potentially affecting forest vigor, the southern pine beetle (*Dendroctonus frontalis* Zimmermann) has also been of concern to forest managers. In ONF, there was no awareness of a southern pine beetle problem occurring in the area in recent years (Dwight Scarbrough, USDA Entomologist, USFS, May 5, 2006, *personal communication*). When conducting field work in ONF in 2006, I found no evidence of insect outbreaks (Figures 2 and 3).

Figure 2 Photograph taken May 25, 2006 overlooking Ouachita National Forest.

Figure 3 Additional photograph taken May 25, 2006 overlooking Ouachita National Forest.

December 2000 Ice Storms

In December of 2000, two separate ice storms heavily impacted sections of Oklahoma, Texas, and much of Arkansas, depositing between 1.3 and 15.2 cm of ice. Thousands of trees were downed or damaged due to the ice accumulation (Ncdc, 2006b). Patchy patterns of ice storm damage were observed throughout ONF (Warren Montague, District Biologist, USFS, May 26, 2006, *personal communication*). During the December 12 - 13 ice storm, the greatest amount of ice accumulation occurred in northern Arkansas and ranged from 7.6 to 15.2 cm (Figure 4). During the December 25th - 28th storm, 3.8 to 7.6 cm of ice accumulated from west-central Arkansas to south-east Oklahoma (Figure 5) (Bragg *et al.*, 2003).

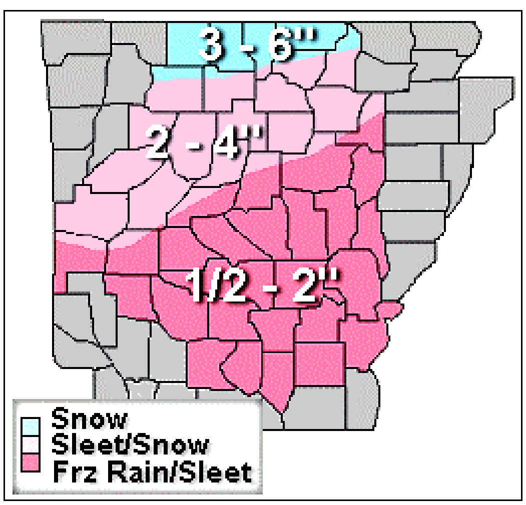


Figure 4 December 12-13 ice storm accumulation (inches) (James M. Guldin, Project Leader for the Arkansas Forestry Sciences Laboratory, USFS, March 2, 2006, *personal communication*)

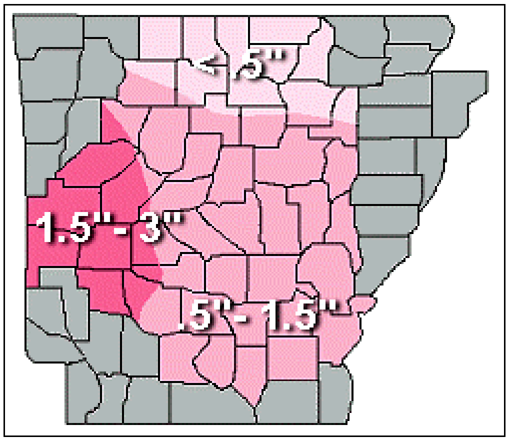


Figure 5 December 25-28 ice storm accumulation (inches) (James M. Guldin, Project Leader for the Arkansas Forestry Sciences Laboratory, USFS, March 2, 2006, *personal communication*)

Data obtained from CLIMVIS (Ncdc, 2006a) illustrate wind speed and wind direction for the two ice storms over a 24-hour period each day at the Little Rock and Fort Smith first-order cooperative weather stations. When available, precipitation in centimeters was provided to examine total accumulation for these time periods (Tables 2 – 5). During the December 12-13 ice storm, the Little Rock and Fort Smith data show the predominant wind direction during the storm was from the east and northeast (Table 2 and 3). During the December 25-28 ice storm, the data show predominant wind directions from the east and northeast (Table 4 and 5).

Table 2 Wind speed, wind direction, and precipitation for Little Rock, AR during December 12 – 13 ice storm.

Date	Hour (cst)	Speed (mph)	Direction (degrees)	Direction	Precip (cm)
12/12/2000	3	16	320	NW	
12/12/2000	6	15	330	NW	
12/12/2000	9	13	360	N	
12/12/2000	12	8	10	N	
12/12/2000	15	7	70	E	
12/12/2000	18	13	70	E	
12/12/2000	21	10	50	NE	trace
12/12/2000	24	14	70	E	trace
12/13/2000	3	13	60	NE	0.0762
12/13/2000	6	14	70	E	0.4064
12/13/2000	9	6	110	E	1.6764
12/13/2000	12	0	0	NA	0.8128
12/13/2000	15	0	0	NA	0.2286
12/13/2000	18	0	0	NA	
12/13/2000	21	0	0	NA	trace
12/13/2000	24	0	0	NA	trace

Note: Zero values may indicate equipment malfunctions

Table 3 Wind speed, wind direction, and precipitation for Fort Smith, AR during December 12 – 13 ice storm. VR = variable wind direction.

Date	Hour (cst)	Speed (mph)	Direction (degrees)	Direction	Precip (cm)
12/12/2000	3	12	310	NW	
12/12/2000	6	9	330	NW	
12/12/2000	9	7	340	N	
12/12/2000	12	3	VR	VR	
12/12/2000	15	6	60	NE	
12/12/2000	18	3	130	SE	trace
12/12/2000	21	13	110	E	0.0762
12/12/2000	24	9	90	E	0.4064
12/13/2000	3	12	110	E	0.762
12/13/2000	6	9	110	E	0.7112
12/13/2000	9	6	100	E	0.5588
12/13/2000	12	0	0	NA	0.2032
12/13/2000	15	0	0	NA	0.2286
12/13/2000	18	0	0	NA	trace
12/13/2000	21	6	290	W	trace
12/13/2000	24	8	270	W	

Table 4 Wind speed, wind direction, and precipitation for Little Rock, AR during December 25 – 28 ice storm. VR = variable wind direction.

Date	Hour (cst)	Speed (mph)	Direction (degrees)	Direction	Precip (cm)
12/25/2000	3	12	30	NE	
12/25/2000	6	18	40	NE	trace
12/25/2000	9	13	40	NE	0.0254
12/25/2000	12	12	40	NE	trace
12/25/2000	15	12	30	NE	0.0254
12/25/2000	18	8	40	NE	trace
12/25/2000	21	12	60	NE	0.0254
12/25/2000	24	14	50	NE	0.1016
12/26/2000	3	8	50	NE	0.1778
12/26/2000	6	10	70	E	0.3556
12/26/2000	9	10	60	NE	0.2286
12/26/2000	12	5	360	N	0.0762
12/26/2000	15	0	0	NA	0.4826
12/26/2000	18	5	30	NE	0.7366
12/26/2000	21	6	100	E	0.7366
12/26/2000	24	5	30	NE	trace
12/27/2000	3	3	40	NE	0.0254
12/27/2000	6	0	0	NA	trace
12/27/2000	9	3	40	NE	trace
12/27/2000	12	0	0	NA	0.0254
12/27/2000	15	3	VR	VR	trace
12/27/2000	18	5	VR	VR	trace
12/27/2000	21	0	0	NA	
12/27/2000	24	0	0	NA	
12/28/2000	3	0	0	NA	
12/28/2000	6	12	40	NE	
12/28/2000	9	6	40	NE	
12/28/2000	12	7	10	N	
12/28/2000	15	12	330	NW	
12/28/2000	18	0	0	NA	
12/28/2000	21	0	0	NA	
12/28/2000	24	7	280	W	

Table 5 Wind speed, wind direction, and precipitation for Fort Smith, AR during December 25 – 28 ice storm. VR = variable wind direction.

Date	Hour (cst)	Speed (mph)	Direction (degrees)	Direction	Precip (cm)
12/25/2000	3	12	100	E	
12/25/2000	6	15	90	E	0.0254
12/25/2000	9	15	100	E	trace
12/25/2000	12	13	110	E	0.0254
12/25/2000	15	14	90	E	0.0762
12/25/2000	18	13	100	E	0.254
12/25/2000	21	15	90	E	0.1524
12/25/2000	24	0	0	NA	0.3302
12/26/2000	3	0	0	NA	0.1524
12/26/2000	6	0	0	NA	0.254
12/26/2000	9	0	0	NA	0.0254
12/26/2000	12	0	0	NA	0.3048
12/26/2000	15	0	0	NA	0.5842
12/26/2000	18	0	0	NA	0.8382
12/26/2000	21	0	0	NA	0.1524
12/26/2000	24	0	0	NA	0.3556
12/27/2000	3	0	0	NA	0.0762
12/27/2000	6	0	0	NA	0.0254
12/27/2000	9	0	0	NA	0.0254
12/27/2000	12	0	0	NA	
12/27/2000	15	0	0	NA	0.0254
12/27/2000	18	0	0	NA	
12/27/2000	21	6	250	W	
12/27/2000	24	5	260	W	0.0254
12/28/2000	3	5	240	SW	
12/28/2000	6	6	230	SW	
12/28/2000	9	5	320	NW	
12/28/2000	12	7	260	W	
12/28/2000	15	6	280	W	
12/28/2000	18	6	240	SW	
12/28/2000	21	9	260	W	
12/28/2000	24	9	270	W	

Note: Zero values may indicate equipment malfunction

Though damage in urbanized settings was more easily accounted for as a result of higher population densities and therefore more witness accounts, damage throughout the uninhabited forested regions is not so easily quantifiable. Approximately $154 million of damage was caused by the two ice storms in forested areas in Arkansas alone. An estimated 500,000 acres were considered severely damaged and of the roughly 18.3

million acres of federal forest land, approximately forty percent experienced some level of damage. Approximately $12 million in damage was caused in ONF(Forgrave, 2001). According to records from the National Weather Service (NWS), these ice storms were the most severe and widespread since 1819 (Ncdc, 2007). Vicki Metcalf (Receptionist, USFS, May 27, 2006, *personal communication*) stated, “I have lived here for fifty years and have never seen an ice storm that bad.”

METHODS

Data

One Level-1G systematically processed Landsat 7 ETM+ scene (October 6, 1999) (Table 6) in the visible and near-infrared portions of the electromagnetic spectrum at a spatial resolution of 30 m * 30 m was obtained from the United States Geological Survey (USGS) Earth Resource and Observation Science (EROS) center. Level-1G imagery is radiometrically and geometrically corrected by the EROS Data Center and the amount of error and noise is less than found in Level-0R or1R imagery. The lower level imagery, though cheaper, is difficult to correct without specific software and knowledge of techniques. Though Level-1G is more expensive, the reduction of subsequent processing efforts by the user and the knowledge that this data has been processed thoroughly by proven USGS techniques, makes these data acquisitions the most suitable choice for research. A second Landsat 7 ETM+ scene (September 25, 2001) (Table 6) was obtained from the University of Maryland – Global Land Cover Facility (GLCF) Website (glcf.umiacs.umd.edu/index.shtml), produced by the NASA Landsat Program. This scene had been systematically processed to Level-1G status and received augmented processing in a standardized, orthorectification procedure performed by the USGS.

These data were from path 25 and row 36, which encompassed most of the ONF. These dates were chosen on the basis of temporal proximity to the 2000 ice storms, similarities in forest phenology, minimal cloud cover, and suitable atmospheric conditions (e.g. lack of haze and smoke). Selection of the 2001 scene ensured that the forest vegetation received sufficient recovery time from the ice storms to avoid abnormalities in spectral signatures (i.e. uprooted conifer foliage transitioning from green to brown) (Everham & Brokaw, 1996; Olthof *et al.*, 2004; Roberts *et al.*, 2004).

Table 6 Landsat 7 ETM+ image parameters for the September 25, 2001 and October 6, 1999 scenes.

Parameter	**92501**	**10699**
Acquisition date	9/25/2001	10/6/1999
Projection	UTM15	UTM15
Datum	WGS84	WGS84
Pixel Size	28.5	28.5
Sun Elevation Angle	48.74542	45.9784777
Sun Azimuth Angle	145.1919	150.5145282

7.5 minute Digital Elevation Models (DEMs) were obtained from the USGS Seamless Data Distribution. These DEMs can contain vertical errors of +/- 7 - 15m. The DEM provides the topographical data, including slope, aspect, and elevation for this research. Digital layers for the study area including county boundaries and cities were obtained from the University of Arkansas Spatial Analysis Laboratory. Forest species level data were obtained from the GAP Analysis Program (GAP) at a 30 m * 30 m spatial resolution. These data are maintained by the USGS National Biological Information Infrastructure (NBII) and created in cooperation with several federal, state, local, and private organizations including the National Park Service and The Nature Conservancy. GAP data are based on Landsat imagery, existing localized vegetation data gathered from field surveys, aerial photographs, ground verification points, and additional data sources. A complete description can be found at the GAP website (http://gapanalysis.nbii.gov/).

Wildfire and prescribed burn information and data were obtained from the Forest Inventory Database maintained by the Forest Inventory and Analysis National Program (FIA). Additional data were obtained from the National Fire Occurrence Database, also known as the National Interagency Fire Management Integrated Database (Usda, 1998), developed by multiple government organizations and maintained by the USDA National Information Technology Center. The fire data obtained were used to determine locations within ONF where wildfires or prescribed burns had occurred.

Image Pre-processing

Geometric Correction

Landsat 7 ETM+ scenes typically contain residual spatial errors of 250 m or less on flat surfaces at sea level, but these errors are exacerbated in mountainous landscapes (Itten & Meyer, 1993; Nasa, 2006). Level 1-G processed images are geometrically corrected for errors created by the sensor and the satellite but do not use a terrain correction method to reduce horizontal error. Therefore, additional geometric corrections were performed to reduce spatial distortions and make the images more suitable for quantitative analyses in mountainous terrain. The September 25, 2001 image had been previously orthorectified by the GLCF. An orthorectification with subsequent image-to-image co-registration technique was applied to the October 6, 1999 image. Whereas simply applying the image-to-image co-registration technique has been found to contain as much as 250 m of horizontal error, performing an orthorectification prior to the image-to-image co-registration has been found to reduce the horizontal error to within 30 m (Nasa, 2006).

Orthorectification

As a result of the unevenness of the Earth's surface along with distortions caused by the satellite, horizontal error can be as much as 250 m (Itten & Meyer, 1993). More topographically complex landscapes tend to produce added geometric and radiometric distortion in the image. The orthorectification process increases the accuracy of the positional location of pixels and preserves original brightness values of the image (Nasa, 2006). An orthorectification was performed on the October 6, 1999 Landsat scene using GCPs, elevation information extracted from a DEM, and sensor path (orbital) data. The DEM was used to correct for terrain relief distortions. The orthorectification process was performed using the PCI Geomatica V10.0 OrthoEngine tool.

To correct for distortions, the appropriate math empirical model needs to be chosen to reduce errors in the resultant orthorectified image. An empirical model corrects for known distortions by linking individual image pixels to their associated locations on the ground. A parametric empirical model was used due to this model's ability to correct for both terrain relief and image acquisition distortions. This technique alters the entire image and typically has sub-pixel accuracy. Orthorectification minimizes some of the remaining geometric errors on the Level-1G images (Cheng *et al.*, 2002). The process requires the collection of ground control points (GCPs) at easily identifiable areas, such as road intersections, to geometrically correspond one image to another. The GCPs establish location of raw data pixels to features on the surface of the Earth (Jensen, 2005). The 1999 and 2001 Landsat ETM+ scenes were co-registered with 25 GCPs and an initial RMSE of 0.199 pixels to achieve the less than 0.5 pixels RMSE recommended by Jensen (2005). Each of the 25 GCPs had a corresponding elevation extracted from the DEM with up to 15 m vertical error.

Image-to-Image Co-registration

An image-to-image co-registration technique is a process applied to two images of similar geometry and spatial area. This process was performed using ENVI 4.2. In this instance, the October 6, 1999 Landsat scene was co-registered to the original September 25, 2001 reference scene, which had been previously orthorectified by the GLCF. Along with the co-registration comes the awareness that the newly co-registered scene will contain the geometric errors of the reference image (Jensen, 2005). An additional 25 GCPs were chosen for additional co-registration following the orthorectification process to reduce the RMSE to 0.18 pixels and in turn reduce potential error. Again, GCPs were collected in easily identifiable areas in the Landsat scenes. The two scenes were co-registered using the second-order polynomial warping method utilizing the 25 GCPs spread throughout the entire Landsat scene. The second-order polynomial math model was chosen because it produces the best fit mathematically in mountainous environments based upon the x and y coordinates of the selected GCPs (Curran & Williamson, 1985). During the image-to-image co-registration process, there is no compensation for topography; therefore the second-order polynomial math model is considered the better fit for the data (Jensen, 2005).

Radiometric Correction

The Landsat images may contain "noise" or distortions due to sensor characteristics, atmospheric scattering, and differences in illumination geometry which distort pixel brightness values (Smith & Milton, 1999; Song & Woodcock, 2001). Because two Landsat scenes are being compared, normalization techniques (especially relevant when temporal disparities between images are involved) were used to correct for these errors. Both the pre- and post-storm images should be subjected to radiometric corrections (Nielsen *et al.*, 1998). Differences between sun elevations and sun azimuths for 1999 and 2001 images can also affect the degree to which the landscape develops shadows (Jensen, 2005). Sun elevation was 45.9791 degrees for the 1999 image and 48.7493 degrees for the 2001 image. Subsequent radiometric corrections include the calculation of radiance units, at-satellite reflectance, and a Dark Subtract.

The calculations of radiance units and at-satellite reflectance compensate for differences in sun angle and elevation during the satellite acquisition process to reduce pixel brightness value variation by normalizing the data. Digital numbers of available Landsat TM scenes were scaled according to gain and bias values for each band (example of values used in subsequent equations found in Appendix A) (Song & Woodcock, 2001). These values were then converted back to calibrated radiance units and at-satellite reflectance using the following two equations (Markham & Barker, 1986):

Calibrated radiance was calculated using equation 1:

$$L_\lambda = gain_\lambda * DN_\lambda + Offset_\lambda \tag{1}$$

Where L_λ is the calibrated radiance units for wavelength λ, gain and offset are the rescaled units corresponding to the respective state of acquisition for the images, and DN is the original digital value of the data. Gain was calculated using the equation 2:

$$Gain = \frac{(L_{\max} - L_{\min})}{(Q_{\max} - Q_{\min})} \text{ : Rescaled gain, units } w.m^{-2}.sr^{-1}.\mu m^{-1} \quad (2)$$

L_{max}, L_{min}, Q_{max}, and Q_{min} data were obtained via the metadata provided with the Landsat scene. *Offset* is equivalent to the L_{min} value for each band (Tables 7 and 8). L_{max} and L_{min} are the upper and lower spectral radiance limits for each band, and Q_{max} and Q_{min} correspond to the upper and lower digital number limits (1 to 255) for each band.

Table 7 Spectral radiance parameters for the September 25, 2001 Landsat ETM+ scene.

Band	Lmax	Offset (Lmin)	Qmax	Qmin	Gain	Wavelength
Band 1	191.6	-6.200	255.00	1.00	0.77874	0.4850
Band 2	196.5	-6.400	255.00	1.00	0.798819	0.5600
Band 3	152.9	-5.000	255.00	1.00	0.621654	0.6600
Band 4	241.1	-5.100	255.00	1.00	0.969291	0.8300
Band 5	31.06	-1.000	255.00	1.00	0.12622	1.6500
Band 7	10.8	-0.350	255.00	1.00	0.043898	2.2150

Table 8 Spectral radiance parameters for the October 6, 1999 Landsat ETM+ scene.

Band	Lmax	Offset (Lmin)	Qmax	Qmin	Gain	Wavelength
Band 1	191.6	-6.200	255.00	1.00	0.77874	0.4850
Band 2	196.5	-6.400	255.00	1.00	0.798819	0.5600
Band 3	152.9	-5.000	255.00	1.00	0.621654	0.6600
Band 4	157.4	-5.100	255.00	1.00	0.639764	0.8300
Band 5	31.06	-1.000	255.00	1.00	0.12622	1.6500
Band 7	10.8	-0.350	255.00	1.00	0.043898	2.2150

At-satellite reflectance was then calculated using equation 3:

$$\rho_\lambda = \frac{\pi * L_\lambda * d^2}{ESUN_\lambda * \cos in \theta_s} \tag{3}$$

Where ρ_λ is the at-satellite reflectance, L_λ is the calibrated spectral radiance at the sensor's aperture calculated from equation 1, d^2 is the Earth-Sun distance in astronomical units calculated based on the Julian Day, $ESUN_\lambda$ is the mean solar exoatmospheric irradiance, and θ_s is the solar elevation angle in degrees. Julian Day can be obtained by adding up all the days of the year prior to the acquisition date (e.g. 1/1 → 9/25 = 268). At-satellite reflectance results provided two normalized images compensating for some of the differences in sun angle and elevation between 1999 and 2001.

Atmospheric scattering can cause variations in reflectivity resulting in enhancing or subduing real-world events. NDVI results have been found to have inflated values of approximately 50 percent or more in open or damaged environments (Jensen, 2005). Minimal atmospheric scattering was evident in both images as observed in the histograms of the bands from the images (see Appendix B). Therefore, a dark subtract was implemented to minimize the effects of atmospheric scattering (Smith & Milton, 1999). A dark subtract forces reflectance values of remotely sensed data to normalize by subtracting the smallest reflectance value in a band from every other reflectance value in the same band (Liang *et al.*, 2002; Millward & Kraft, 2004). Prior to the dark subtraction process, reflectance values in the bands may contain negative numbers. The reflectance values should be rescaled to normalize the data by returning them to 0 - 255 brightness value range. Reflectance values were rescaled using equation 4:

$$(band_n + 1) - NewMin_\mathrm{n}) * 255 / (NewMax_\mathrm{n} - NewMin_\mathrm{n}) \tag{4}$$

Normalized Difference Vegetation Index

The Normalized Difference Vegetation Index (NDVI) is a commonly used index of vegetation vigor (Rouse *et al.*, 1974; Tucker, 1979). The technique has been applied widely in vegetation research, including evaluation of the effects of ice storm damage on forested landscapes (Burnett, 2002; Dupigny-Giroux *et al.*, 2003; Millward & Kraft, 2004; Stueve *et al.*, 2007). NDVI is a versatile measure of vegetation vigor due to the chlorophyll concentrations in the leaves of trees. Healthy vegetation absorbs the highest amount of radiation in the red band, whereas the mesophyll in the leaves reflects much of the radiation in the near-infrared spectrum (Becker & Choudhury, 1988; Jensen, 2005). NDVI is calculated from the following equation (Rouse *et al.*, 1974; Tucker, 1979; Lillesand & Kiefer, 2000):

$$NDVI = \frac{NIR - Red}{NIR + Red} \tag{5}$$

Where *NIR* is the near-infrared band (band 4 of Landsat 7 ETM+) and *Red* is the red band (band 3 of Landsat 7 ETM+). NDVI values range from -1 to 1, with high positive values indicating the presence of healthy and dense vegetative cover associated with closed forest canopies (Jensen, 2005). Ratio assessments of vegetation are especially useful in mountainous regions as they help diminish the effects of shadows (Xiao *et al.*, 2002; Jensen, 2005). NDVI values were calculated for the radiometrically and geometrically corrected October 6, 1999 and September 25, 2001 Landsat ETM+ scenes.

Change Detection

The October 6, 1999 NDVI values were subtracted from the September 25, 2001 NDVI values to create an NDVI difference image identifying ice storm damage impacts on the forest canopy. Prior to performing the NDVI difference calculation, the images were subset via a region of interest (ROI) with the intention of creating equivalent spatial extents for each image. A 3 x 3 low pass filter was then run on the resultant NDVI difference image to smooth the data and reduce the potential for anomalous values to cause skewed results in later calculations(Guerschman *et al.*, 2003).

Field Verification and Calibration

A total of 46 geolocated field sites was used to determine the relationship of NDVI difference values to actual forest damage caused by the ice storm (Figure 1). The level of ice storm damage was assessed in the field by counting the number of downed tree boles intersecting a 100 m transect, following Stueve et al. (2007). The field sites encompassed a broad range of each of the physical variables and ice storm damage. An equal number of field sites were established in the conifer-dominated and the hardwood-dominated forests to characterize the relationships between forest type and damage. No undamaged field sites were selected due to the widespread nature of the ice storms, with the entire study area receiving at least minor damage (Ncdc, 2007). To help ensure a wide range of field data were collected, visits to two ranger stations were conducted. Meetings with two District Biologists intimate with the study area and the ice storm events provided information concerning spatial patterns of ice storm damage on the national forest.

The average of a 3x3 pixel area was calculated to determine the NDVI difference values at each of the 46 sites, and linear regression was used to characterize the relationship between the density of downed boles and NDVI difference values. Linear regression has been applied successfully when used in conjunction with multiple ground plots (Dungan, 1998; Larsson, 2002). Therefore, the regression model was used to determine whether NDVI was representative of ice storm damage in the study area. My expectation was that NDVI declined in ice-damaged forests, with the greatest declines occurring in the most heavily damage stands because of the reduction in canopy biomass (Millward & Kraft, 2004; Stueve *et al.*, 2007).

The relationship between NDVI difference values and downed bole densities were plotted (Figures 6 to 8). NDVI values were found to decline with an increase in the number of downed boles. Total, hardwood-dominated, and conifer-dominated forest damage were all found to have significant relationships between the number of downed boles and NDVI difference values. Hardwood-dominated areas were found the have the strongest relationship of the three. The strength of these relationships validates that NDVI difference is a good measure of ice storm damage.

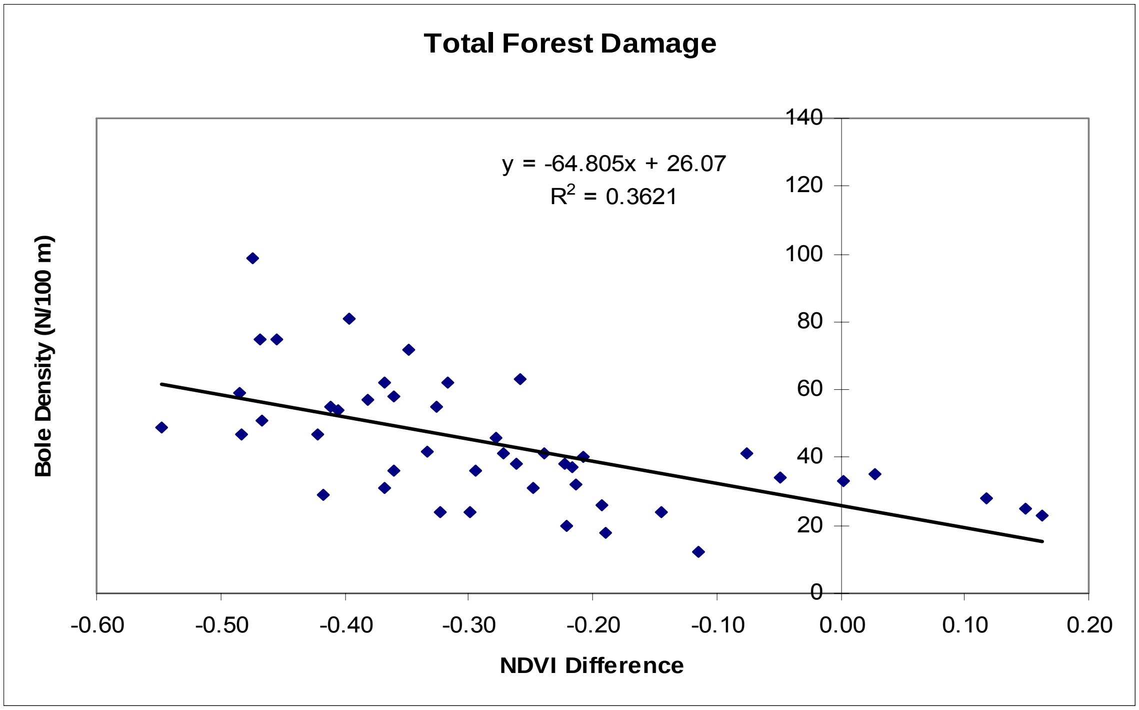


Figure 6 Linear regression results corresponding to NDVI versus bole damage for the 46 geolocated sites.

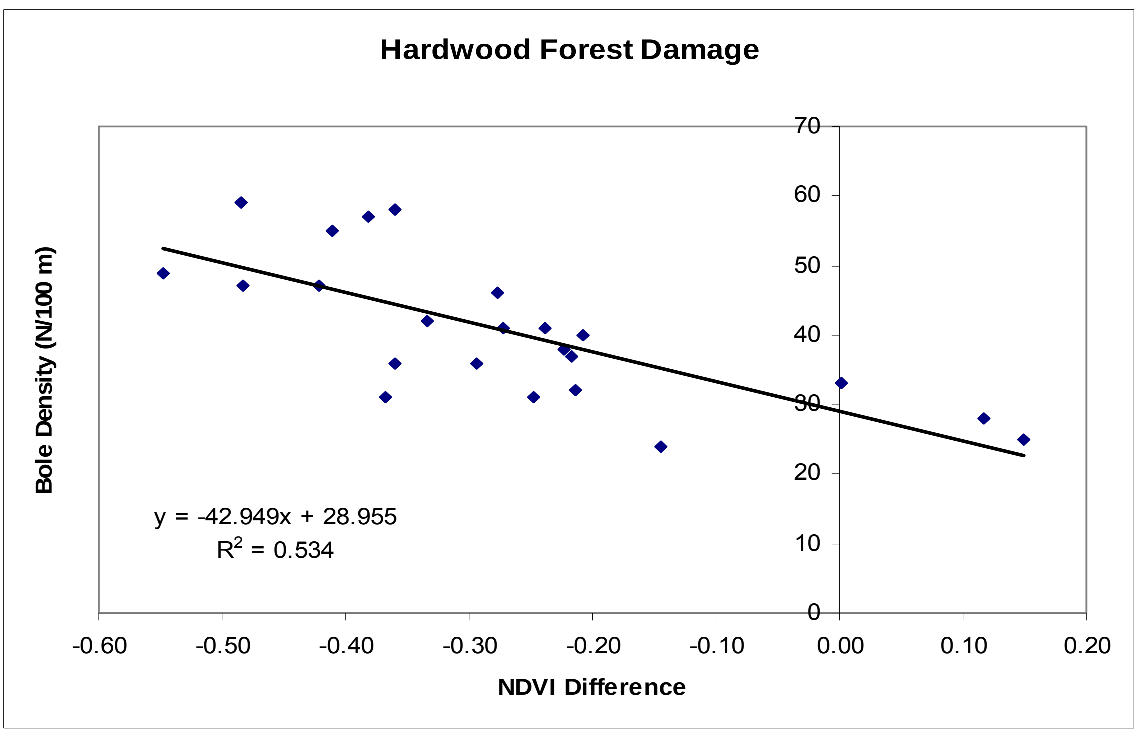


Figure 7 Linear regression results corresponding to NDVI versus bole damage for the 23 hardwood-dominated sites.

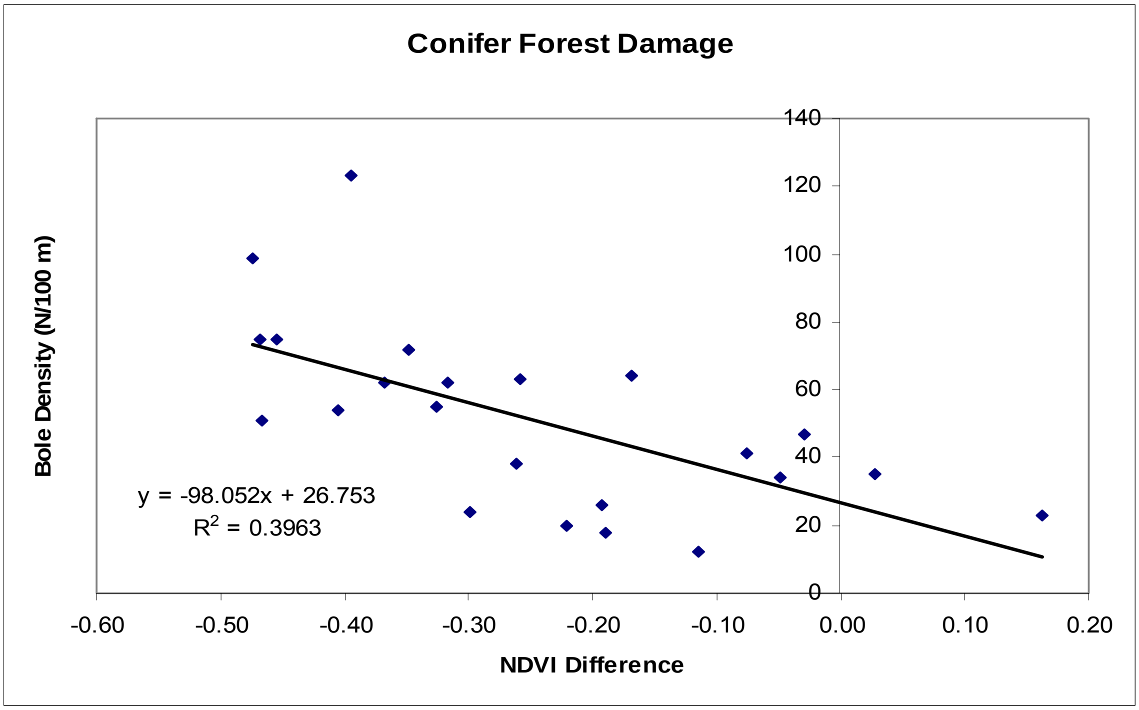


Figure 8 Linear regression results corresponding to NDVI versus bole damage for the 23 conifer-dominated sites.

Data from CLIMVIS (Ncdc, 2006a) were explored to verify that the 2000 ice storm was the only major weather event to have significantly influenced forest damage in ONF between October 6, 1999 and September 25, 2001 (see Appendix C). Small storms occurred throughout this time period, but all storms mentioned were stated by the NCDC to have little impact beyond scattered downed trees or broken limbs. Anomalous data beyond small weather impacts can affect the resulting NDVI (Table 9). Any pixels with the potential to produce anomalies in the results were removed. These include any areas within the National Forest lands that contain clouds, had major fire damage (this includes areas in which prescribed burns or wildfires occurred), or areas that were logged after the 1999 image acquisition date. The remaining pixels with negative values of NDVI difference were hypothesized to have experienced substantial ice storm damage.

Table 9 Environmental factors assumed to have minor influence on the study area. These factors can decrease NDVI values and be confused with ice storm damage

Environmental Factor	Description	Compensating Actions and Assumptions
Wildfires/Prescribed Burns	No major fire greater than 202 ha had occurred in the area for over 50 years. Burned areas can alter satellite reflectance values	Excluded prescribed burn and wildfire locations and assumed any remaining potential data did not influence NDVI difference results
Logging	Logged areas can expose understory vegetation altering satellite reflectance values	Excluded logged area data and assumed any remaining potential data did not influence NDVI difference results
Red Oak Borer/ Southern Pine Beetle	Major insect outbreaks can cause large-extent mortality throughout a forested area potentially altering satellite reflectance values	Neither of these two insect species were observed by USFS Entomologists working in the ONF study area
Additional Storms	Additional major storms (e.g. blizzards, ice storms, blow-downs, etc.) can occur obscuring the ability to discern patterns from the storm(s) in question	According to NCDC, no other major storms had occurred within the study area and minor ones were found to minimally affect the area
Precipitation	Abnormally dry or wet years potentially stressing vegetation	NCDC data show average monthly precipitation for the study area to follow similar trends throughout the year with precipitation, in general, increasing from the month of July through December
Temperature	Abnormally cold or hot years potentially stressing vegetation	NCDC data show average monthly temperatures for the study area to be approximately the same between 1999 - 2001
Drought	Moisture patterns that are considered departures from normal conditions could potentially stress vegetation. A 16 month drought in the area could have reduced vegetation vigor.	NCDC data show mid-range drought conditions for the study area with the exception of five months in the year 2000. Ice storm damage is assumed to still be detectable based on the NDVI difference versus bole density relationship graphs.

Though negative values of NDVI are hypothesized to indicate ice storm damage, other factors such as drought, seasonal temperature variations, and other climatic conditions between the two image acquisition dates can affect the conclusion that the NDVI values strictly measure forest damage from the ice storm (Dymond *et al.*, 2002). Pixels less than or greater than the field verified NDVI difference range were excluded prior to performing statistical procedures because it is impossible to confirm ice storm damage, or lack thereof, in these pixels (Millward & Kraft, 2004; Stueve *et al.*, 2007).

Slight variations of interannual precipitation or temperature anomalies can impact forest phenological processes enough to influence NDVI values by at least 0.1 (Walsh, 1987; Masellli, 2004). Differences between the growing seasons of 1999 and 2001 may have impacted forest phenological processes. Examining local climatic records in detail for variations in temperature and precipitation can establish whether there may be variations in canopy cover (Jolly *et al.*, 2005). The Palmer Drought Severity Index (PDSI) (Table 10) was examined for the duration and intensity of events that may have influenced canopy cover reflectance values. These values represent moisture patterns that are departures from normal with positive values indicating wetter than usual conditions and negative values indicating drier than usual conditions.

A 16 month drought in the study area may have had an influence on vegetation vigor thus decreasing NDVI difference values (Table 11). This potential decrease in NDVI may be confused with ice storm damage. However, though a long-term drought did occur in the study area, the relationship graphs (Figures 6 – 8) appear to indicate that much of the observed decrease in NDVI values is a result of ice storm damage because of the strong, negative relationship between the number of downed boles and NDVI difference values. Also notable in the relationship graphs are the appearance of six positive NDVI difference values indicating an increase in vegetation vigor in these areas of the forest. These positive values could indicate that drought conditions did not have a strong impact on vegetation vigor and that conditions were more favorable in these areas during 2001 growing season than in 1999.

Table 10 The Palmer Drought Severity Index (PDSI) range as defined by the NCDC.

Palmer Drought Severity Index (PDSI)	
Extreme Drought	¯ 4.0 <
Severe Drought	¯ 3.0 – ¯ 3.99
Moderate Drought	¯ 2.0 – ¯ 2.99
Mid-Range	¯ 1.99 – 1.99
Moderately Moist	2.0 – 2.99
Very Moist	3.0 – 3.99
Extremely Moist	4.0 >

Table 11 Values in the table below represent monthly average PDSI from 1990 through 2001 obtained from NCDC.

	Month											
Year	J	F	M	A	M	J	J	A	S	O	N	D
1990	0.7	1.12	1.79	2.47	4.32	-0.74	-0.88	-1.17	-1.04	-0.8	-1.04	-0.57
1991	-0.21	-0.89	-0.97	1.01	-0.5	-0.9	-0.98	0.06	0.27	1.55	2.03	2.35
1992	-0.22	-0.74	-1.08	-0.155	-1.77	0.65	1.12	1.21	1.92	1.26	1.73	2.19
1993	2.65	2.41	1.61	2.04	1.97	1.94	1.17	0.78	1.4	1.99	2.19	2.03
1994	2.31	1.96	1.65	1.44	1.07	0.71	1.77	1.93	1.46	1.08	2.75	2.74
1995	2.84	-0.72	-1.19	0.28	0.43	0.73	0.94	-0.63	-0.74	-1.12	-1.65	-1.49
1996	-1.31	-1.91	-1.99	-1.54	-2.03	0.33	1.07	1.39	2.05	1.94	4.06	-0.3
1997	-0.73	0.82	0.6	0.72	-0.69	-0.27	-0.67	-0.91	-1.3	0.48	0.44	0.85
1998	1.98	2.05	2.42	-0.54	-0.87	-1.18	-1.58	-2.18	0	0.74	-0.1	-0.1
1999	-0.04	-0.76	0.27	0.51	1.08	1.57	-0.17	-0.89	-1.32	-1.43	-1.9	-1.13
2000	-1.32	-1.73	-2.16	-2.52	-2.52	-0.73	-1.08	-1.98	-2.03	-2.16	1.01	0.87
2001	0.64	1.74	-0.47	-1.19	-1.08	-1.39	-1.95	-2.28	0.19	0.35	-0.33	1.09

To further support that decline in NDVI difference values were mostly related to ice storm damage rather than climatic influences, temperature and precipitation were examined for the years 1999 through 2001. Monthly average surface data (Figures 9 and 10) for Arkansas was obtained from CLIMVIS (Ncdc, 2006a).

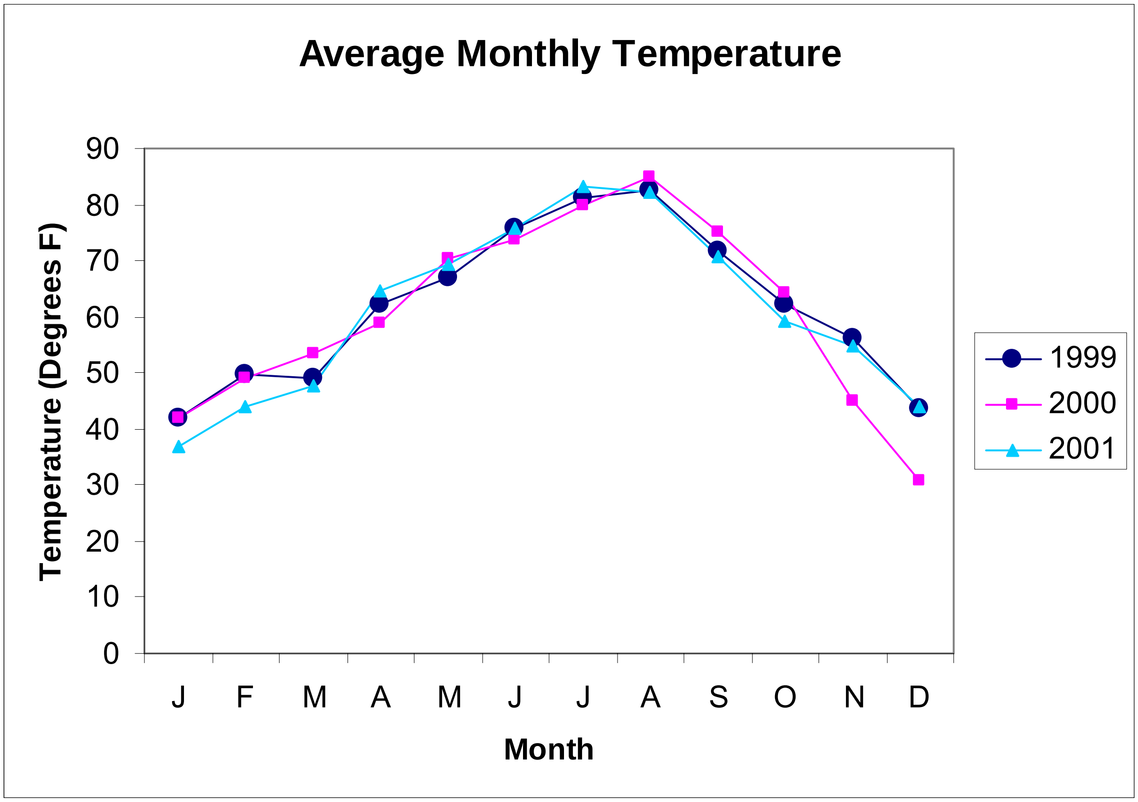


Figure 9 Average monthly temperature for Arkansas, Division 4 (Western).

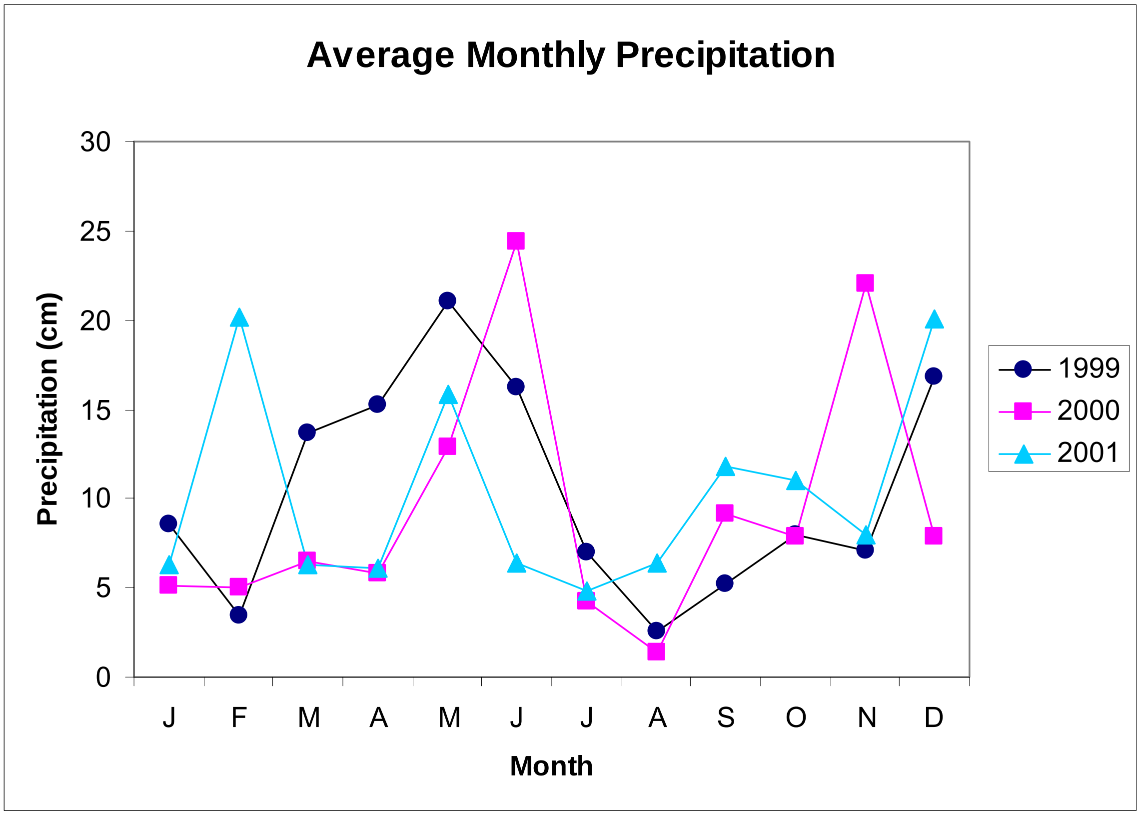


Figure 10 Average monthly precipitation for Arkansas, Division 4 (Western).

The monthly average temperature and precipitation data for the three years suggest that climatic influences had minimal influences on NDVI difference values (Figures 9 and 10). The field verification points provide a range to eliminate most of the extreme values. Normally, negative NDVI difference values are expected to indicate stressed vegetation and positive values indicate vegetation vigor. Previous research demonstrates that this pattern does not always hold true (Millward & Kraft, 2004; Stueve *et al.*, 2007).

The majority of the field verification points were below zero indicating there was rather comprehensive ice storm damage. Ice storm damage should cause NDVI to decrease from 1999 to 2000. If, however, in 2001 there was major climate stress in the area, all NDVI difference values would decrease even more, causing all points to fall below zero. The NDVI difference values for the data range between -0.55 to 0.17. The field verification points provide the NDVI difference range within which to examine the data and what values are indicative of vigorous and stressed vegetation. Therefore, the entire study area should have received at least minor damage from the two ice storms resulting in the majority of pixels depicting a decline in NDVI between October 6, 1999 and September 25, 2001. Additionally, some positive NDVI difference values could indicate a more rapid understory recovery rate in these areas influencing reflectivity amounts to satellite sensors.

Analysis of Topographic Patterns

Bilinear resampling, via ArcGIS 9.1, was performed on the DEM to be consistent with the 30 m x 30 m spatial resolution of the NDVI difference image (Jensen, 2005). Elevation, slope, and aspect were calculated based on individual pixels from the DEM. Slope and aspect were calculated using the ‘queen’ algorithm assigning values to each pixel based on the eight surrounding pixels, which has been found to be superior in mountainous regions (Burrough & Mcdonnell, 1998). Aspect was classified into the commonly used eight cardinal directions of north, northeast, east, southeast, south, southwest, west, and northwest (Asner *et al.*, 2002; Gardner & Gustafson, 2004). Slope was classified mostly into five degree increments. Elevation was broken down into 100 m increments (Millward & Kraft, 2004). Forest species data (from GAP) were classified into conifer and hardwood-dominated forests, with areas of agriculture, pastureland, and water areas masked out. NDVI difference values were calculated for all pixels in every category on National Forest Land.

The data for each of the variables were imported into SPSS 12.0 to conduct the statistical analyses. The numerical ranges for the different levels of damage were determined by dividing the pixels into three classes of equal size. The three classes of damage were categorized as major, moderate, and minor damaged areas (Figures11 – 13).

Figure 11 An example of a minor ice storm damaged area (James M. Guldin, Project Leader for the Arkansas Forestry Sciences Laboratory, USFS, March 2, 2006, *personal communication*).

Figure 12 An example of a moderate ice storm damaged area (James M. Guldin, Project Leader for the Arkansas Forestry Sciences Laboratory, USFS, March 2, 2006, *personal communication*).

Figure 13 An example of a major ice storm damaged area (James M. Guldin, Project Leader for the Arkansas Forestry Sciences Laboratory, USFS, March 2, 2006, *personal communication*)

Categories of damage were extracted from the total number of pixels within the NDVI difference range from the entire study area (Tables 12 – 14). Three categories of damage were identified by dividing the total number of points into three classes of minor, moderate, and major, containing an equal number of points. To identify patterns, the major category of damage was segregated from the minor and moderate damage (major). Also, the minor category of damage was segregated from the major and moderate damage (major/moderate).

Table 12 Categories of damage extracted from the NDVI difference range corresponding to total forest damage

Category	Even Breaks
Minor	-0.2369 – 0.1699
Moderate	-0.3772 – -0.2369
Major	-0.5499 – -0.3772

Table 13 Categories of damage extracted from the NDVI difference range corresponding to hardwood-dominated forest damage

Category	Even Breaks
Minor	-0.2441 – 0.1499
Moderate	-0.3756 – -0.2441
Major	-0.5499 – -0.3756

Table 14 Categories of damage extracted from the NDVI difference range corresponding to conifer-dominated forest damage

Category	Even Breaks
Minor	-0.2149 – 0.1699
Moderate	-0.3581 – -0.2149
Major	-0.4799 – -0.3581

NDVI difference values were then exported as a text file and the chi-square (X^2) test of correspondence was applied to the values to evaluate the relationships between the variables. The chi-square test of correspondence analyzes the statistical significance between variables (Nicholas & Zedaker, 1989; Jolayemi, 1990; Zar, 1999; Millward & Kraft, 2004; Stueve *et al.*, 2007). The Cramer's V test was then used to explain any significant relationships among those variables considered statistically significant by the chi-square test of correspondence (Kiefer, 1959; Cramer, 1999; Zar, 1999; Agresti, 2002). The Cramer's V value established the strength of these relationships with values ≥ 0.1 indicative that a somewhat strong relationship exists and values > 0.3 indicative of a very strong relationship (Kent & Coker, 1994; Burt & Barber, 1996; Stueve *et al.*, 2007).

RESULTS

Spatial patterns of ice storm damage corresponding to the categories of damage (minor, moderate, and major) were observed (Figure14). Statistical tests were performed for the major damage category, and the major and moderate categories combined. The chi-square analysis of correspondence confirmed elevation, aspect, slope, and species all had associations with the NDVI difference results ($p < 0.001$) for the data. The strength of the relationship between elevation, aspect, and slope are indicated by Cramer's V results performed on the values, demonstrating spatial patterns of ice storm damage (Table 15). The results indicated elevation had the strongest influence on degree of ice storm damage, followed closely by slope and aspect.

Table 15

Cramer's V results for total study area

Variable	Major	Major/Moderate
Elevation	0.177	0.254
Aspect	0.124	0.053
Slope	0.108	0.201
Forest Type	0.057	0.058

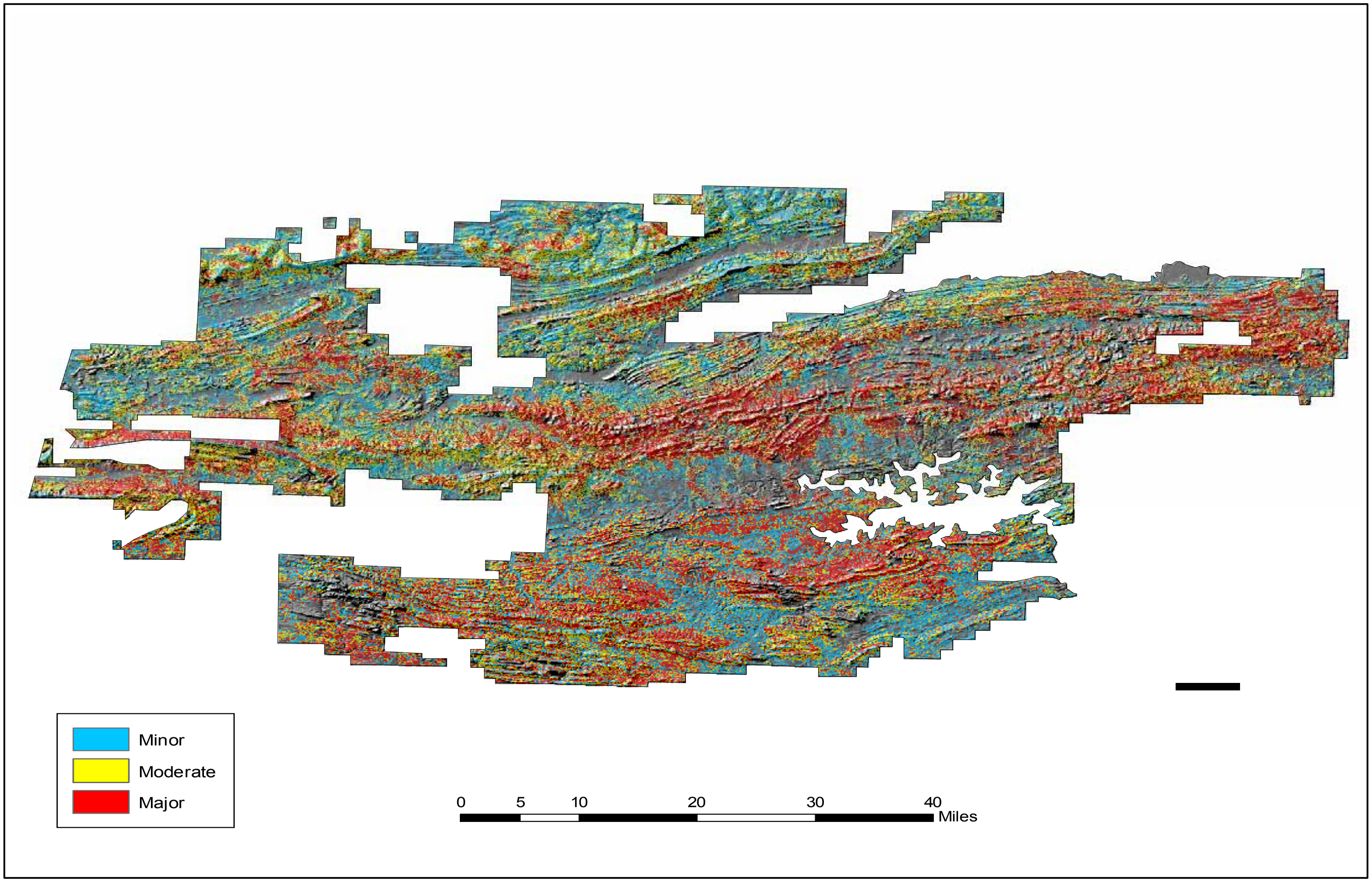


Figure 14 Ice storm damage for the Ouachita National Forest. Gray areas indicate those pixels excluded from the study.

Differences in the degree of physiological impacts to different tree species may obscure the relationship of ice storm damage impacts when examining the entire study area (versus one homogenous region) comprehensively. Therefore, Cramer's V was calculated for those sites corresponding to the conifer-dominated areas and those sites corresponding to hardwood-dominated areas (Tables 16 - 17).

Table 16

Cramer's V results for total study area: conifer dominant

Variable	Major	Major/Moderate
Elevation	0.188	0.245
Aspect	0.071	0.044
Slope	0.112	0.191

Table 17

Cramer's V results for total study area: hardwood dominant

Variable	Major	Major/Moderate
Elevation	0.178	0.220
Aspect	0.141	0.056
Slope	0.117	0.266

Elevation

The elevations receiving both the greatest amount and most severe damage are at moderate elevations ranging from 380 – 480 m (Figure 15 - 17). The least impacted elevations were at the lowest and highest elevations studied. In all cases, the Cramer's V values indicate a moderately strong relationship was found to exist between damage and elevation (Table 15). Hardwood-dominated impacted areas displayed a stronger relationship with elevation than conifer-dominant areas (Tables 16 – 17).

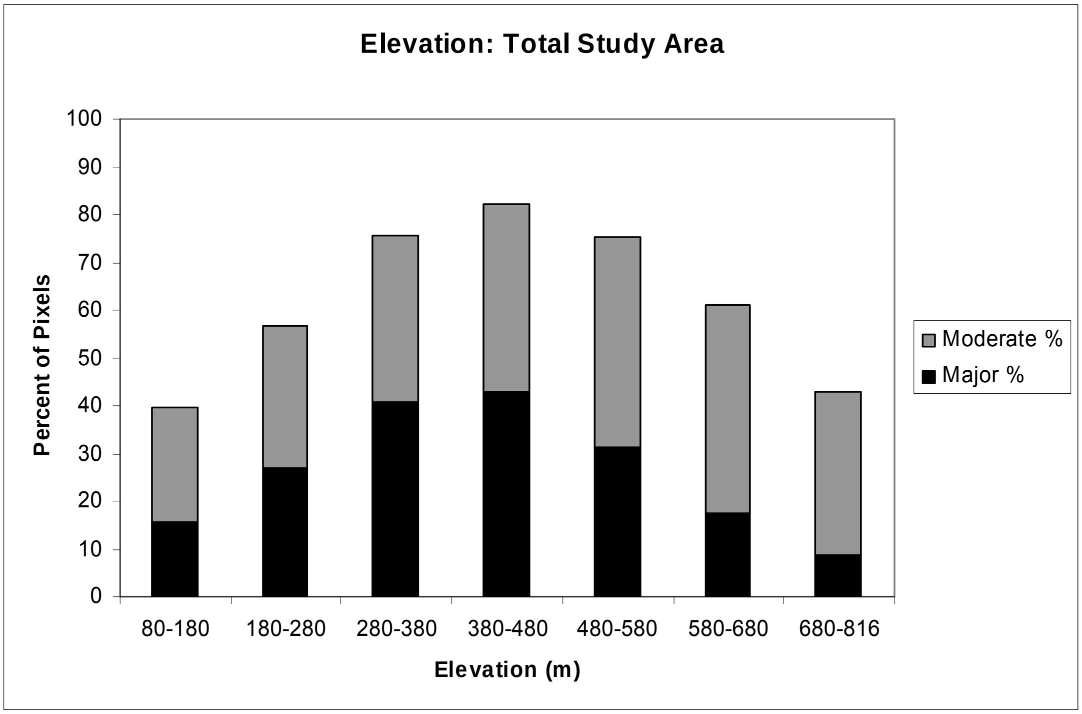


Figure 15 Spatial patterns of the categories of ice storm damage for elevation.

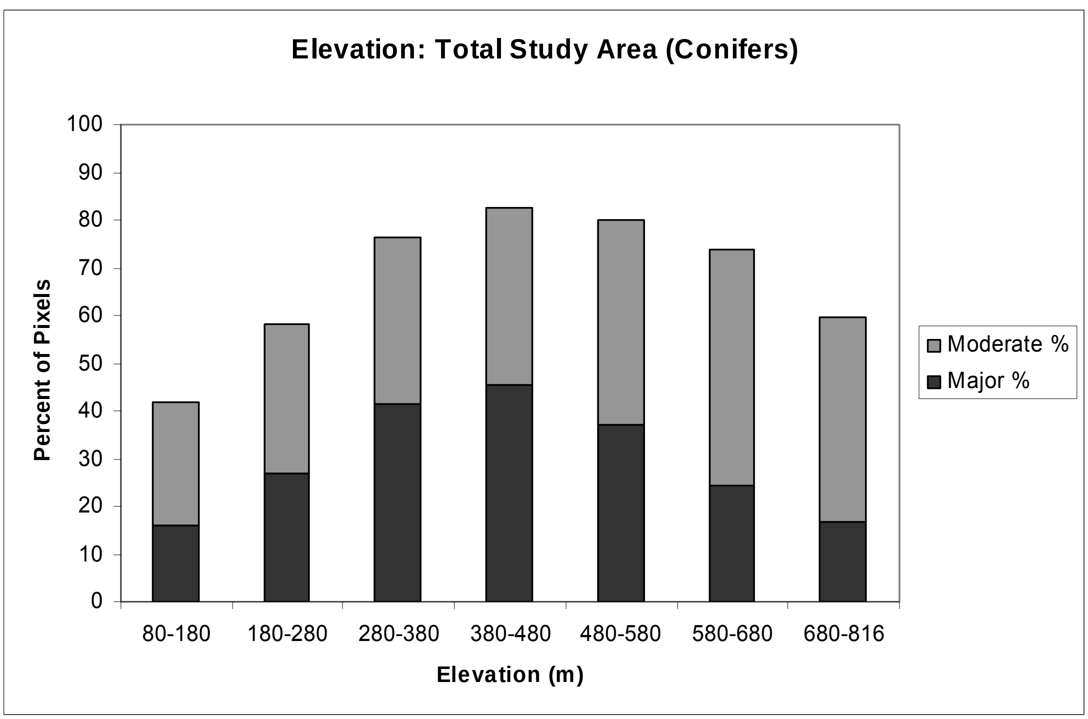


Figure 16 Spatial patterns of the categories of ice storm damage for elevation in conifer-dominated areas.

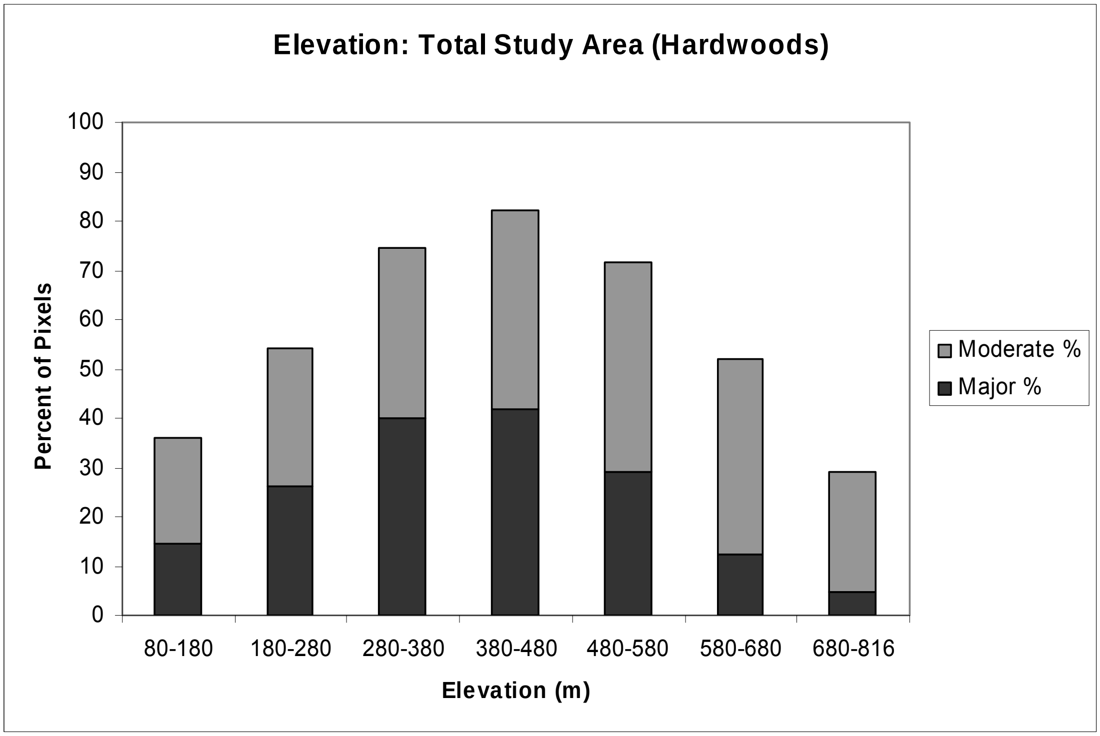


Figure 17 Spatial patterns of the categories of ice storm damage for elevation in hardwood-dominated areas.

Slope

Slope steepness was found to have a stronger influence on ice storm damage patterns than aspect in most cases, though less influential than elevation. The major extent of the damage occurred at moderate slopes ranging between 10° to 20° (Figures 18 – 20). The Cramer's V values indicate a relationship exists between damage and slope (Tables 15). Hardwood-dominated areas displayed a stronger relationship between slope and damage than both the hardwood/conifer combined dataset, and the conifer-dominated dataset (Tables 16 – 17).

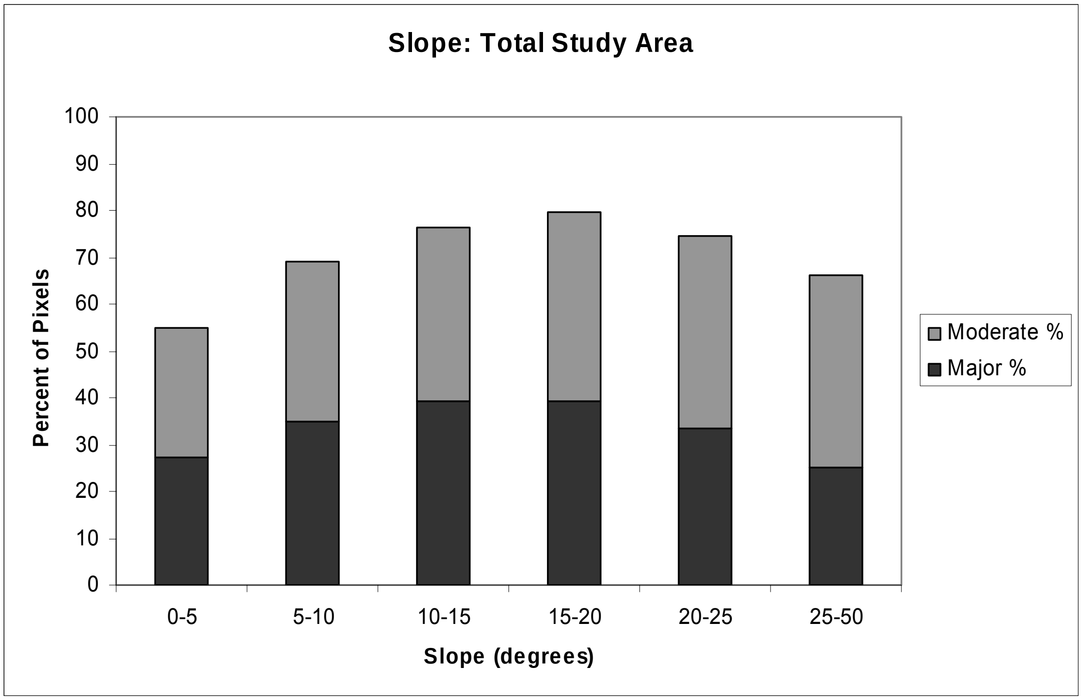


Figure 18 Spatial patterns of the categories of ice storm damage for slope.

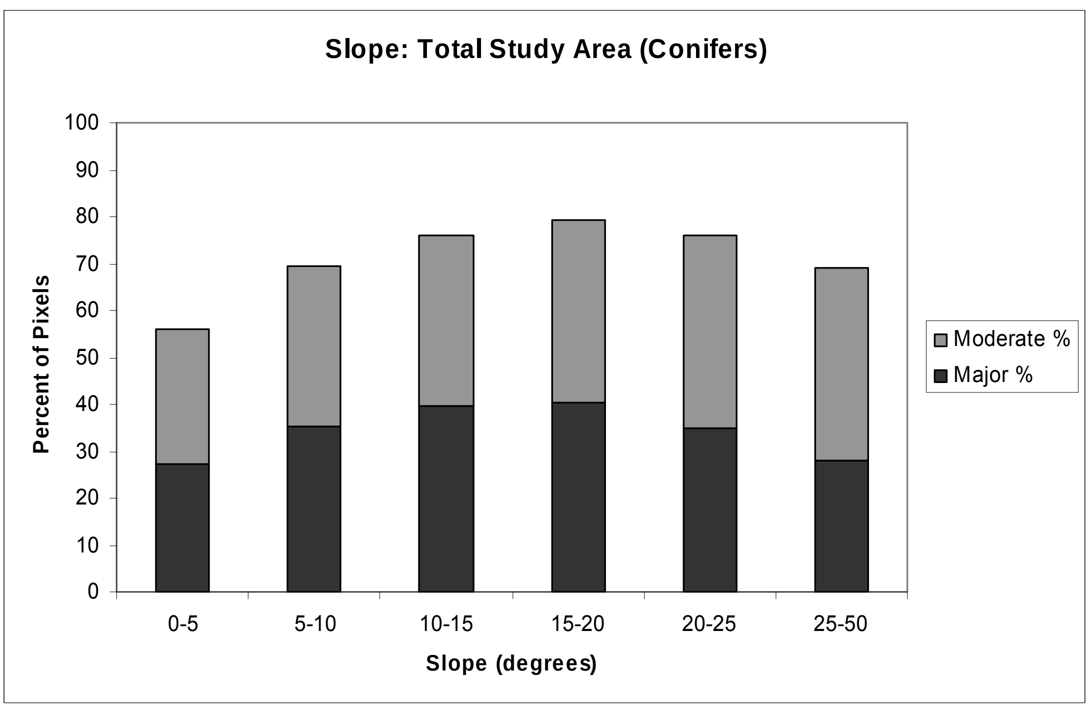


Figure 19 Spatial patterns of the categories of ice storm damage for slope in conifer-dominated areas.

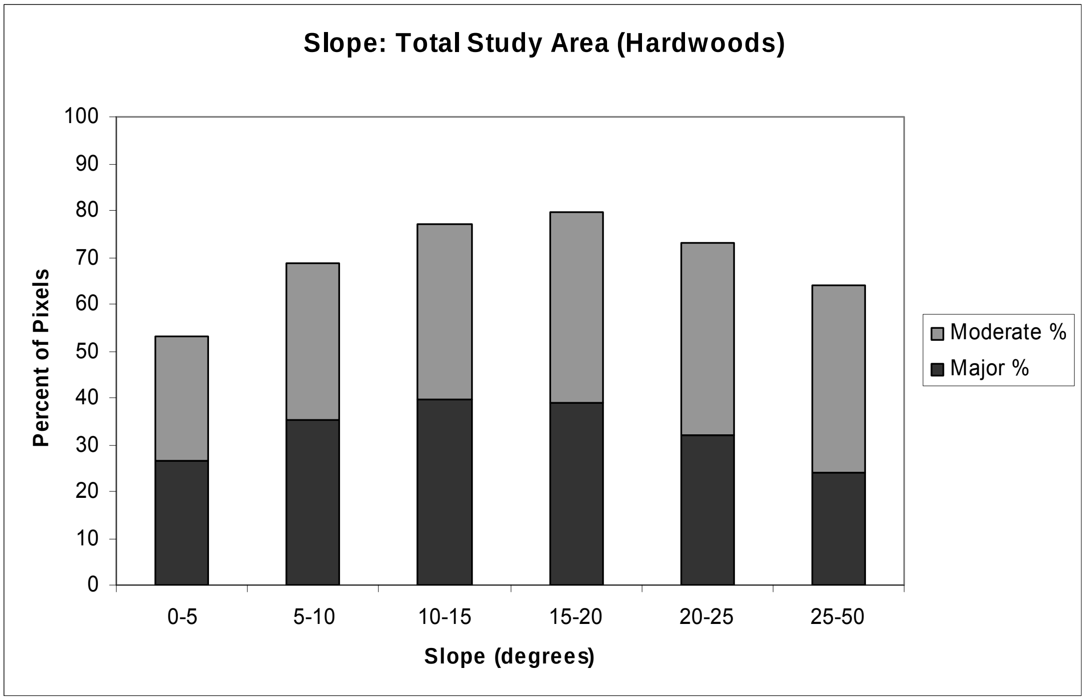


Figure 20 Spatial patterns of the categories of ice storm damage for slope in hardwood-dominated areas.

Aspect

The aspects exhibiting the most severe levels of damage in the study area are the north and northeast facing slopes (Figure 21). The conifer-dominated areas display a less distinctive pattern of damage (Figure 22). The patterns of damage in hardwood-dominated areas, in this instance, are more strongly influenced by aspect than the conifer-dominated areas (Figure 23). The Cramer's V values for aspect have low Cramer's values indicating weak to somewhat strong relationships with the NDVI difference values (Tables 15 - 17).

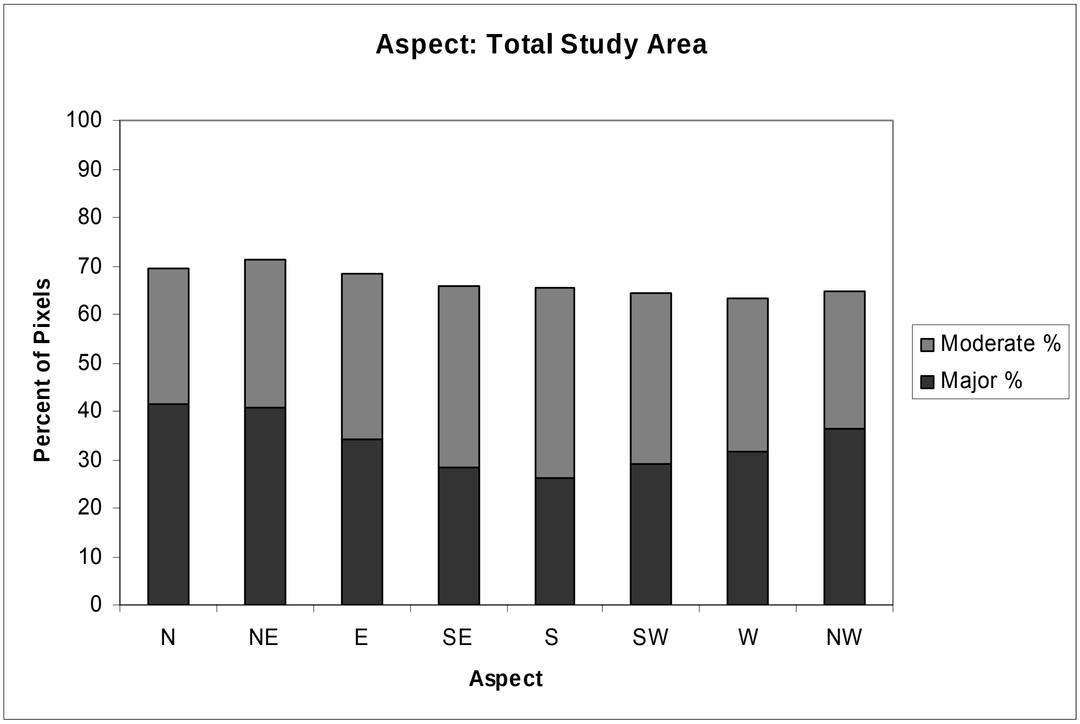


Figure 21 Spatial patterns of the categories of ice storm damage for aspect.

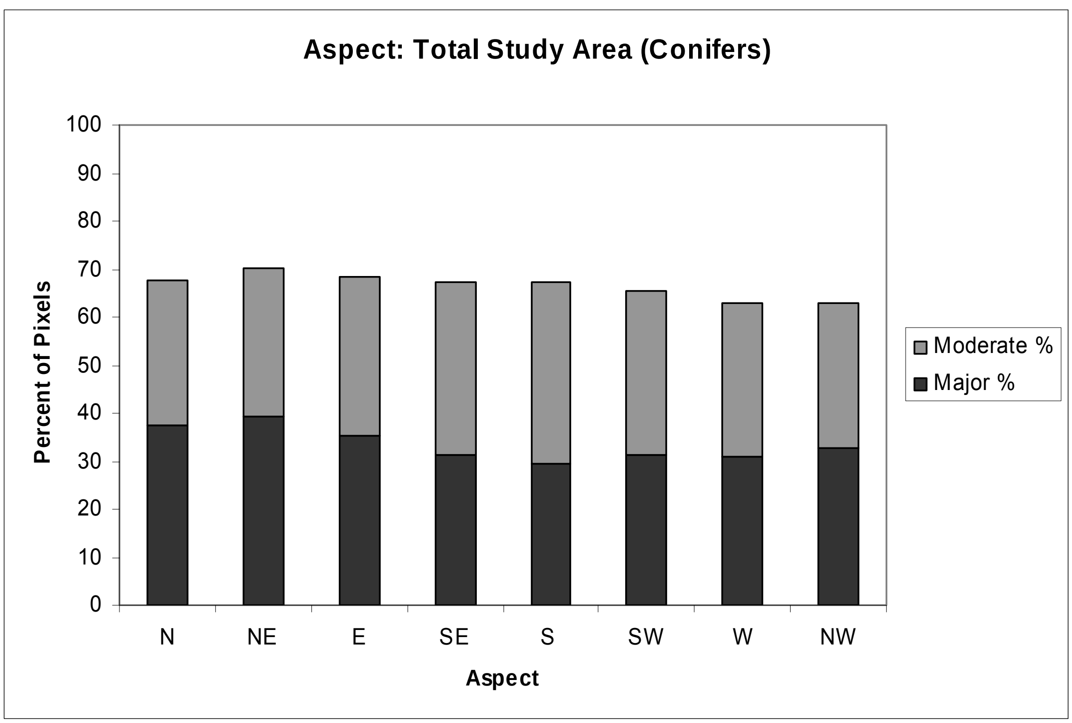


Figure 22 Spatial patterns of the categories of ice storm damage for aspect in conifer-dominated areas.

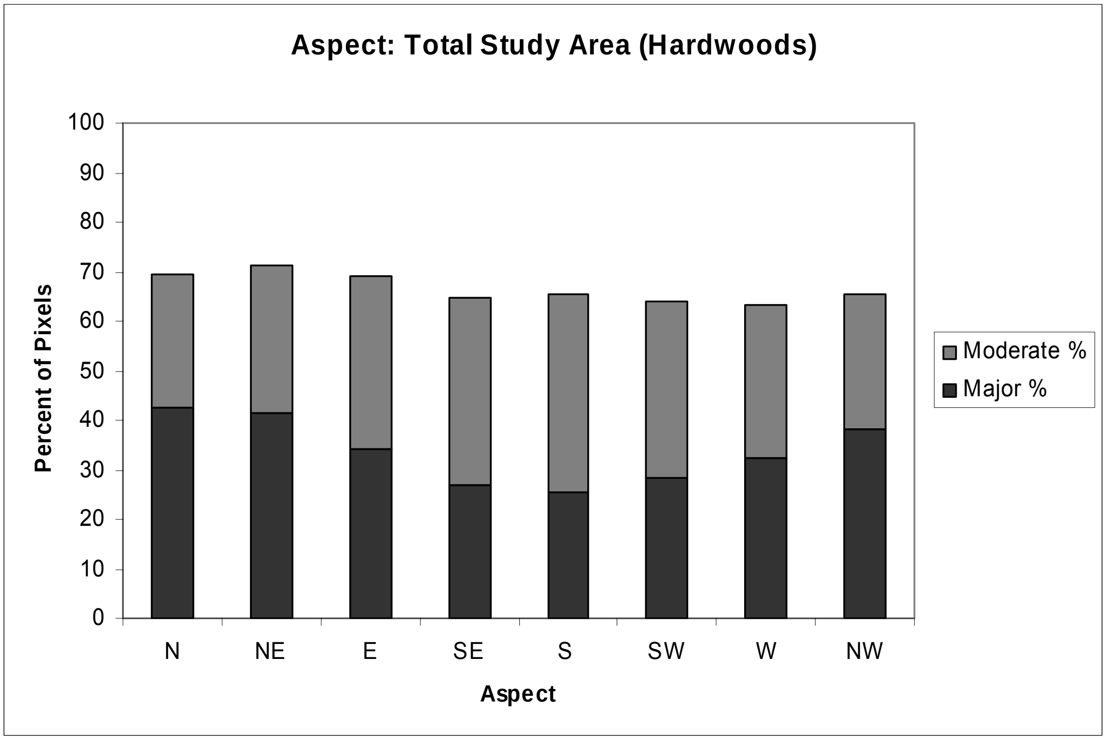


Figure 23 Spatial patterns of the categories of ice storm damage for aspect in hardwood-dominated areas.

Species

Hardwood-dominated and conifer-dominated stands show no discernable difference in ice storm damage patterns in this study (Figure 24). This variable (forest type) was the weakest of the independent variables. The Cramer's V values for the forest type variable have very low values in all of the categories indicating a weak relationship between forest type and degree of damage (Tables 15 – 17).

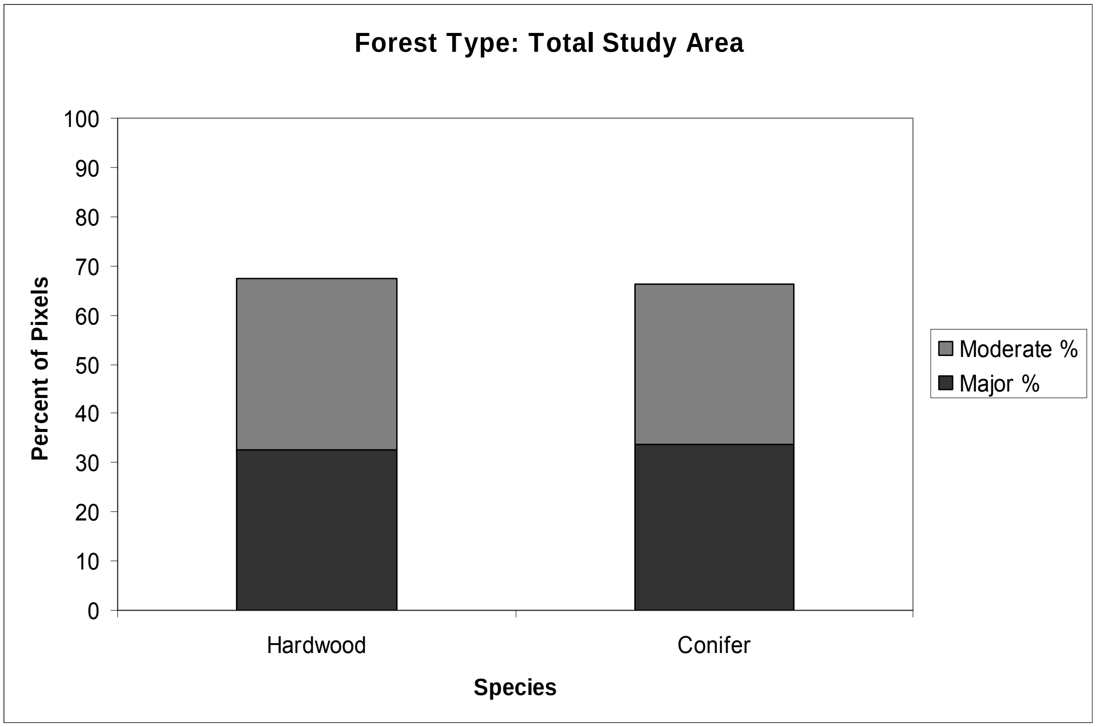


Figure 24 Spatial patterns of the categories of ice storm damage for hardwood-dominated and conifer-dominated areas.

DISCUSSION

Spatial Patterns of Ice Storm Damage

Spatial patterns of damage likely reflect the path of the two ice storms throughout the area, ice deposition throughout the national forest (Figures 4 – 5), and the complex nature of the physical landscape. Moderate elevations, moderate slopes, and windward aspects received the highest percentages of major ice storm damage. The strength of the relationships between each of the independent variables and the severity of damage are weaker than those found in previous studies (Millward & Kraft, 2004; Stueve *et al.*, 2007). However, the topographic patterns of damage are similar to previous research in ice storm disturbance (Lafon *et al.*, 1999; Warrillow & Mou, 1999; Millward & Kraft, 2004; Stueve *et al.*, 2007).

Similar to the results of Stueve, et al. (2007), the majority of severe damage was observed at moderate elevations. The most likely explanation is that these elevations received the greatest amount of ice deposition. The vertical temperature profile in mountainous environments most likely had the greatest influence on the amount of ice deposition across the study area (Rauber *et al.*, 2001; Bragg *et al.*, 2003). Liquid precipitation typically occurs at the highest elevations before passing through the temperature inversion to much cooler temperature at the moderate elevations, at which point liquid rain transforms into freezing rain. As the freezing rain continues to fall to lower elevations, temperatures began to increase causing the freezing rain to melt (Konrad, 1998). Additionally, as elevation increases, precipitation typically increases as temperatures decrease. This environmental gradient also creates more favorable conditions for producing freezing rain. In this study, the severity of damage decreased once elevation surpassed 480 m, which may reflect the decrease in slope angle at the high elevations. Ice storm damage was also observed in the valleys, most likely caused by valley pooling of cold air (James L. Hill, District Biologist, USFS, May 26, 2006, *personal communication*).

Moderate slope angles were observed to have impacted the degree of ice storm damage. Similar to the Stueve, et al. (2007) study, the severity of damage increased with slope angle when at 20°, the severity of damage began to decrease with this trend continuing to the steepest slopes. Slope angle may cause a scarcity in vegetation at the steeper slopes as a result of increased moisture runoff and less developed soils thus reducing NDVI values. These steeper slopes may also contribute to an increase in NDVI difference values by exposing more of the understory vegetation to satellite sensors. Furthermore, the stressful conditions found at steeper slopes and exposure of understory vegetation would most likely result in low NDVI values prior to the ice storm. Following the storm, NDVI values in these areas would likely decrease less than NDVI in other locations. More often, the severity of ice storm damage has been found to increase as the slope angle increases (Lafon, 2004). In this study, the results were counterintuitive to conclusions drawn from the Millward and Kraft (2004) study, where slope steepness was found to be a very weak variable having little effect on ice storm damage impacts.

The highest percentages of ice storm damage were observed on north and northeast-facing slopes. These spatial patterns corresponded with predominant wind directions during the ice storms. Wind patterns clearly show predominant wind direction from the north, east, and northeast (Ncdc, 2006a). These windward slopes are areas where ice deposition was most likely to have been the greatest (Lafon *et al.*, 1999). It has been noted that the location and degree of damage to tree crowns can be further exacerbated by the direction of wind flow (Cain and Shelton, 2002). Moreover, slightly greater wind speeds at these windward slopes may have reduced temperatures slightly transforming liquid rain into freezing rain (Kiviat, 1949). Dissimilar to patterns previously observed, aspect had less influence on the degree of ice storm damage (Millward & Kraft, 2004; Stueve *et al.*, 2007).

Aspect and elevation are commonly the most influential topographical variables controlling the effects of ice storm damage, with slope exhibiting little to no influence (Millward & Kraft, 2004; Stueve *et al.*, 2007). The dissimilarities found in this study is most likely due to the extremely large study area obscuring much of the complex variability in the landscape. For example, maximum ice deposition may have varied between the two ice storms. The temperature inversion might have increased or decreased in altitude altering the vertical temperature profile and generating differing elevational zones of maximum ice accumulation (Konrad, 1998). The variability observed in wind direction and wind speed between the two ice storms could also influence maximum ice accumulation throughout the study area. More topographical homogeneity may be observed in a smaller section within the larger study area producing more pronounced topographical patterns.

Several environmental factors assumed to cause declines in NDVI values were considered in this study. Based on personal communication (i.e. red oak borer and southern pine beetle), database research (i.e. additional storms), and GIS data used to exclude areas likely to alter satellite reflectance values (i.e. fires, logged areas), these factors were assumed to have a minor influence on the study area. Drought, especially a long-term drought such as this study area experienced, most likely affected NDVI values. However, much of the decrease in NDVI is still speculated to be a result of ice storm damage because of the strong, negative relationship between the number of downed boles and NDVI difference values. The six positive NDVI difference values also indicate an increase in vegetation vigor in those areas of the forest.

Conifer/Hardwood-Dominated Areas Patterns of Ice Storm Damage

Counter to previous research, conifer-dominated areas had a weak relationship between NDVI difference values and the number of downed boles (Lemon, 1961; Halverson & Guldin, 1995). Hardwood-dominated and conifer-dominated areas had similar percentages in the degree of ice storm damage. Hardwoods are more frequently found on north, northeast, and east-facing slopes which are the more mesophytic areas. Conifers are typically found on the more xerophytic, south-facing slopes, Interestingly, though hardwood-dominated areas are found on these windward-facing slopes, conifer-dominated areas were observed to have slightly more severe damage occurring in spite of the fact that they were found on the least severely damaged slope-aspects.

In the southern states, hardwood species are typically late-successional species resulting in species with denser wood and bigger branches, characteristically more resistant to ice storm damage (Jacobs, 2000; Lafon, 2006). Hardwoods exhibited more limb breakage, rather than “bowing” or snapped crown damage observed among conifer species. Hardwoods also were found to have experienced more uprooting, most likely due to their dominance in more mesophytic locations (James L. Hill, District Biologist, USFS, May 26, 2006, *personal communication*).

Conifers are early-successional species and are therefore characteristically more prone to severe ice storm damage (Halverson & Guldin, 1995). Conifers in the southern states are shade-intolerant and less sound structurally (Lafon *et al.*, 1999; Cain & Shelton, 2002). Amongst the conifer species, loblolly pines (*Pinus taeda* L.) were observed to have experienced the most severe level of damage with crowns snapped. Shortleaf pine (*Pinus echinata* P. Mill) typically experienced more "bowing," i.e. it was able to bend under the weight of ice accumulation without snapping (James L. Hill, District Biologist, USFS, May 26, 2006, *personal communication*). More pronounced patterns of damage reflecting conifer species susceptibility to ice storm damage might present themselves if north-facing slopes were extracted from the study area and once again, a comparison of severity of ice storm damage was conducted.

CONCLUSION

Remote sensing efforts in vegetation studies have proven to be useful in understanding and predicting large-extent patterns of disturbances on forested landscapes. In this study, topography and to a lesser degree stand composition were found to influence spatial patterns of ice storm damage. Elevation was found to be the topographical variable to have the most control over susceptibility to damage followed closely by slope steepness and aspect. Similar patterns are likely to exist in those areas in the southern U.S. with mountain-ridge systems analogous to the Ouachita National Forest study area. However, additional research is needed to elucidate landscape-level spatial patterns of ice storm damage to forests in mountainous environments.

As discussed with forest managers in Ouachita National Forest, identifying spatial patterns of disturbances is essential to management procedures. Disturbed forest environments are much more susceptible to insect outbreaks. One of the most important results of this study, as indicated by USFS personnel, would be to aid in directing forest managers to areas most likely to sustain the most severe level of ice storm damage. These areas can then be harvested for timber prior to loss from decomposition, insect, or fire damage and overall economic losses can be reduced (James L. Hill, District Biologist, USFS, May 26, 2006, *personal communication*; Warren Montague, District Biologist, USFS, May 26, 2006, *personal communication*).

Other aspects of damage observed, but not examined in this study included areas in which trees had been thinned (Jacobs, 2000). These areas were not segregated from the study area. Moister areas were also suspected to have more damage due to wet and loose soil. Though high-resolution soil data were not found for the entire study area, examining this variable in the smaller scale study areas would be useful to clarify the patterns of ice storm damage and soil type. The effect of solar insolation should also be examined with the supposition that localized temperature variations can mitigate the degree of damage. South-facing slopes receive more insolation during the day, remaining warmer, longer throughout the day, potentially resulting is less ice accretion and mitigating the severity of damage (Warren Montague, District Biologist, USFS, May 26, 2006, *personal communication*).

Most importantly, successional patterns may be elucidated by determining patterns of ice storm damage in conjunction with the topographical variables. Knowledge concerning spatial patterns can aid in determining influences on vegetation development components such as species composition and diversity (Lafon, 2006). Because ice storms in the southern states are typically large-scale events and can have such long-lasting influences, determining their impacts are critical for future studies and forest management practices. Inclusive in this are the USFS' prescribed burning programs implemented to control the dominance of hardwoods and a desire to return to a vegetation species composition of more open woodlands composed of shortleaf pine and bluestem grasses (Guldin *et al.*, 1994). Future species-level research needs to be conducted to fully determine species-level dynamics in ONF. Extracting windward aspects and moderate elevations may clarify the patterns of the degree of ice storm damage to forest type. If species-level patterns of ice storm damage in the study area consequently correspond to usual patterns of conifers susceptibility to damage in the southern states, transitioning species composition could have major implications.

REFERENCES

Abell, C.A. (1934) Influence of glaze storms upon harwood forest in the southern Appalachians. *Journal of Forestry*, **32**, 35-37

Abrams, M.D. & Scott, M.L. (1989) Disturbance-mediated accelerated succession in two Michigan forest types. *Forest Science*, **35**, 42-49

Agresti, A. (2002) *Categorical data analysis*, 2nd edn. Wiley-Interscience, New York.

Arkansas Forestry Commission (2001) Forest health bulletin #2: Red oak borer fact sheet In. Arkansas Forestry Commission, Little Rock, AR

Asner, G.P., Keller, M., Pereira, R. & Zweede, J.C. (2002) Remote sensing of selective logging in Amazonia assessing limitations based on detailed field observations, Landsat ETM+, and textural analysis. *Remote Sensing of Environment*, **80**, 483-496

Attiwill, P.M. (1994) The disturbance of forest ecosystems - the ecological basis for conservative management. *Forest Ecology and Management*, **63**, 247-300

Becker, F. & Choudhury, B.J. (1988) Relative sensitivity of normalized difference vegetation index (NDVI) and microwave polarization difference index (MPDI) for vegetation and desertification monitoring. *Remote Sensing of Environment*, **24**, 297-311

Bennett, I. (1959) Glaze: Its meteorology and climatology, geographical distribution, and economic effects. Edited by *U.S. Army, Quartermaster Research and Engineering Command*, pp. EP-105 Natick, MA

Bragg, D.C., Shelton, M.G. & Zeide, B. (2003) Impacts and management implications of ice storms on forests in the southern United States. *Forest Ecology and Management*, **186**, 99-123

Burnett, J.S. (2002) *Assessing differing levels of ice storm damage to northern hardwood forest canopies using Advanced Solid-State Array Spectroradiometer (*ASAS) and Landsat TM imagery. University *of New Hampshire, Durham, NH*

Burrough, P.A. & Mcdonnell, R.A. (1998) *Principles of geographical information systems*. Oxford University Press, New York

Burt, J.E. & Barber, G.M. (1996) *Statistics for geographers*. The Guilford Press, New York

Burton, J.D. & Gwinner, M.W. (1960) Plateau pines weather ordeal by ice. *Southern Lumber*, **201**, 106-108

Cain, M.D. & Shelton, M.G. (2002) Glaze damage in 13- to 18-year old natural, even-aged stands of loblolly pines in southeastern Arkansas. *Proceedings of the 11th Biennial Southern Silvicultural Research Conference* (ed. K. Outkalt), pp. 579-583, Knoxville, TN

Cannell, M.G.R. & Morgan, J. (1989) Branch breakage under snow and ice loads. *Tree Physiology*, **5**, 307-317

Carvell, K.L., Tryon, E.H. & Ture, R.P. (1957) Effects of glaze on the development of Appalachian hardwoods. *Journal of Forestry*, **55**, 130-132

Cheng, P., Toutin, T. & V., T. (2002) Orthorectification and data fusion of Landsat 7 data. *Unpublished technical paper http://www.pcigeomatics.com/services/support center/tech_papers/techpapers_main.php*

Connell, J.H. (1978) Diversity in tropical rain forests and coral reefs. *Science*, **199**, 1302-1310

Cool, B.M., Goebel, N.B., Wooten, T.E. & Loadholt, C.B. (1971) Glaze damage to pine trees in the sandhill area of South Carolina. *Forest Research Series*, p. 12. Clemson University, Department of Forestry

Cramer, H. (1999) *Mathematical methods of statistics*, Princeton University Press, Princeton, NJ.

Curran, P.J. & Williamson, H.D. (1985) The accuracey of ground data used in remote-sensing investigations. *International Journal of Remote Sensing*, **6**, 1637-1651

Dungan, J. (1998) Spatial prediction of vegetation quantities using ground and image data. *International Journal of Remote Sensing* **19**, 267-285

Dupigny-Giroux, L.A., Blackwell, C.F., Bristow, S. & Olson, G.M. (2003) Vegetation response to ice disturbance and consecutive moisture extremes. *International Journal of Remote Sensing*, **24**, 2105-2129

Dymond, C.C., Mladenoff, D.J. & Radeloff, V.C. (2002) Phenological differences in tasseled cap indices improve deciduous forest classification. *Remote Sensing of Environment*, **80**, 460-472

Everham, E.M. & Brokaw, N.L. (1996) Forest damage and recovery from catastrophic wind. *The Botanical Review* **62**, 113-185

Forgrave, R. (2001) *State's ice-storm costs top $547 million*, Friday, November 2, 2001 edn., Arkansas Democratic Gazzette, Little Rock, AR

Foster, D.R., Aber, J.D., Melillo, J.M., Bowden, R.D. & Bazzaz, F.A. (1997) Forest response to disturbance and anthropogenic stress. *Bioscience*, **47**, 437-445

Foster, D.R., Knight, D.H. & Franklin, J.F. (1998) Landscape patterns and legacies resulting from large, infrequent forest disturbances. *Ecosystems*, **1**, 497-510

Fountain, M.S. & Burnett, F.E. (1979) Ice damage to plantation grown loblolly pine in south Arkansas. *Arkansas Farm Research*, **28**, 3

Fox, J.F. & Connell, J.H. (1979) Intermediate-disturbance hypothesis. *Science*, **204**, 1344-1345

Gardner, R.H. & Gustafson, E.J. (2004) Simulating dispersal of reintroduced species within heterogeneous landscapes. *Ecological Modelling* **171**, 339-358

Graney, D.L. (1992) *Site index relationships for shortleaf pine*. Gen. Tech. Rep. SO-90. U.S. Department of Agriculture, Forest Service, Southern Forest Experiment Station, Little Rock, AR.

Guerschman, J.P., Parnelo, J.M., Di Bella, C., Giallorenzi, M.C. & Pacin, F. (2003) Land cover classification in the Argentine Pampas using multi-temporal Landsat TM data. *International Journal of Remote Sensing*, **17**, 3381-3402

Guldin, J.M., Baker, J.B. & Shelton, M.G. (1994) Midstory and overstory plants in mature pine/hardwood stands on south-facing slopes of the Ouachita/Ozark national forests. *Proceedings of the symposium on ecosystem management research in the Ouachita Mountains: Pretreatment conditions and preliminary findings;* 1993 October 26-27;Hot Springs, AR. Gen. Tech. Rep. So-112. New Orleans, LA: U.S. Department of Agriculture, Forest Service, Southern Forest Experiment Station.

Halverson, H.G. & Guldin, J.M. (1995) Effects of a severe ice storm on mature loblolly pine stands in north Mississippi. *Proceedings of the Eight Biennial Southern Silvicultural Research Conference*, pp. 147-153, Asheville, NC

Harlin, B.W. (1952) The great southern glaze storm on 1951. *Weatherwise*, **5**, 10-13

Hopkin, A., Williams, T., Sajan, R., Pedlar, J. & Nielsen, C. (2003) Ice storm damage to eastern Ontario forests: 1998-2001. *Forestry Chronicle*, **79**, 47-53

Huston, M.A. (1994) *Biological diversity: The coexistence of species on changing landscapes*. Cambridge University Press, Cambridge.

Irland, L.C. (2000) Ice storms and forest impacts. *Science of the Total Environment*, **262**, 231-242

Itten, K.I. & Meyer, P. (1993) Geometric and radiometric correction of TM data of mountainous forested areas. *IEEE Transactions on Geoscience and Remote Sensing* **31**, 764-770

Jacobs, D.M. (2000) February 1994 ice storm: Forest resource damage assessment in northern Mississippi. Resource bulletin, pg. 11. U.S. Department of Agriculture, Forest Service, Southern Research Station, Asheville, NC.

James, D.A. & Neal, J.C. (1986) *Arkansas birds: Their distribution and abundance*. University of Arkansas Press, Fayetteville, AR.

Jensen, J.R. (2005) *Introductory digital image processing : A remote sensing perspective*, 2nd edn. Prentice Hall, Upper Saddle River, NJ

Jolayemi, E.T. (1990) On the measurement of agreement between two raters. *Biometrical Journal*, **32**, 87-93

Jolly, W.M., Nemani, R. & Running, S.W. (2005) A generalized, bioclimatic index to predict foliar phenology in response to climate. *Global Change Biology*, **11**, 619-632

Jones, K.F. & Mulherin, N.D. (1998) An evaluation of the severity of the January 1998 ice storm in northern New England. US Army Corp of Engineering, CRREL Report FEMA Reg. 1, Hanover, NH

Kent, M. & Coker, P. (1994) *Vegetation description and analysis : A practical approach*. Wiley, Chichester ; New York.

Kiefer, J. (1959) K-sample analogues of the Kolmogorov-Smirnov and Cramer-V. Mises tests. *The Annals of Mathematical Statistics*, **30**, 420-447

Kiviat, L. (1949) The ice storm: a winter menace. *Weatherwise*, **2**, 123-125

Konrad, C.E. (1998) An empirical approach for delineating fine scaled spatial patterns of freezing rain in the Appalachian region of the USA. *Climate Research*, **10**, 217-227

Lafon, C.W. (2004) Ice-storm disturbance and long-term forest dynamics in the Adirondack Mountains. *Journal of Vegetation Science*, **15**, 267-276

Lafon, C.W. (2006) Forest disturbance by ice storms in Quercus forests of the southern Appalachian Mountains, USA. *Ecoscience*, **13**, 30-43

Lafon, C.W., Graybeal, D.Y. & Orvis, K.H. (1999) Patterns of ice accumulation and forest disturbance during two ice storms in southwestern Virginia. *Physical Geography*, **20**, 97-115

Lafon, C.W. & Kutac, M. (2003) Effects of ice storms, southern pine beetle infestation, and fire on table mountain pine forests of southwestern Virginia. *Physical Geography*, **24**, 502-519

Larsson, H. (2002) Acacia canopy cover changes in Rawashda Forest Reserve, Kassala Province, eastern Sudan, using linear regression NDVI models. *International Journal of Remote Sensing*, **23**, 335-339

Lemon, P.C. (1961) Forest ecology of ice storms. *Bulletin of the Torrey Botanical Club*, **88**, 21

Levin, S.A. & Paine, R.T. (1974) Disturbance, patch formation, and community structure. *Proceedings of the National Academy of Science*, **71**, 2744-2747

Liang, S., Fang, H., Morisette, J.T., Chen, M., Shuey, C.J., Walthall, C.L. & Daughtry, C.S.T. (2002) Atmospheric correction of Landsat ETM+ land surface imagery: II. validation and applications. *IEEE Transactions on Geoscience and Remote Sensing*, **40**, 2736-2746

Lillesand, T.M. & Kiefer, R.W. (2000) *Remote sensing and image interpretation*. John Wiley and Sons Inc., New York

MacDonald, G.M. (2003) *Biogeography : Space, time and life*. Wiley, New York.

Markham, B.L. & Barker, J.L. (1986) Landsat MSS and TM post-calibration dynamic ranges, exoatmospheric reflectances and at-satellite temperatures. *EOSAT Landsat Technical Notes*, **89**, 422-423

Masellli, F. (2004) Monitoring forest conditions in a protected Mediterranean coastal area by the analysis of multiyear NDVI data. *Remote Sensing of Environment*, **89**, 423-433

Millward, A.A. & Kraft, C.E. (2004) Physical influences of landscape on a large-extent ecological disturbance: The northeastern North American ice storm of 1998. *Landscape Ecology*, **19**, 99-111

NASA (2006) Landsat 7: Science data users handbook. http://ltpwww.gsfc.nasa.gov /IAS/handbook/handbook_htmls/chapter1/chapter1.html

NCDC (2006a) Climvis: World's largest archive of climate data: Protecting the past, revealing the future. http://lwf.ncdc.noaa.gov/oa/ncdc.html

NCDC (2006b) Storms events database. http://www4.ncdc.noaa.gov/cgi-win/wwcgi.dll?wwEvent~Storms

NCDC (2007) Climate-watch: December 2000. http://www.ncdc.noaa.gov

/oa/climate/extremes/2000/december/extremes1200.html

Nicholas, N.S. & Zedaker, S.M. (1989) Ice damage in Spruce-Fir forests of the Black Mountains, North Carolina. *Canadian Journal of Forest Research*, **19**, 1487-1491

Nielsen, A.A., Conradsen, K. & Simpson, J.J. (1998) Multivariate alteration detection (MAD) and MAF postprocessing in multispectral, bitemporal image data: new approaches to change detection studies. *Remote Sensing of Environment*, **64**, 1-19

NWS (2005) Winter weather safety and awareness. http://www.nws.noaa.gov/

Olthof, I., King, D.J. & Lautenschlager, R.A. (2004) Mapping deciduous forest ice storm damage using Landsat and environmental data. *Remote Sensing of Environment*, **89**, 484-496

Rauber, R.M., Olthoff, L.S., Ramamurthy, M.K. & Miller, D. (2001) A synoptic weather pattern and sounding-based climatology of freezing precipitation in the United States east of the Rocky Mountains. *Journal of Applied Meteorology*, **40**, 1724-1747

Roberts, D.A., Ustin, S.L., Ogunjemiyo, S., Greenberg, J., Dobrowski, S.Z., Chen, J.Q. & Hinckley, T.M. (2004) Spectral and structural measures of northwest forest vegetation at leaf to landscape scales. *Ecosystems*, **7**, 545-562

Robinson, H.W. (2000) Crayfishes of the Ouachita National Forest, Arkansas and Oklahoma. Final report to the USDA Forest Service. *http://www.fs.fed.us/r8/ouachita/publications/ouachita_crayfish.pdf*

Romme, W.H., Everham, E.H., Frelich, L.E., Moritz, M.A. & Sparks, R.E. (1998) Are large, infrequent disturbances qualitatively different from small, frequent disturbances? *Ecosystems*, **1**, 524-534

Rouse, J.W., Haas, R.H., Schell, J.A. & Deering, D.W. (1974) Monitoring vegetation systems in the great plains with ERTS. *Third Earth Resources Technology Satellite-1 Symposium*, pp. 309-317, Washington, D.C.

Sealander, J.A. & Heidt, G.A. (1990) *Arkansas mammals: Their natural history, classification, and distribution*. The University of Arkansas Press, Fayetteville, AR.

Shepard, R.K. (1975) Ice storm damage to Loblolly-Pine in northern Louisiana. *Journal of Forestry*, **73**, 420-423

Smith, G.M. & Milton, E.J. (1999) The use of empirical line method to calibrate remotely sensed data to reflectance. *International Journal of Remote Sensing* **20**, 2653-2662

Song, C. & Woodcock, C.E. (2001) Classification and change detection using Landsat TM data: When and how to correct atmospheric effects. *Remote Sensing of Environment*, **75**, 230-244

Sousa, W.P. (1984) The role of disturbance in natural communities. *Annual Review of Ecology & Systematics*, 353

Sprugel, D.G. (1991) Disturbance, equilibrium, and environmental variability: What is 'natural' vegetation in a changing environment? *Biological Conservation*, **58**, 1-18

Stueve, K.M., Lafon, C.W. & Isaacs, R.E. (2007) Spatial patterns of ice storm disturbance on a forested landscape of the Appalachian Mountains. *Area*, In press

Tucker, C.J. (1979) Red and photographic infrared linear combinations for monitoring vegetation. *Remote Sensing of Environment*, **8**, 127-150

Turner, M.G. (2005) Landscape ecology: What is the state of the science? *Annual Review of Ecology & Systematics*, **36**, 319-344

Turner, M.G. & Dale, V.H. (1998) Comparing large, infrequent disturbances: What have we learned? *Ecosystems*, **1**, 493-496

Turner, M.G., Gardner, R.H. & O'neill, R.V. (2001) *Landscape ecology in theory and practice : Pattern and process*. Springer, New York.

USDA (1998) National interagency fire management integrated database (NIFMID): Technical guide. *Technical Guide*. Washington, D.C.: USDA Forest Service, Fire and Aviation Management

Walsh, S.J. (1987) Comparison of NOAA AVHRR data to meteorologic drought indices. *Photogrammetric Engineering and Remote Sensing* **53**, 1069-1074

Warrillow, M. & Mou, P. (1999) Ice storm damage to forest tree species in the Ridge and Valley Region of southwestern Virginia. *Journal of the Torrey Botanical Society*, **126**, 147-158

Wickham, J.D., O'Neill, R.V. & Jones, K.B. (2000) A geography of ecosystem vulnerability. *Landscape Ecology*, **15**, 495-504

Xiao, X., Moore Iii, B., Qin, X., Shen, Z. & Boles, S. (2002) Large-scale observations of alpine snow and ice cover in Asia: Using multi-temporal vegetation sensor data. *International Journal of Remote Sensing* **23**, 2213-2228

Zar, J.H. (1999) *Biostatistical analysis*. Prentice Hall, Englewood Cliffs, NJ

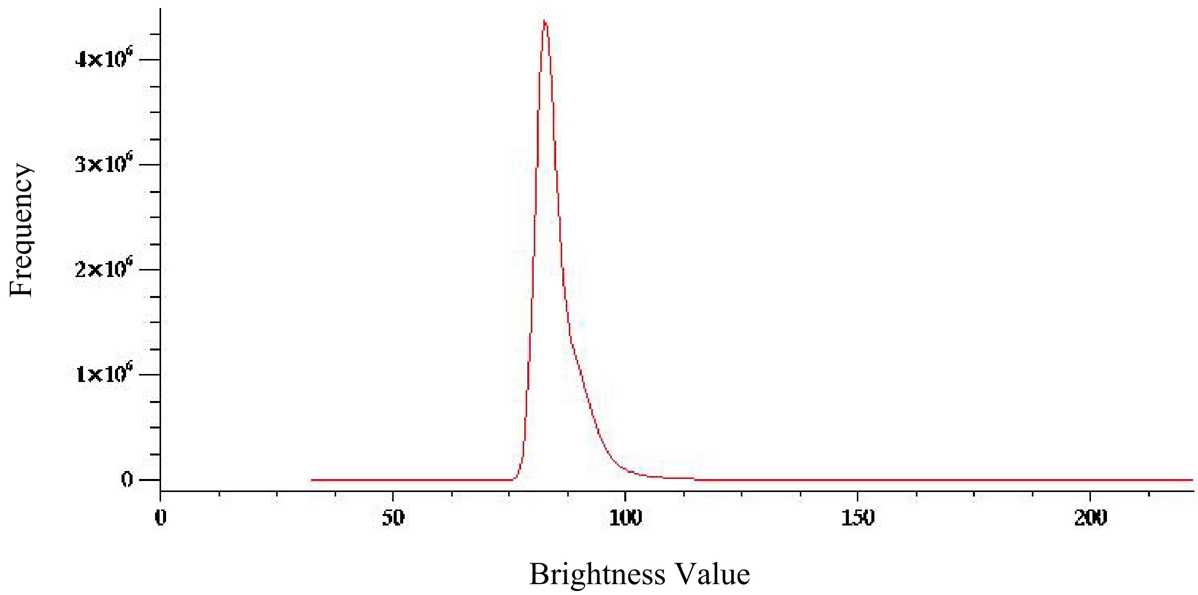
APPENDIX A: METADATA FOR THE SEPTEMBER 25, 2001 IMAGE

An example from the metadata of the September 25, 2001 Landsat ETM image for Ouachita National Forest:

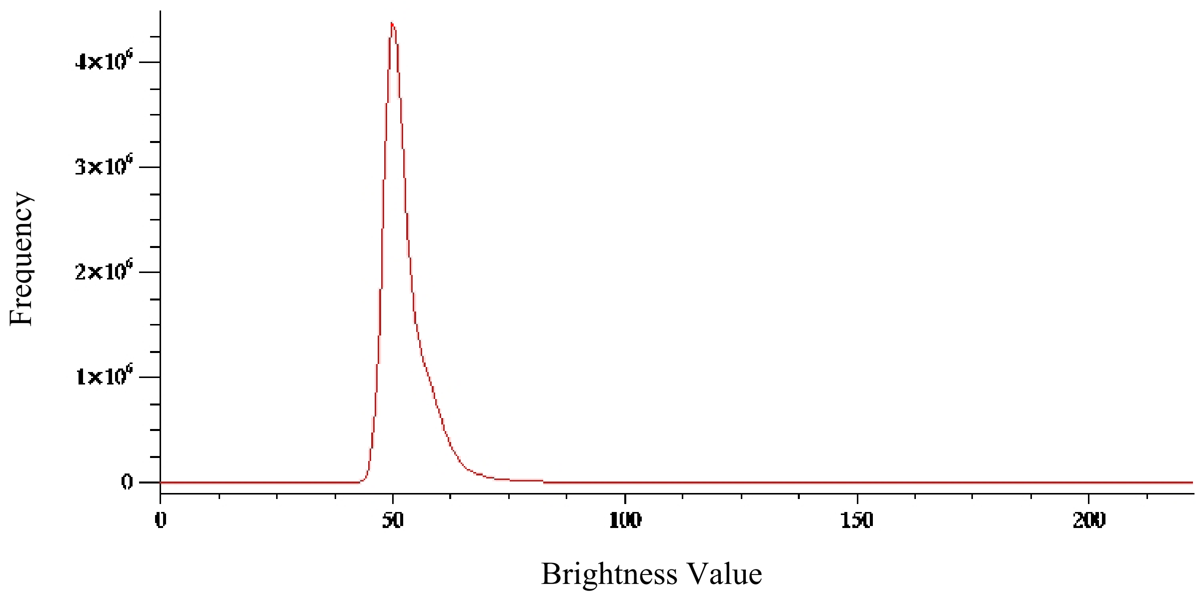
```
GROUP = MIN_MAX_RADIANCE
        LMAX_BAND1 = 191.600
        LMIN_BAND1 = -6.200
        LMAX_BAND2 = 196.500
        LMIN_BAND2 = -6.400
        LMAX_BAND3 = 152.900
        LMIN_BAND3 = -5.000
        LMAX_BAND4 = 241.100
        LMIN_BAND4 = -5.100
        LMAX_BAND5 = 31.060
        LMIN_BAND5 = -1.000
        LMAX_BAND61 = 17.040
        LMIN_BAND61 = 0.000
        LMAX_BAND62 = 12.650
        LMIN_BAND62 = 3.200
        LMAX_BAND7 = 10.800
        LMIN_BAND7 = -0.350
        LMAX_BAND8 = 243.100
        LMIN_BAND8 = -4.700
    END_GROUP = MIN_MAX_RADIANCE


    GROUP = MIN_MAX_PIXEL_VALUE
        QCALMAX_BAND1 = 255.0
        QCALMIN_BAND1 = 1.0
        QCALMAX_BAND2 = 255.0
        QCALMIN_BAND2 = 1.0
        QCALMAX_BAND3 = 255.0
        QCALMIN_BAND3 = 1.0
        QCALMAX_BAND4 = 255.0
        QCALMIN_BAND4 = 1.0
        QCALMAX_BAND5 = 255.0
        QCALMIN_BAND5 = 1.0
        QCALMAX_BAND61 = 255.0
        QCALMIN_BAND61 = 1.0
        QCALMAX_BAND62 = 255.0
        QCALMIN_BAND62 = 1.0
        QCALMAX_BAND7 = 255.0
        QCALMIN_BAND7 = 1.0
        QCALMAX_BAND8 = 255.0
        QCALMIN_BAND8 = 1.0
```

APPENDIX B: DARK SUBTRACT HISTOGRAMS

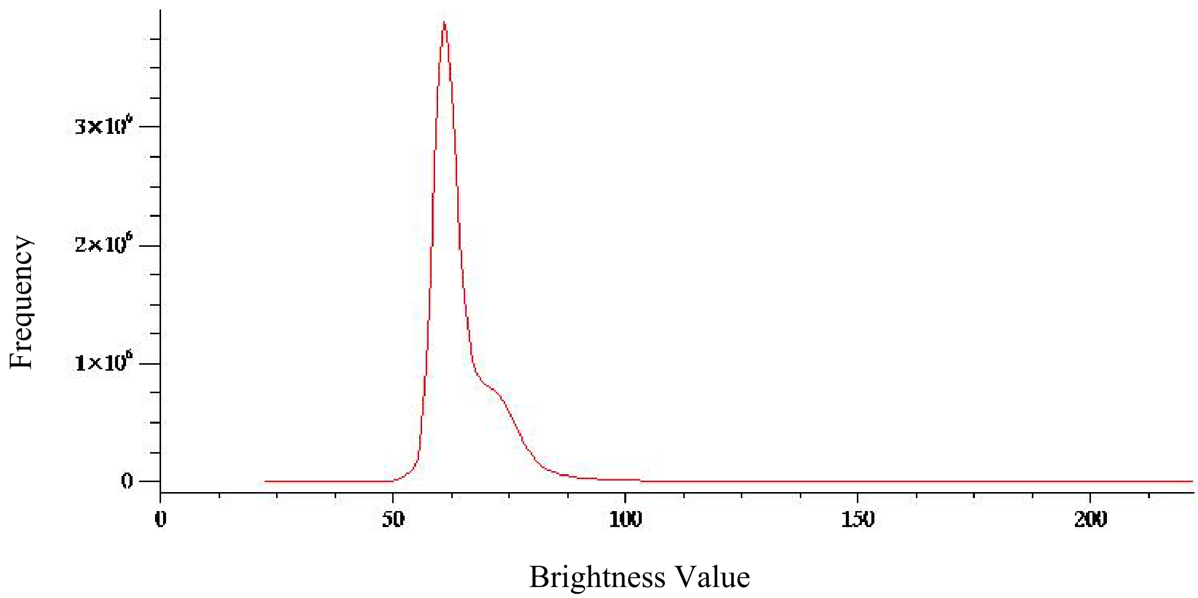
September 25, 2001 histograms:



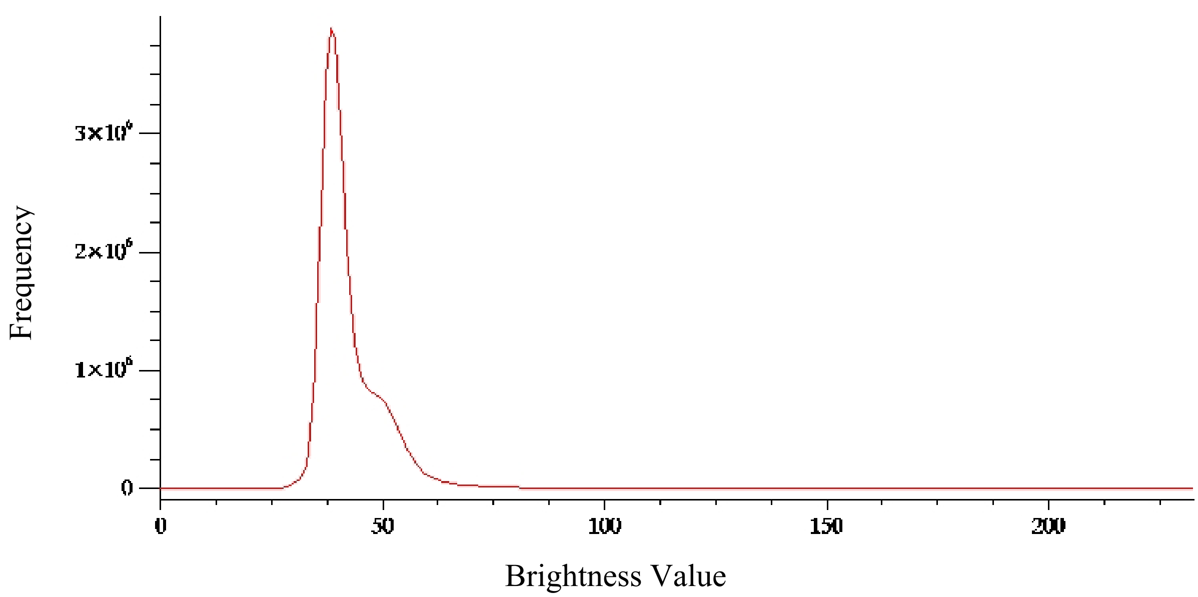
Band 1 Before dark subtract histogram adjustment.



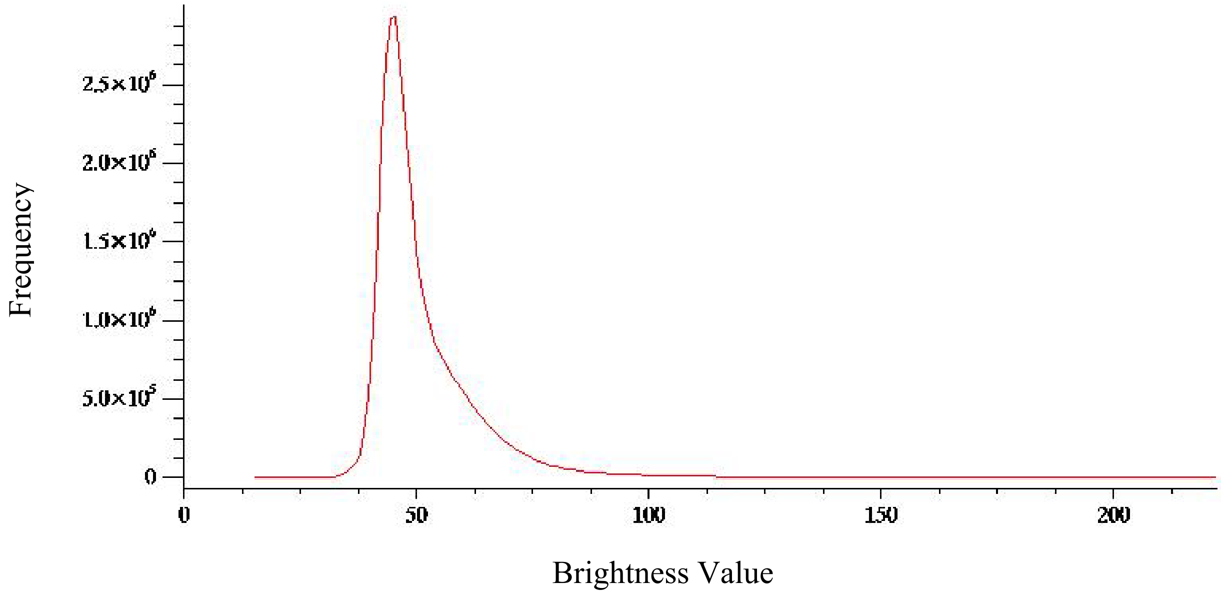
Band 1 After dark subtract histogram adjustment.



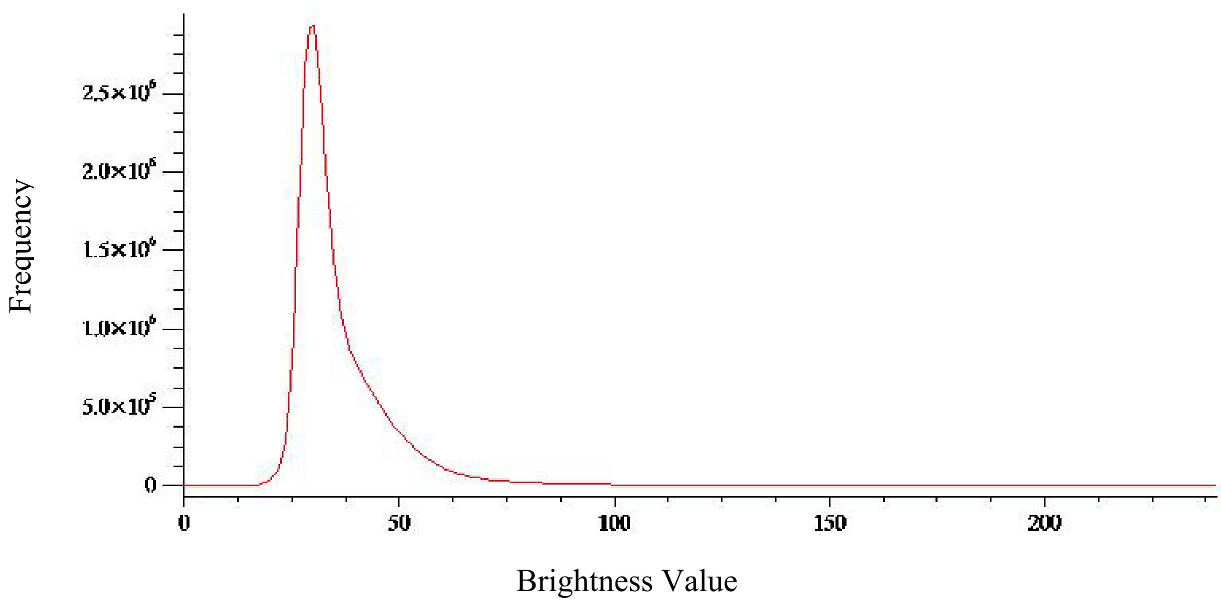
Band 2 Before dark subtract histogram adjustment.



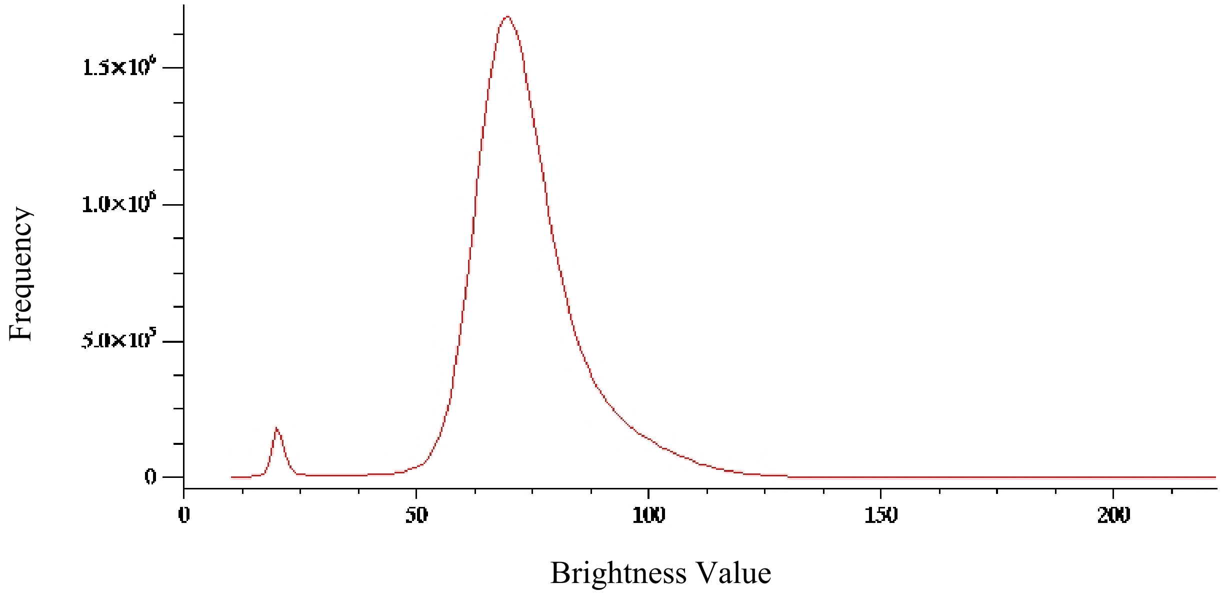
Band 2 After dark subtract histogram adjustment.



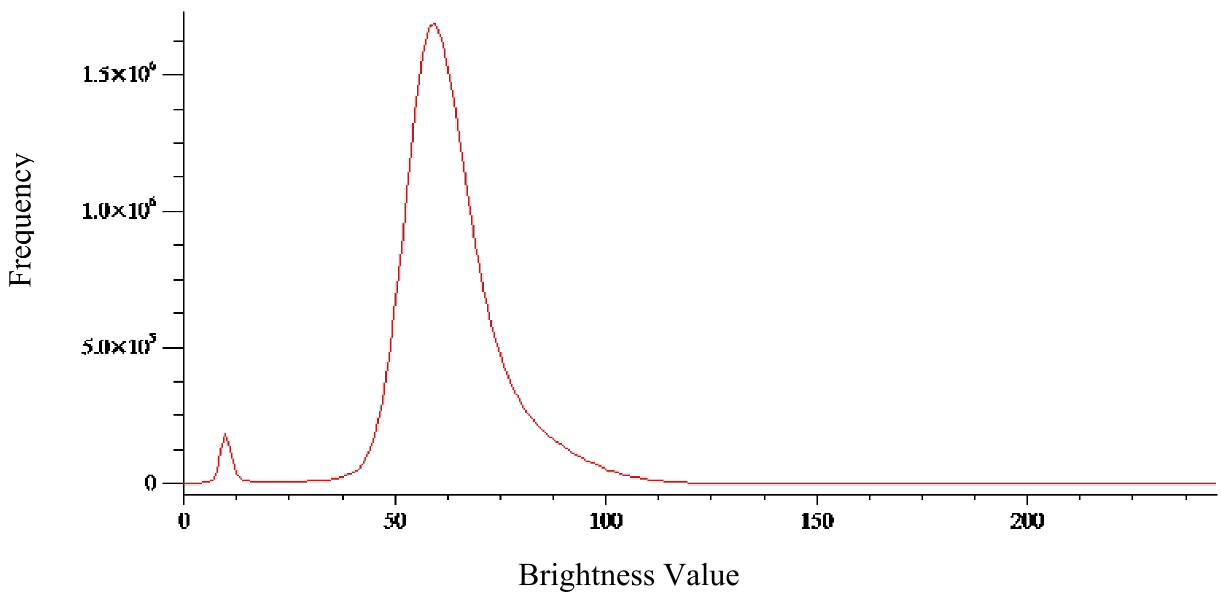
Band 3 Before dark subtract histogram adjustment.



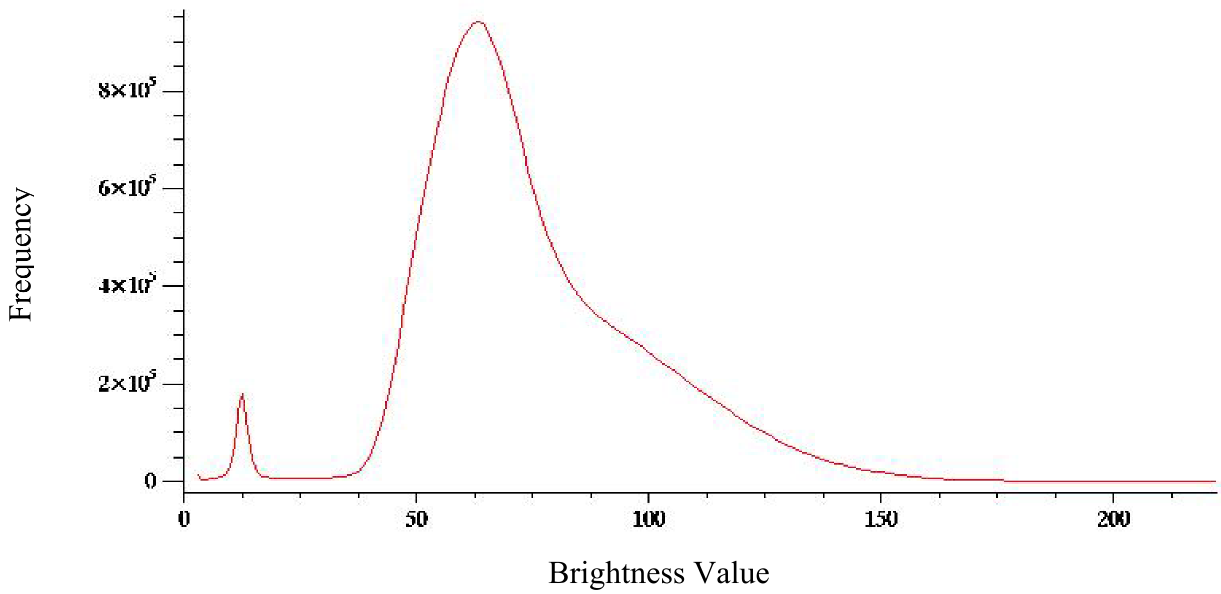
Band 3 After dark subtract histogram adjustment.



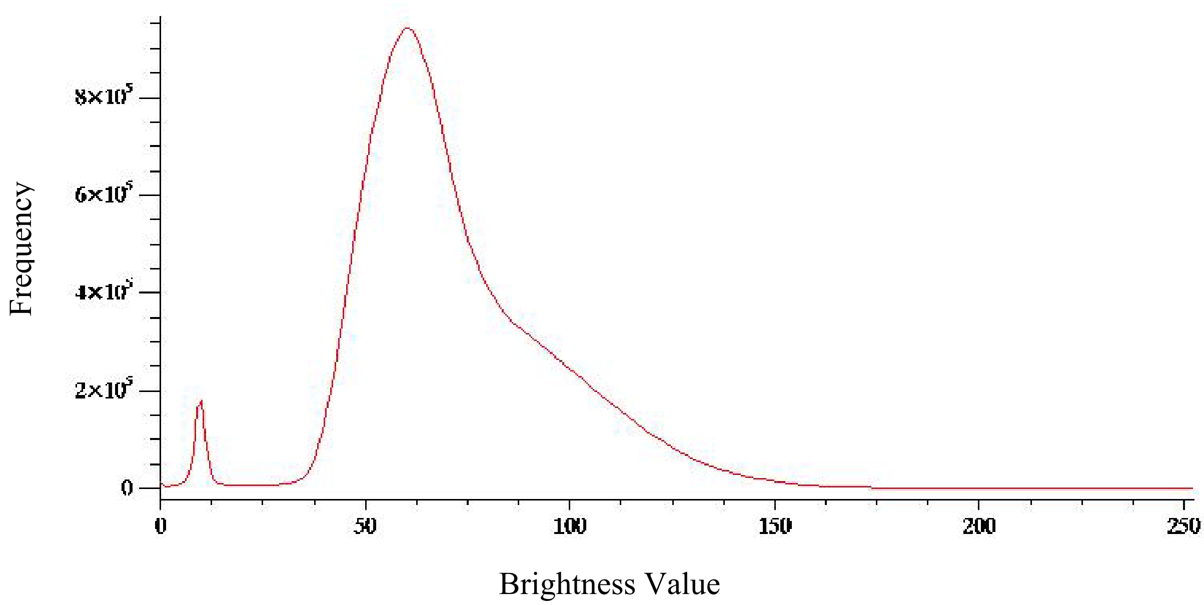
Band 4 Before dark subtract histogram adjustment.



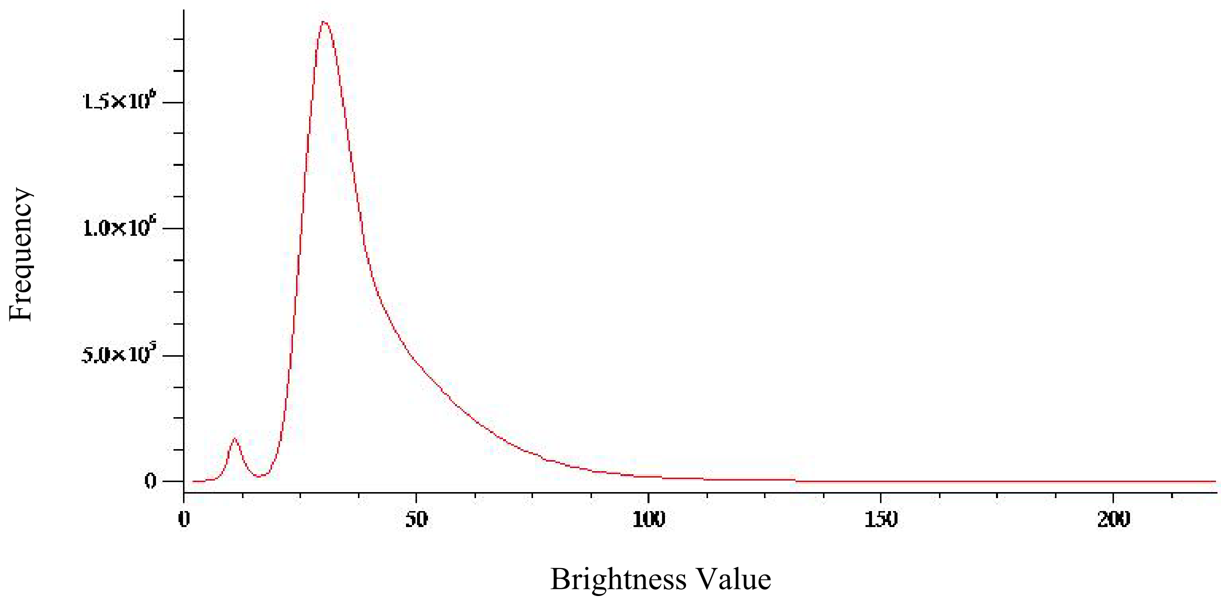
Band 4 After dark subtract histogram adjustment.



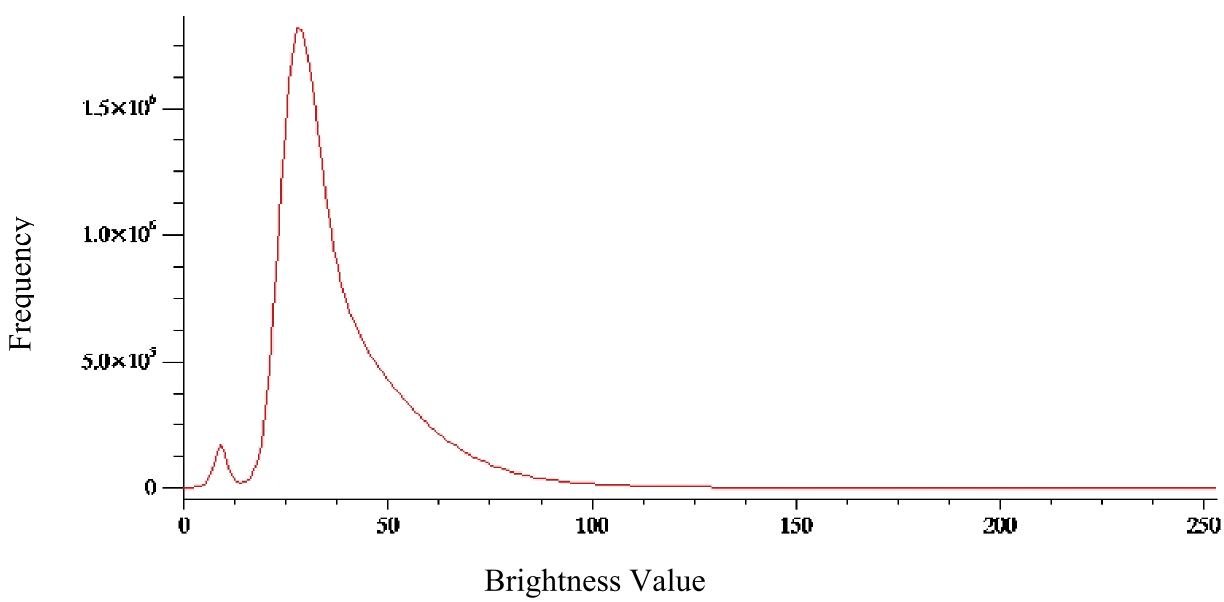
Band 5 Before dark subtract histogram adjustment.



Band 5 After dark subtract histogram adjustment.

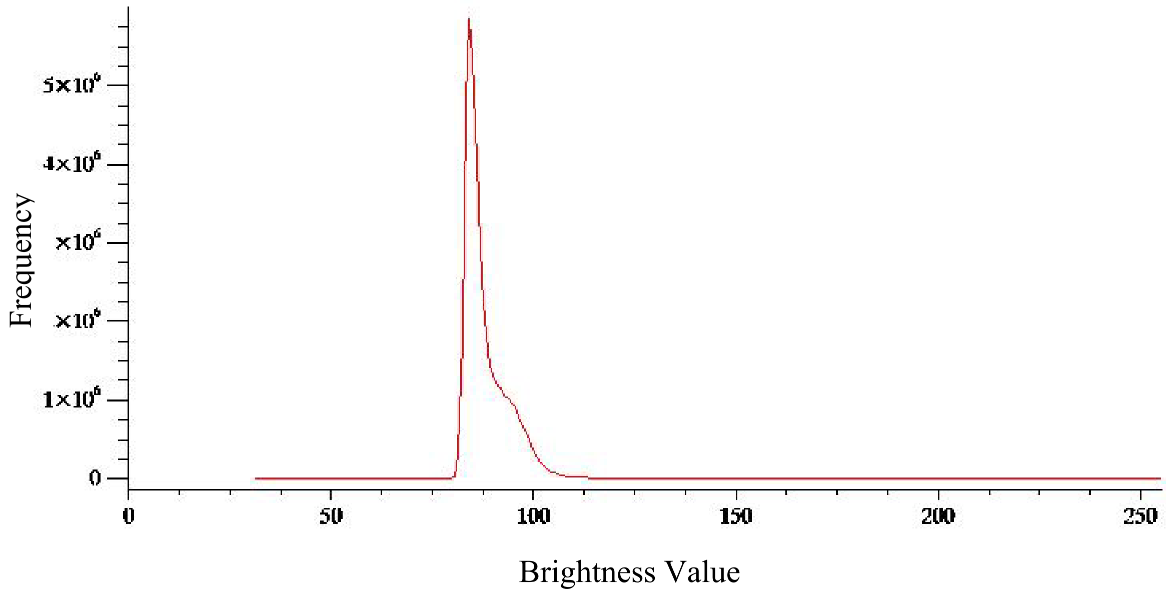


Band 7 Before dark subtract histogram adjustment.

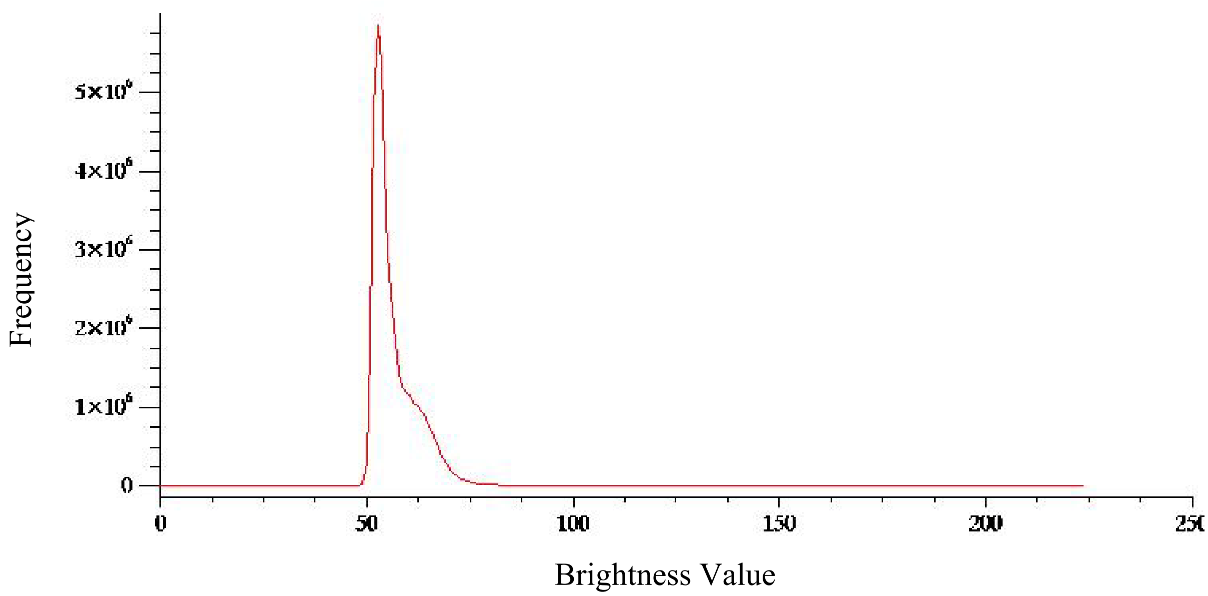


Band 7 After dark subtract histogram adjustment.

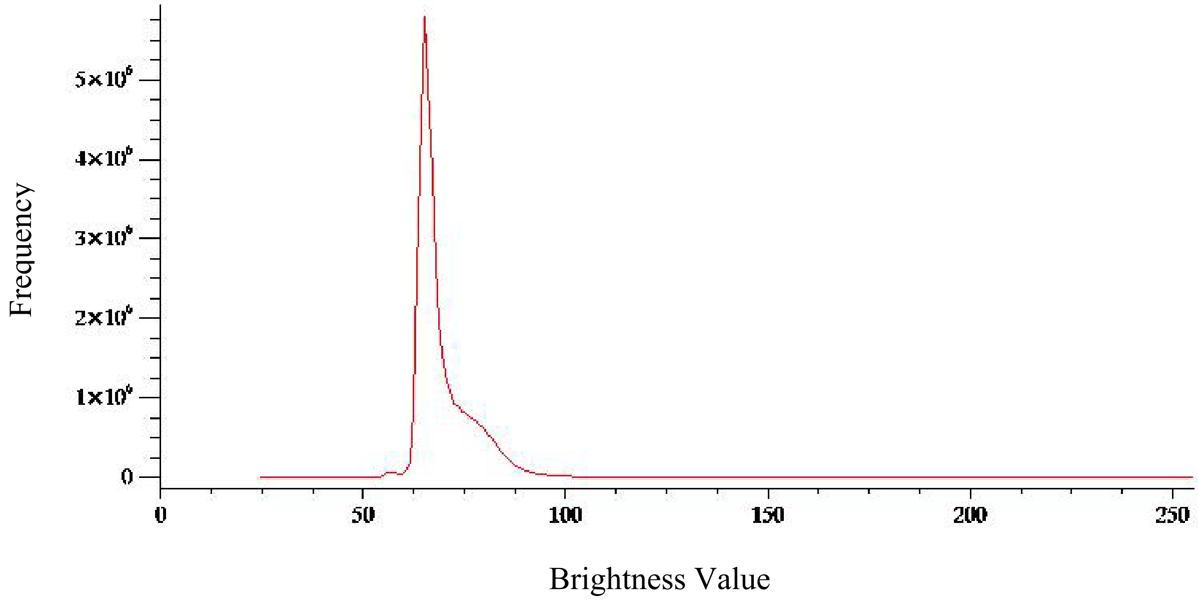
October 6, 1999



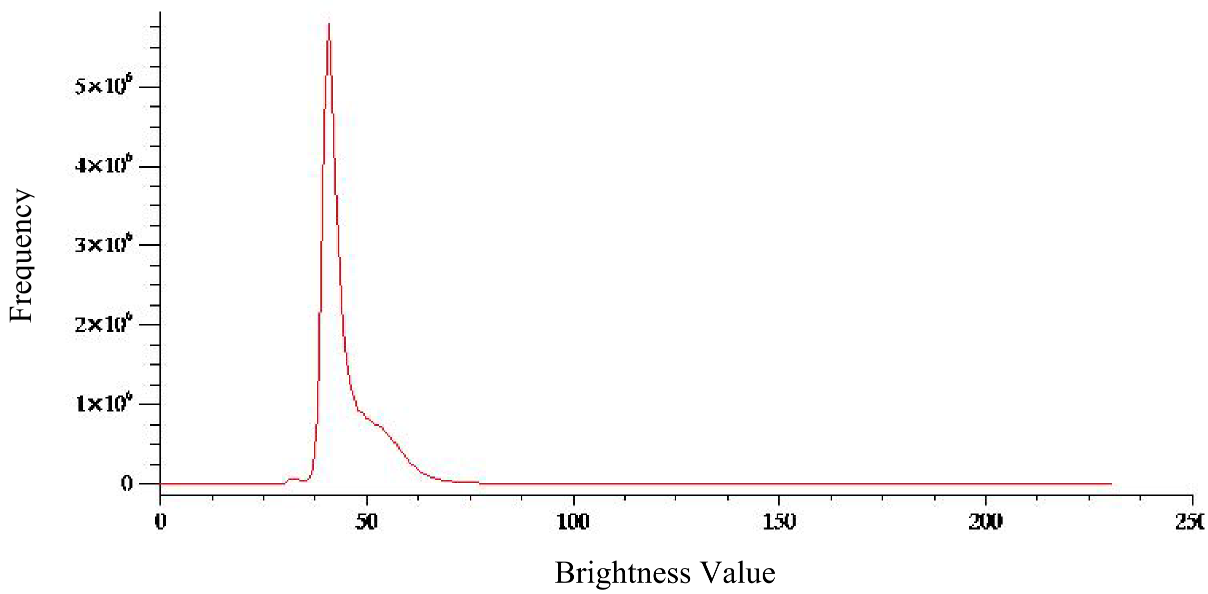
Band 1 Before dark subtract histogram adjustment.



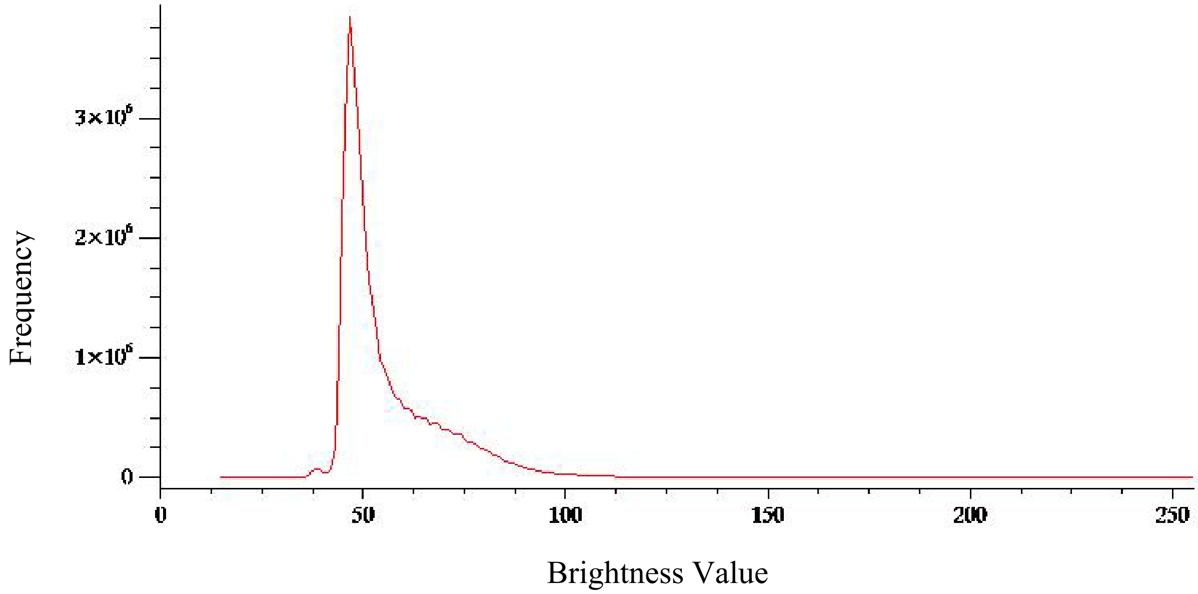
Band 1 After dark subtract histogram adjustment.



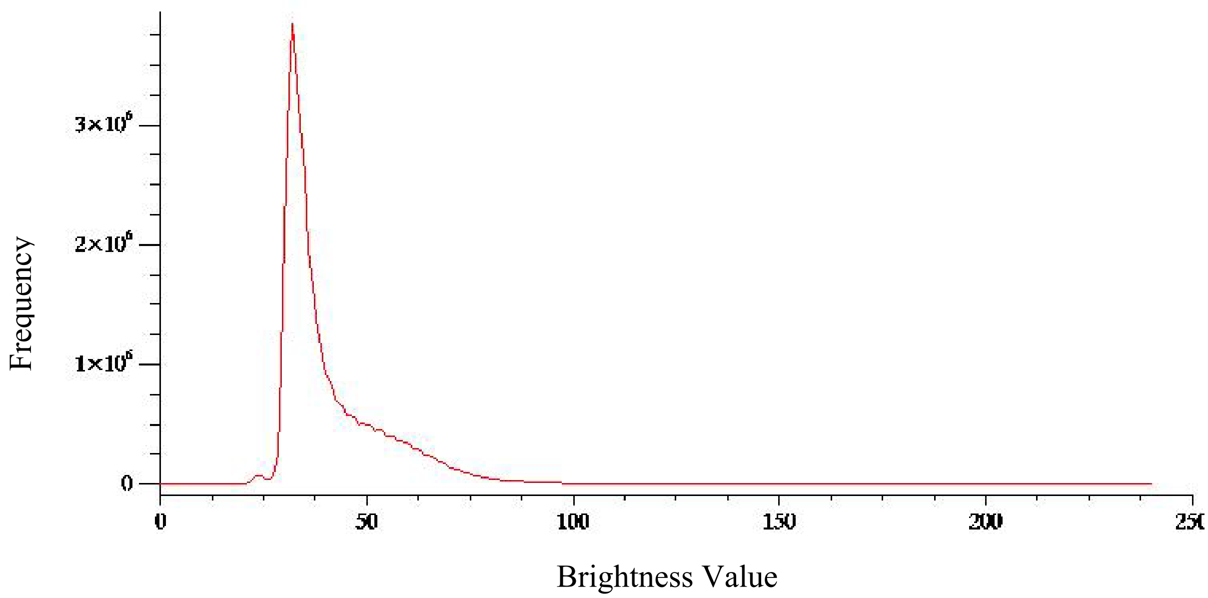
Band 2 Before dark subtract histogram adjustment.



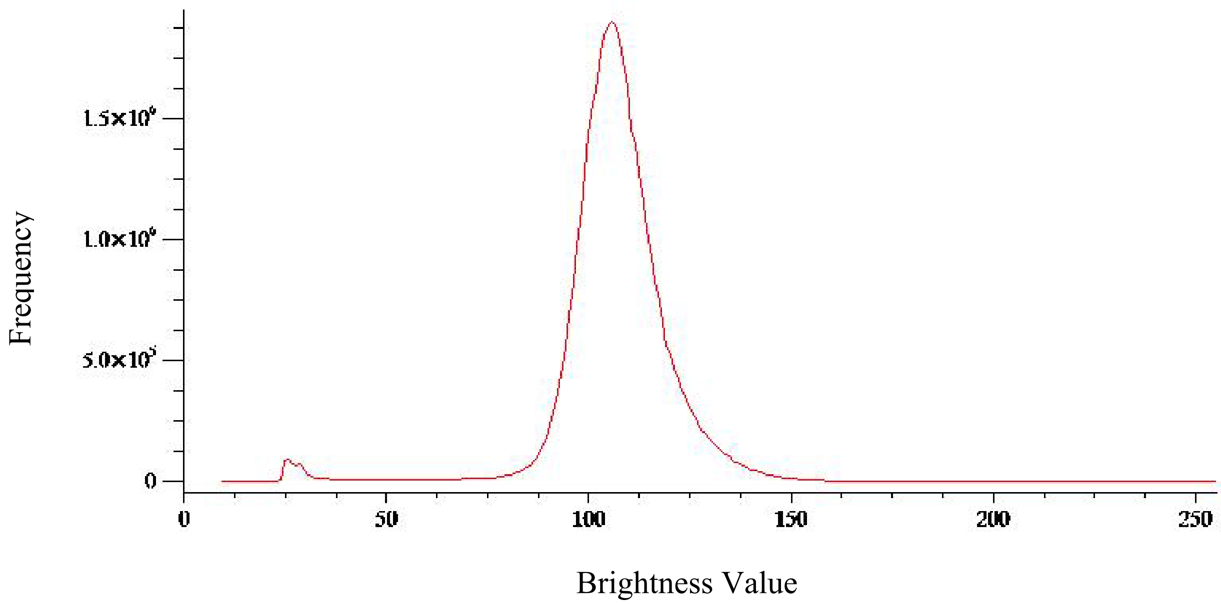
Band 2 After dark subtract histogram adjustment.



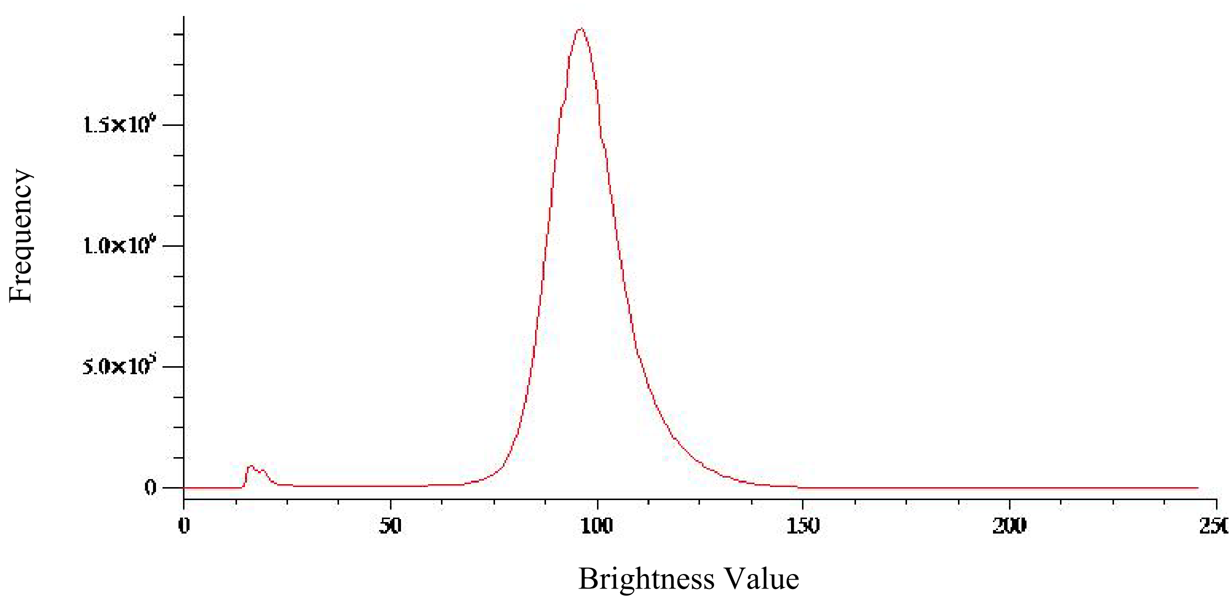
Band 3 Before dark subtract histogram adjustment.



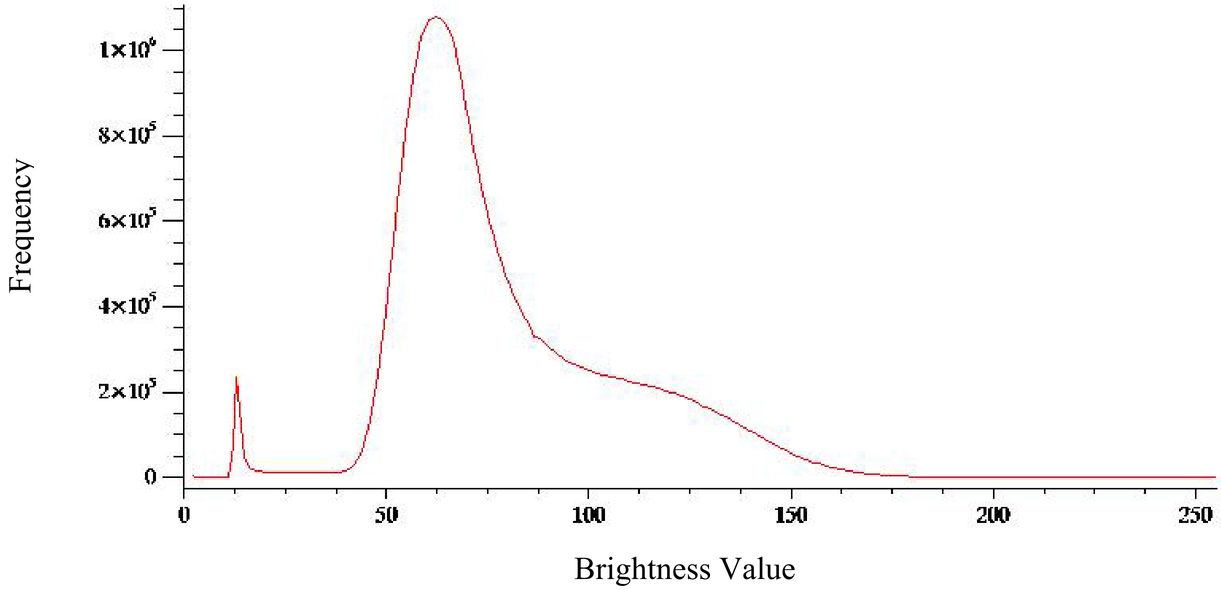
Band 3 After dark subtract histogram adjustment.



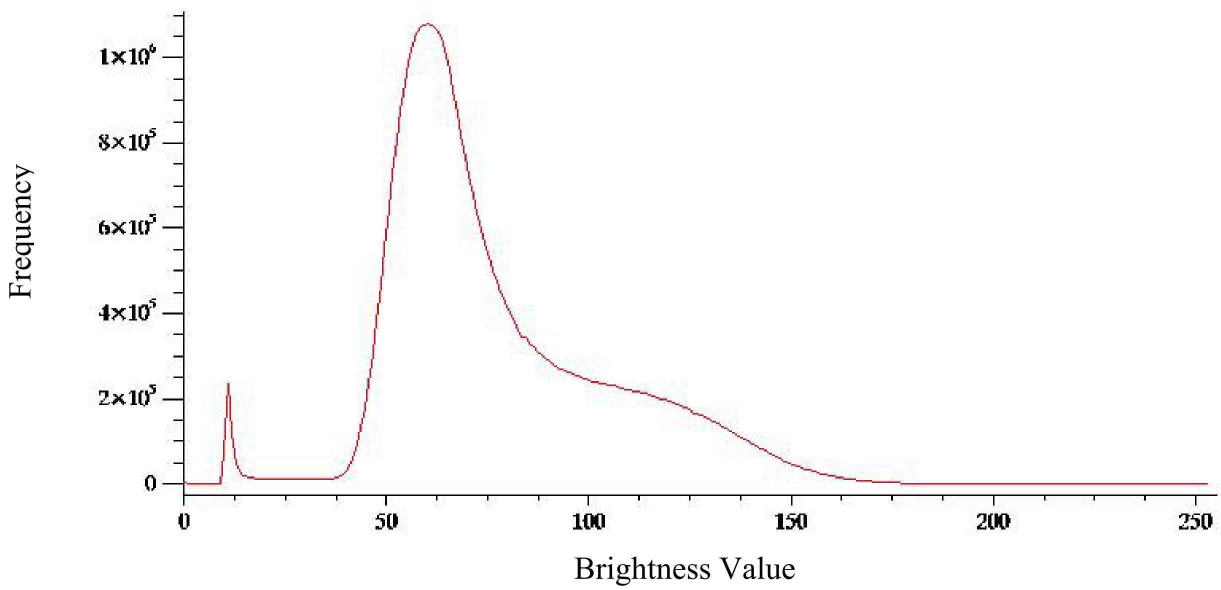
Band 4 Before dark subtract histogram adjustment.



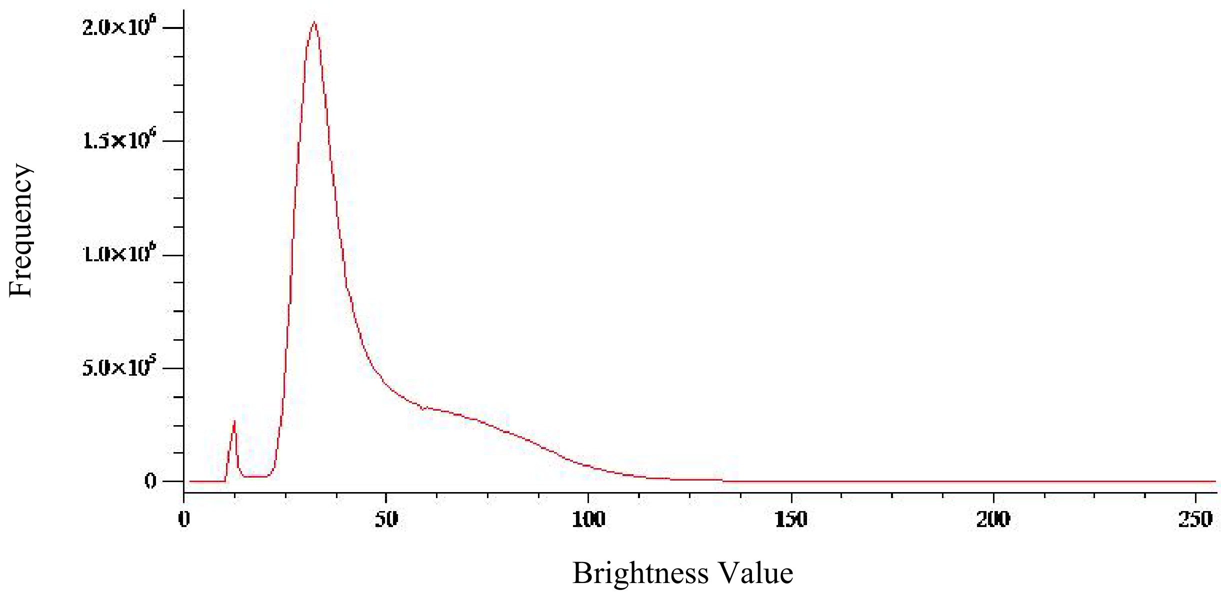
Band 4 After dark subtract histogram adjustment.



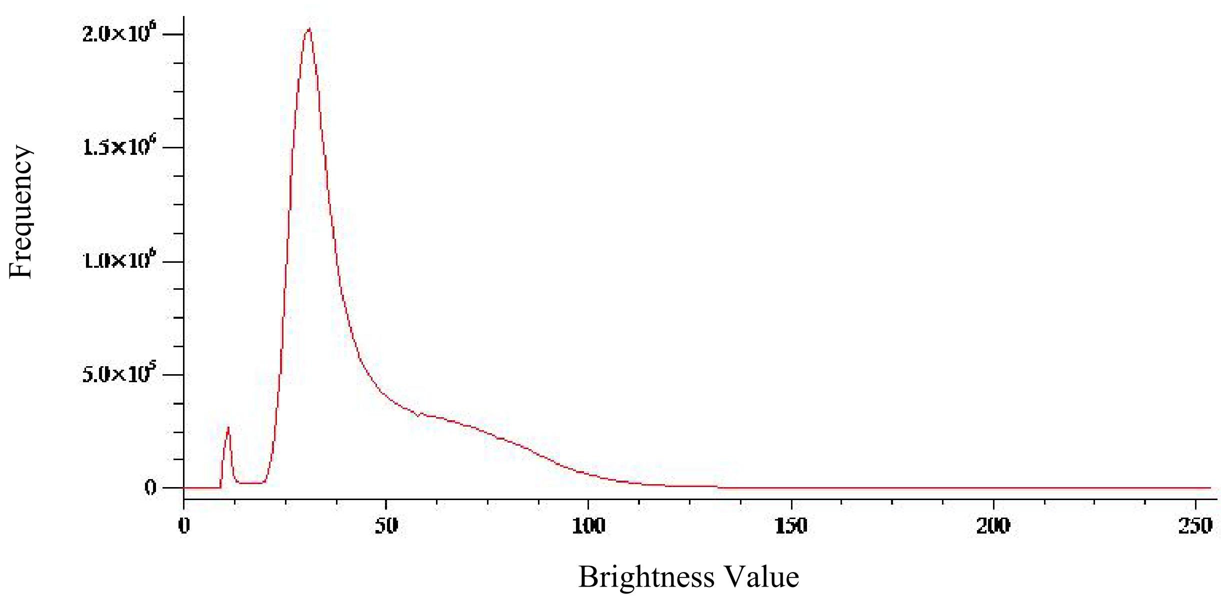
Band 5 Before dark subtract histogram adjustment.



Band 5 After dark subtract histogram adjustment.



Band 7 Before dark subtract histogram adjustment.



Band 7 After dark subtract histogram adjustment.

Bands	Min	Max	DS Min	DS Max
B1	32.622787	254.9998	0	222.376968
B2	22.488693	254.9999	0	232.511246
B3	15.237267	255.0002	0	239.762894
B4	10.318264	255.0002	0	244.681961
B5	2.843159	255.0013	0	252.158157
B7	2.067495	254.9949	0	252.927414

September 25, 2001 Band histogram adjustments before and after dark subtract applied.

Bands	Min	Max	DS Min	DS Max
B1	31.520103	254.9998	0	223.479706
B2	24.523134	255.0001	0	230.47699
B3	14.754609	254.9999	0	240.245331
B4	9.479937	254.9999	0	245.519928
B5	2.138529	254.9997	0	252.861206
B7	1.37115	255.0000	0	253.628891

October 6, 1999 Band histogram adjustments before and after dark subtract applied.

APPENDIX C: STORM SEARCH INFORMATION FROM NCDC

Storm Search Information for Ouachita National Forest counties in Arkansas and Oklahoma:

(Source: CLIMVIS (NCDC) Storm Database search for storms between July 1, 1999 – September 31, 2001. All information taken directly from the website.)

Statewide Events

9/8/00
After two months with almost no rain in much of Arkansas, drought conditions worsened...especially in eastern sections of the state. In Little Rock, for example, only .67 inches of rain was measured in July and August combined...and was accompanied by the hottest month on record in August. A severe thunderstorm brought some rain to the Little Rock area on September 1st ending 27 straight days with no precipitation (a record).

12/12/00 – 12/13/00

Summary of winter weather on December 12, 2000. A powerful winter storm developed over the Southern Plains and produced a mixture of snow...sleet and some freezing rain. Precipitation was mostly in the form of snow over Benton, Carroll, Washington and Madison counties, while a mixture of sleet and freezing rain occurred further south in West Central Arkansas. In far Northwest Arkansas, up to 10 inches of snow was reported by late afternoon on the 12th of December. Further south in Crawford County, freezing rain caused extensive power losses. The sheriff's office in Crawford County reported blackouts in Uniontown, Alma, Kibler, Mountainburg, Rudy and Georgia Ridge. Other counties in West Central Arkansas reported only scattered power losses. Numerous accidents were reported south of Fayetteville on ice-slickened Interstate 540, where large trucks could not make it up steep hills. Most businesses, schools and other entities were closed for the day. While damages from this storm are expected to be large, estimates were not available at the time of publication. Some snowfall totals include Bella Vista...10, Rogers...10, Bentonville...7, Siloam Springs...7, Berryville...6, Fayetteville...6, Mulberry...5, Huntsville...4, Springdale...4, Cedarville...3, Ozark...3, Clarksville...3, Van Buren...3, Fort Smith...2, Greenwood...2, Midland...1.

An arctic air mass spilled southward out of the central plains and into the lower Mississippi Valley. This cold, surface air mass was overrun by a warm humid air mass which combined with a strong upper level storm system across west Texas. The result was widespread freezing rain across all of southwest Arkansas. The precipitation was a mixture of freezing rain, sleet and some light snow northwest of a Texarkana to Prescott Arkansas line while further east the precipitation was all freezing rain. Ice accumulations of two to four inches were common. An estimated 235,000 residents lost electrical power due to ice covered power lines snapping or ice covered trees splitting and falling across the lines. This was the worst storm in the history of the power companies supplying the power as far as damage but not total ice accumulations. A total of 29 transmission lines atop "H" shaped steel towers were snapped due to the weight of the ice. Numerous traffic accidents were also reported and many homes suffered damage from fallen trees and tree limbs. As a result, the Governor of Arkansas declared a State of Emergency for all of southwest Arkansas. Cleanup costs along reached upwards of 15 million dollars. Several Pine Plantations throughout southwest Arkansas suffered catastrophic damage from the ice storm with upwards of 25 million dollars worth of young trees destroyed.

A major Winter Storm developed in Arkansas late on December 12, 2000 and lasted through the evening of December 13, 2000. Arctic high pressure began moving east of the region, with clockwise flow around the high pumping warm and moist air from the Gulf Coast region over below freezing air in Arkansas. The end result was heavy snow and sleet across northern and western sections of the state...and freezing rain and sleet in central and southern sections. More specifically, 3 to 6 inches of snow fell across the extreme north before mixing with sleet...with 2 to 4 inches of snow and sleet across much of the north and west. In central and southern sections, one half to 1 inch of freezing rain accumulated...with some sleet mixed in at times. Where icing occurred, there were massive power outages with entire trees falling in some areas due to the weight of the ice. Where trees and tree limbs fell, there was some property damage reported...mainly to roofs and vehicles. The media reported some injuries due to falling tree limbs, but specific numbers were not provided. Power companies in Arkansas reported that about 250,000 customers lost power during the event...which is believed to be the largest outage in Arkansas history. Many people were without power for several days. Extra utility crews and tree trimmers from surrounding states were contacted to help restore power and to remove tree debris from lines. Winter Storm Warnings were posted almost a day in advance, with highway crews able to treat roads before the event began. Many schools announced they would be closed on the 13th, and the Arkansas Department of Emergency Management opened their Emergency Operations Center before precipitation began.

12/25/00 – 12/27/00

After trying to recover from an ice storm two week earlier in the month, another even more devastating ice storm struck all of southwest Arkansas. Freezing rain resulted in ice accumulations ranging from 1/4 inch to as much as 6 inches. After taking a tour of the state, the Governor of Arkansas used words such as apocalyptic and cataclysmic to describe the damage. Power was knocked out across all of southwest Arkansas with nearly 300,000 homes and business without power due to thousands of trees and 2500 power poles either broken or toppled. Utility crews from 23 different states were summoned to help repair lines. Some residents were without power as late as the middle of January 2001.

After a major Winter Storm on the 12th and 13th, a long term Ice Storm developed during the morning of December 25, 2000 and continued through the early morning hours of December 27, 2000. The setup was similar to the previous storm, with warm and moist air from the southwest overrunning shallow below freezing air in Arkansas provided by Arctic high pressure. Mostly freezing rain and sleet were noted, with one and a half to 3 inches of ice in western sections of the state and one half to 2 inches of ice elsewhere. The icing was devastating, with about 300,000 customers losing power. Many people were without power for several days. In parts of western Arkansas, there was no water due to power failures and/or generators failing. Hot Springs was the largest city to lose water service. The Governor's Mansion lost electricity and phone service, with the Governor forced to contact some counties with HAM Radio. Roads became nearly impassible due to the ice and trees that had fallen due to the weight of the ice. The National Guard was contacted to help stranded motorists and to deliver emergency generators. Soldiers driving Humvees had to assist the Little Rock ambulance service...which could not reach patients who lived on steep hills in the western part of the city. FEMA officials, which were due into Arkansas to assess damage from the December 12-13, 2000 Winter Storm could not reach the state. Little Rock National Airport was closed from the evening of the 25th until midday on the 27th due to ice on the runways. This was the first time since 1975 that the airport had been closed for more than 24 hours. Ice Storm Warnings were posted well in advance, with one power company already having 3,000 people on standby in other states before the event began. This event combined with the event on the 12th and 13th was believed to be the worst natural disaster in Arkansas history.

A slow moving winter storm moved across the Southern Plains on Christmas day bringing freezing rain and dangerous ice accumulations to all of Northwest Arkansas. The freezing precipitation slowed or prevented most traffic, stranding many motorists and leaving numerous communities without power. The precipitation lasted until mid-day on the 27th of December. Ice accumulations of 1 to 2 inches were common with locally higher amounts in some areas. In Fort Smith, the 117-year old Newspaper was shut down on the 26th of December for the first time ever. Over 10,000 customers in Northwest Arkansas were without electricity after utility lines were snapped due to falling tree branches. Numerous accidents and dozens of stranded motorists were reported in much of Northwest Arkansas. While damages from this storm are expected to be large, estimates were not available at the time of this publication.

Summary of winter weather events for December 25-27 2000. A slow moving winter storm moved across the State Christmas day bringing heavy freezing rain and dangerous ice accumulations. While all of Eastern Oklahoma received significant ice accumulations, East Central and Southeast Oklahoma were hardest hit. One to two inches of ice accumulation were common in these areas with locally higher amounts. Over 500 power poles were downed during the event and over 200,000 Oklahomans were without power. The heavy ice accumulations also left thousands without telephone and water service. Some locations in Southeast Oklahoma were without utility services for more than a week. Numerous shelters and feeding sites were established across Southeast Oklahoma to provide water, food and a warm place to sleep. Thousands of trees were damaged across Southeast Oklahoma including 7 State parks where damage was estimated at over 1 million dollars. Numerous reports of trees downed on vehicles and homes were reported across Southeast Oklahoma. Some of the areas that experienced the most damage were in Pittsburg, Latimer and LeFlore counties. While damage estimates were not finalized as of late February, a preliminary total for the state was $168.9 million.

<u>Scott County</u>

Waldron 8/9/99 Tstm Winds 50 knts
Mansfield 2/9/01 Tstm Winds 50 knts
Boles 2/24/01 Tstm Winds 50 knts
Parks 5/20/01 Tstm Winds 50 knts
Mansfield 9/8/01 Tstm Winds 50 knts

<u>Yell</u>

Ola 12/4/99 Tornado F1 1 mile N of Ola to 2 miles NE of Centreville
Countywide 7/20/00 Tstm 50 knts
Centreville 9/1/00 Tstm 50 knts
Havana 9/3/00 Tstm 50 knts
Dardanelle 5/20/01 Tstm 50 knts
Rover 5/20/01 Tstm 50 knts
Bluffton 6/14/01 Tstm 50 knts

<u>Montgomery</u>

Norman 8/26/99 Tstm 50 knts
Sims 2/26/00 Tstm 50 knts
Entire County 3/26/00 Tstm 50 knts
Mt Ida/Story/Joplin 7/20/00 Tstm 50 knts
Norman/Caddo Gap 8/18/00 Tstm 50 knts
Countywide (particularly west) 6/14/01 Tstm 50 knts
Black Springs 7/26/01 Tstm 50 knts
Mt. Ida 9/8/01 Tstm 50 knts
Welsh 9/9/01 Tstm 50 knts

<u>Perry</u>

Bigelow 7/20/00 Tstm 50 knts
Houston 7/20/00 Tstm 50 knts
Perryville 5/20/01 Tstm 50 knts
Hollis 6/14/01 Tstm 50 knts
Aplin 7/12/01 Tstm 50 knts

<u>Polk</u>

Ink 8/2/99 Tstm 50 knts
Big Fork 8/10/99 Tstm 50 knts
Dallas 12/3/99 Tstm 50 knts
Mena 12/4/99 Tornado F0
Mena 1/3/00 Tstm 50 knts
Grannis 8/18/00 Tstm 50 knts

Wickes 8/18/00 Tstm 50 knts
Cove 9/1/00 Tstm 50 knts
Wickes 9/3/00 Tstm 50 knts
Countywide 2/16/01 Flash flood
Cove 6/14/01 Tstm 50 knts
Mena 6/14/01 Tstm 50 knts
Ink 6/14/01 Tstm 50 knts
Cherry Hill 9/18/01 Tstm 50 knts
Wickes 9/8/01 Tstm 50 knts
SE Polk County 9/9/01 Flash flooding

Garland

Hot Springs 7/26/99 Tstm 50 knts
Mountain Valley 7/26/99 Tstm 50 knts
Fountain Cake 7/26/99 Tstm 50 knts
Hot Springs 8/9/99 Tstm 50 knts
Hot Springs 8/26/99 Tstm 50 knts
Hot Springs 3/26/00 Tstm 50 knts
Pearcy 5/18/00 Tstm 50 knts
Mountain Pine 5/18/00 Tstm 50 knts
Hot Springs 5/18/00 Tstm 50 knts
Hot Springs 7/20/00 Tstm 50 knts
Pearcy 8/18/00 Tstm 50 knts
Pearcy 9/1/00 Tstm 50 knts
Pettyview 5/27/01 Tstm 50 knts
Hot Springs 6/14/01 Tstm 50 knts
Fountain Cake 6/14/01 Tstm 50 knts
Countywide 9/9/01 Tstm 50 knts
Mountain Pine 9/9/01 Tstm 50 knts

Saline

Avilla 8/11/99 Tstm 50 knts
Congo 8/11/99 Tstm 50 knts
Salem 8/11/99 Tstm 50 knts
Bauxite 8/13/99 Tstm 50 knts
Trackwood 8/13/99 Tstm 50 knts
Owensville 2/18/00 Tstm 50 knts
4 miles WNW of Benton 2/18/00 Tornado F1 8 miles to 1.2 miles SW of Bryant
East End 5/12/00 Tstm 50 knts
Sardis 5/12/00 Tstm 50 knts
Benton 5/12/00 Tstm 50 knts
Countywide 9/8/00 Drought – after 2 months with little rain
Vimy Ridge (3 miles ESE) 2/24/01 Tornado F2 2 miles (went to Pulaski)
East End 2/24/01 Tstm 50 knts

Trackwood 4/4/01 Tstm 50 knts
Benton 5/20/01 Tstm 50 knts
Benton 6/14/01 Tstm 50 knts
Bryant 6/14/01 Tstm 50 knts

Le Flore

2 miles NW of Hodgen 3/26/00 Tornado F2 (no downed trees mentioned)
Heavener 3/26/00 Tstm 50 knts
Wister 5/20/01 Tstm 50 knts
6 miles NE of Talihina Tornado F1

VITA

Name: Rachel E. Isaacs

Address: 2018 Pierce Mill Rd., N.W., Washington, D.C., 20010

Email Address: razz2526@yahoo.com

Education: M.S., Geography, Texas A&M University, 2007

B.A., Geography, University of Hawai'i – Hilo, 2001