LIGHTNING-IGNITED WILDFIRE OCCURRENCES IN A CENTRAL-FLORIDA LANDSCAPE MANAGED WITH PRESCRIBED FIRE

By

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Lightning-ignited wildfires (lightning-fires) in the Green Swamp Wilderness Preserve (GSWP), Florida, were characterized and modeled in relation to acreage burned and time since last burn (Fire Interval) as a function of weather, prescribed burn history, and other predictor variables. Data associated with lightning-fires and prescribed burns dating back to 1981 were organized in a geographic information system. A total of 31 lightning-fires were recorded during the study period and 20 of those occurred in prescribed burn units with known histories. An annual average of 1.4 lightning-fires ranged from 1 ac to 267 ac with a median of 7.0 ac. Landscape type composition of lightning-fires was predominately pine flatwoods and was significantly different than the GSWP (p-value<0.000) as a whole and burn units combined (p-value $= 0.002$). The proportion of planted pine was greater in lightning-fires than in burn units or the GSWP. Mean fire interval (FI) for lightning-fires was 37.1 mo; however those data best fit a Lognormal distribution.

Size of prescribed burns averaged 435.7 ac and the total area involved was 50,158 ac, or 76.2% of the GSWP. An average of 7,258 ac/yr were prescribed burned. Landscape type composition was primarily pine flatwoods but included more cypress systems than lightning-fires.

Multiple linear regression was used to model FI and size of lightning-fires (ACRES) as a function of a set of predictor variables and the resulting models were ranked by use of Akaike's Information Criterion (AICc). The "best" model of FI predicted that FI increased as the size of lightning-fires increased. The implication was that the longer an area remains unburned, the larger the resulting wildfire will be when it occurs. ACRES was best predicted as a function of greater 30-day rainfall totals and longer FI. This model supported the conclusion indicated by the FI model; however, the inclusion of increased near-term rainfall was contradictory to established empirical fire behavior and spread models. An additional regression model indicated that the annual number of lightning-fires decreased as annual prescribed burn acres increased. Overall, models had low predictive value ($R^2 < 32\%$), likely due, in part, to fire suppression activities which prevented lightning-fires from coming to their natural conclusions.

Compared to a similar study in north Florida the GSWP experienced fewer average annual number of lightning-fires which burned a smaller proportion of the study area. Managers of the GSWP should continue the active program of prescribed burning to reduce lightning-fire occurrence rates and acreages by maintaining fire intervals to 3 yr or less. Burns should be conducted during the May-August lightning-season if mimicking the historic timing of lightning-fires is a management goal.

CHAPTER 1
INTRODUCTION

Wildfires occur in every state of the U.S. and annually cause the loss of human lives, property, and natural resources. Nationwide, during the latest 10-year reporting period (1992-2001) an average of 103,112 fires burned 4,215,089 acres each year (NIFC, 2003). The annual trend has been toward larger fires and greater acreages burned as evidenced by the 2002 fire season in which 88,458 fires consumed 6,937,584 acres. A total of 835 homes and 46 commercial buildings were lost in 2002 and the suppression costs were estimated at $16 billion, including only federal expenditures.

Although the majority of the acreages burned are located in the western U.S. and Alaska, Florida suffers its share of wildfires. In 1998 a total of 4,899 fires burned across 506,970 acres causing an estimated $620 million in damages, primarily to timber resources (FDOF 2003; Mercer et al. 2000). During the period from 1999 through 2001 an annual mean of 5,724 fires resulted in 323,276 acres consumed each year. As an apparent result of increased rainfall amounts, 2002 was a relatively mild year with 3,065 wildfires scorching only 56,835 acres.

Types of Wildfire Occurrences

Wildfires may be initiated by a number of different ignition sources. The Florida Division of Forestry (2003) maintains records for ten different categories of wildfire causes. Table 1-1 lists the causes of wildfire ignitions with their average annual percent of the total acreage burned in Florida for the period 1995 – 2001.

Table 1-1. Causes of wildfires in Florida during 1995-2001 by percent of total acreage

Cause	Average annual percent of total acreage burned
Lightning	36.1
Campfires	1.3
Smoking	0.4
Debris burning	7.6
Incendiary	20.5
Equipment	13.0
Railroad	0.5
Children	0.9
Unknown	13.7
Miscellaneous	5.6

Lightning stands out as a major source of wildfire ignitions and is the only category of wildfire not caused by humans (excluding Unknown). During the period from 1995 through 2001 lightning-ignited wildfires accounted for over one-third of the annual acreage burned in Florida and 20% of the number of total fires reported.

Predicting Lightning Ignitions

Florida's geographic location and subsequent climate lead to intense and numerous thunderstorms, accompanied by frequent lightning strikes, particularly during the summer rainy season (Trewartha 1981). An individual storm may produce over a thousand strikes of varying intensity and charge (Hildebrand pers. comm.). Under the appropriate conditions of fuel moisture, humidity, and temperature, vegetative fuel may ignite and become a wildfire. The Lightning-Caused Fire Occurrence Prediction system was developed by Anderson (2002) based upon a model which uses the number of lightning strikes detected, weather, and fuel conditions. An additional conceptual model was also developed to predict the probability of a wildfire ignition as:

$$p\text{fire(t)} = p\text{lcc}*p\text{ignition}*p\text{survival(t)}*p\text{arrival} \quad ,$$

where lcc is long continuing current (type of lightning strike), survival is the smoldering phase of combustion, and arrival is flaming combustion. This model suggests that wildfire ignition probability is a function not only of weather and fuel conditions, but also of lightning strike variables. Polarity of lightning flashes may also be a determining factor in the likelihood of an ignition. Fuquay (1980) found a correlation between positively charged flashes and wildfire occurrences. However, this association was not detected for fires in a different study which found no statistically significant correlation with positively-charged flashes or negative flashes and wildfire occurrence (Rorig and Ferguson, 1999). Strike density, or the number of strikes per unit area, may also not contribute to the prediction of ignition probability. An investigation of fires which occurred in the northwest U. S. during the active fire season of 2000 revealed that high atmospheric instability and high dewpoint depression were much more significantly correlated with wildfire ignition than strike density (Rorig and Ferguson 2002).

Geographic location may be a factor in the significance of strike density with wildfire occurrence. In Alaska, strike density was a significant variable in a regression model which included elevation and percent tree cover (Kasichke et al. 2002). Their model explained 84% of the variation in fire return interval (R^2 = .84). Similarly, strike density was a significant variable in Canada's lightning wildfire occurrences (Wierzchowski et al. 2002). Interestingly, they found that fewer strikes in British Columbia resulted in more fires than in Alberta which experienced a greater number of flashes during the study period.

Wildfire Mitigation

Heat, fuel, and oxygen are basic ingredients of all fires (Pyne 1996). In wildlands only the fuel variable is readily manipulated by man. Vegetative fuels may be reduced or removed by a) mechanical methods such as logging or machine clearing, b) livestock grazing, c) herbicide application, or d) prescribed burning. Prescribed burning, the application of fire to a designated location, under specific conditions, to achieve a pre-determined objective, is probably the most commonly utilized fuel management tool in the southeast.

Prescribed Burn Applications

Humans have used fire as a tool in the U.S. since before European settlement. American Indians were known to use fire to drive game, attract game, increase berry production, prepare planting sites, and to create fire-safe boundaries around settlements (Pyne 1997; Lewis and Ferguson 1988). In modern times, prescribed fire is used in much the same way, with the exception of driving game. Prescribed fire has been used for decades by forest plantation managers for the purpose of protecting stands against wildfire damage (Wade 1983). Wildfire hazard reduction has continued to be a major reason for the application of prescribed burns in recent years (DOF 2003). Florida is a leader in total annual acres prescribed burned with an average of approximately 500,000 acres per year during the period 1993-1999 (Butry et al. 2002).

Cleaves et al. (2000) surveyed U. S. Forest Service prescribed burners to determine costs, reasons for burning, and the constraints on accomplishing burn objectives. A similar survey was conducted on prescribed burners of private lands and public lands in the South (Haines and Busby, 2001). In both surveys the reduction of wildfire hazard was listed as one of the main purposes for conducting prescribed burns.

Prescribed Burning Effects on Wildfires

Investigations of the effects of prescribed burns on wildfires generally involve one of two questions: 1) Does prescribed burning reduce the probability of wildfire occurrences, and if so, for how long? ; 2) Are wildfire impacts, intensity, or aerial size reduced by prescribed burning? Fernandes and Botelho (2003) conducted an exhaustive literature review to analyze the premise that prescribed fire is a valuable tool for forest protection and wildfire mitigation. The general conclusion was that prescribed fire reduced the size, intensity, and damage of wildfires, all types included. Prescribed fire effectiveness was reported to extend only for a period of 2-4 yr. The authors indicated that the need exists for more properly designed experiments. A more detailed examination of those studies' results is presented next.

Wildfire Occurrence Probability

In north Florida and south Georgia wildfire occurrence rates were somewhat higher in areas which had not burned in over three years ("three-year rough"), however this difference was described as "not very great" (Davis and Cooper, 1963). Expressed as wildfires per 10,000 acres per year, rates of lightning ignitions ranged from 0.303 in age 0 roughs to 0.607 in age 5+ roughs. No statistical tests of significant difference between the means were reported.

Prescribed burning may either reduce wildfire ignition probability or increase it. In an African savanna system, prescribed burns were conducted on a large conservation area in a random pattern and allowed to burn unaltered for up to seven days (Brockett et al. 2001). This program was monitored for several years and resulted in smaller, but more numerous wildfires than before the prescribed burns were incorporated into the management of the area. Conversely, Butry et al. (2002) found a negative correlation between the number of prescribed burn permits and wildfire ignitions in Florida. Their analysis relied upon the Prescribed Burn Authorization permit process administered by the Florida Department of Forestry. Records of burn permits issued for each cadastral section were compared with the locations of wildfires. Sections in which no permits were issued during the study period experienced roughly 75% of all the wildfires, while sections with >1 permit had only 4% of the total number of fires.

Wildfire Impacts

Davis and Cooper (1963) calculated wildfire burn acreage per 10,000 acres for lightning-ignited wildfires, indicated no significant correlation, and values ranged from 1.42 for age 0 roughs to 2.09 in age 5 roughs. All of the large fires ($\geq$ 200 ac), however, occurred in areas which had not been prescribed burned in over five years. Wildfire intensity was examined as a function of height of crown scorch line on trees and the height of bark char. Variation in crown scorch line height was related more to ambient temperature than to age of rough. Bark char height, however, was determined to be a positive and significant correlate with age of rough. Martin et al. (1988), in a study of the same geographic area, found that the average size of wildfires was 20.4 ac in areas prescribed burned within the previous three years and 60.5 ac in untreated areas.

Koehler (1993) concluded that prescribed burn programs in central Florida, which had been ongoing for an adequate time, resulted in fewer and smaller wildfires. He also suggested that consistent annual wildfire acreages indicated a reduction in fire intensity, despite severe weather conditions. Contradictory to those conclusions, over 24,000 acres in the Osceola National Forest in north Florida burned in one extreme drought year, despite an active prescribed burn program (Outcalt and Wade, 2000).

A reduction in wildfire intensity as a result of a previous prescribed burn has been documented in the U.S.(Pollet and Omi, 2002) and in Europe (Fernandes et al. 1999). In Portugal, an average reduction in fireline intensity of 98%, as a result of prescribed burns in pine (Pinus spp.) stands, was reported by Fernandes et al. (1999). The effectiveness of prescribed burning on fireline intensity may be quite variable, as low as 10%, depending upon the percentage of fuel-load reduction, which is affected by weather parameters at the time of the burn (Omi and Kalabokidis 1998).

Variables such as precipitation, temperature, fuel moisture and fuel age have been utilized in regression analyses to predict variation in wildfire burn acreage (Turner and Romme 1994; Larsen 1996). Those relationships may not be linear. In Los Angeles County, California, wildfire burn area increased steadily as fuel age and temperature increased and precipitation and fuel moisture decreased. Above a certain threshold, however, fire risk did not increase (Schoenberg et al. 2003).

Fire Regime

Fire regime describes the parameters associated with fire in an ecosystem or region and may include burn area extent and fire intensity, as well as fire frequency, burn seasonality, and fire interval (Pyne et al.1996). Fire effects on vegetation are also considered part of a fire regime (Glitzenstein et al. 1995). Bravo et al. (2001) defined fire frequency as the recurrence of fire throughout time. Fire frequency was calculated as a ratio of the number of fires in a given area to the time interval, in years, between the first recorded fire and the last. Fire interval was defined as the interval, in years, between two fires occurring in the same location. Bravo et al. (2001) reported a fire interval with a median of four years for a savanna in Argentina which fit the Weibull frequency distribution, a commonly used model in fire studies (Reed 1994; Johnson and Gutsell 1994). The Weibull distribution of fire interval is derived from a model which assumes that flammability, or probability of ignition, is a power function of time since last burn. However, McCarthy et al. (2001) argue that basing fire interval distributions on the Weibull model may be unnecessarily restrictive and may not make sense from a biological perspective.

Study Objectives

The goal of this study was to further investigate the effects of prescribed burning on lightning-ignited wildfire occurrence in terms of size, number, and fire interval on the Green Swamp Wilderness Preserve (GSWP) in central Florida. The GSWP is a relatively large public landholding of roughly 72,000 acres owned and managed by the Southwest Florida Water Management District (SWFWMD). Prescribed fire has been utilized as a management tool there for over 20 years to reduce wildfire hazard and to restore and enhance ecosystem processes (Love pers. comm.). Despite the frequent and widespread use of prescribed fire, the GSWP has periodically experienced lightning-ignited wildfires in addition to anthropogenic fires. A detailed analysis of the wildfire occurrences in relation to the prescribed burn program and other variables may serve to improve empirical knowledge of those phenomena and to increase predictive modeling accuracy. Specifically, the objectives were as follows:

- 1. Describe the prescribed burn program: a) burn unit acres; b) acres burned per year; c) landscape type proportions burned versus the GSWP as a whole; d) seasonality of burns; e) burn frequency.
- 2. Describe lightning-ignited wildfire occurrences: a) acres burned; b) fire interval; c) fire frequency distributions; d) landscape type proportions versus prescribed burns and versus the GSWP as a whole.
- 3. Model the influence of key variables on the acres burned in individual lightning-ignited wildfires.
- 4. Model the influence of key variables on the fire interval of individual lightning-ignited wildfires.
- 5. Model the influence of key variables on the annual number and total acreage of lightning-ignited wildfires.

The objectives were designed to assist in testing the following hypotheses:

- H1: Annual lightning-ignited wildfire acreage is inversely proportional to annual prescribed burn acreage.

- H2: Landscape type has greater influence on lightning-ignited wildfire size than fire interval which has greater influence than climate variables.

- H3: The fire interval distribution of lightning-ignited wildfires is best modeled by the Weibull frequency distribution.

CHAPTER 2
METHODOLOGY

Study Area

Decision Process

The Green Swamp Wilderness Preserve (GSWP) was chosen as the study area because of its relatively large size (65,820 ac), and the data records existed for prescribed burns and wildfires dating back over 20 years. The occurrence of wildfires on a property with an active prescribed burn program made the GSWP attractive as a site for the study of the relationship between the two phenomena. In the literature review no studies of this type were located which were conducted in central Florida. It is possible that research findings in other parts of the U.S. or elsewhere may be different from those found in central Florida.

Site Description

The GSWP-East is roughly 72,000 ac in total area and is located in west-central Florida. The property encompasses parts of eastern Pasco County, southwestern Lake County, southern Sumter County, and northern Polk County. A portion (6,140 ac) of the northeast extension of the property is managed by the Florida Division of Forestry as the Little Withlacoochee Flood Detention Area. Due to a different management regime and data collection effort, that area was excluded from the analysis resulting in a study site comprised of 65,820 ac, referred to hereafter as GSWP (Figure 2-1).

The GSWP was purchased and is managed by the Southwest Florida Water Management District (SWFWMD) to a) protect the region's water supply and water quality, b) reduce flooding, c) conserve native ecosystems, and d) for public recreation and other benefits. Management activities on the property include prescribed burning, exotic plant and animal control, and timber production from designated plantation sites. Recreational uses include passive activities such as hiking, bicycling, birdwatching, camping, fishing, frogging, and hunting. Hunting is administered by the Florida Fish and Wildlife Conservation Commission through a Wildlife Management Area agreement. Several species of small game and large game, including feral hog (*Sus scrofa*) are hunted on GSWP.

Historical, long-term rainfall averages about 53 in yearly though the average during the study period was 51.2 in, and ranged from 37.5 in to 77.3 in. A matrix predominated by pine flatwoods, dotted with cypress wetlands, and bottomlands lining creeks and rivers, defines the majority of the GSWP landcover. Pine flatwoods consist of an overstory of longleaf pine (*Pinus palustris*) and slash pine (*Pinus elliottii*) and an understory mostly of saw palmetto (*Serenoa repens*), gallberry (*Ilex glabra*), and wiregrass (*Aristida* spp.). Cypress wetlands occur in depression ponds and strands, lake and river shorelines, and are dominated by pond cypress (*Taxodium ascendens*) with bald cypress (*Taxodium distichum*) confined to the lakes and rivers. Bottomlands are in the floodplains along streams and rivers. These are densely forested, mixed landscapes of cypress, laurel oak (*Quercus laurifolia*), sweetgum (*Liquidambar styraciflua*), and red maple (*Acer rubrum*). The GSWP is regionally important as the headwater source for the Oklawaha River, Myakka River, Peace River and the Withlacoochee River. Turpentining of old-growth pines, followed by logging of cypress and pines, and, later, cattle ranching were the historic land uses on the GSWP (Richards pers. comm.).

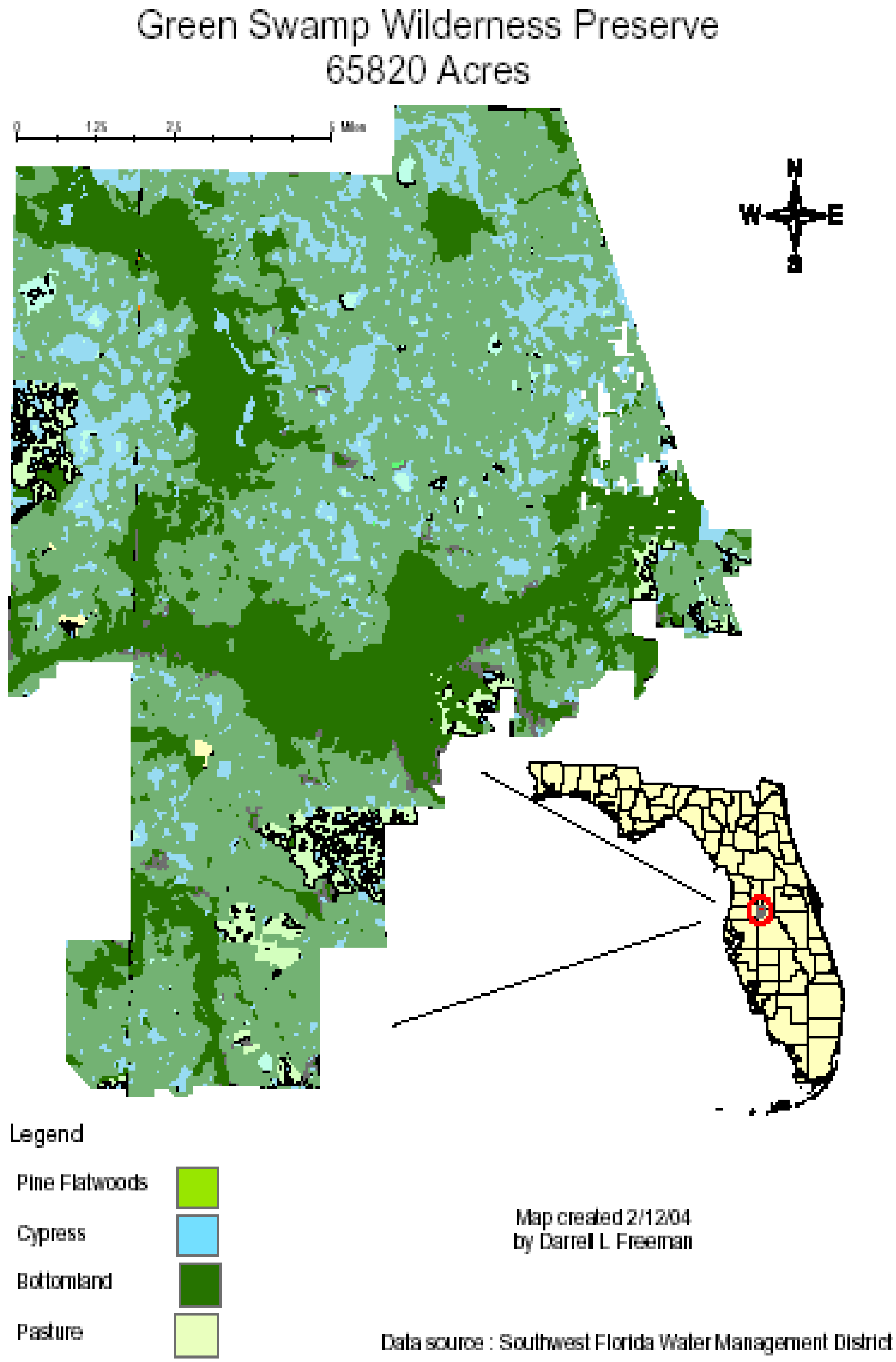

Figure 2-1. Green Swamp Wilderness Preserve location map with generalized habitats

Data Collection

Prescribed Burn Records

The SWFWMD archived all executed burn documents for all of the lands under its management. All burn records for the GSWP, dating back to 1981, were pulled from archives and examined for this study. Burn plans were written in advance for all prescribed burns conducted on the GSWP as directed by the Florida Prescribed Burner Act (F.S. 590). Each burn plan included: 1) the specific location of the burn [both the Section(s), Township(s), and Range(s), and a map], 2) season of the burn, 3) habitats or landscape types to be burned, 4) acres, 5) weather parameters such as wind speed and direction, relative humidity range, temperature range, and smoke dispersion range, 6) smoke plume projection map, 7) purpose and objectives of the burn, 8) burn manager's name and Florida Prescribed Burner certification number.

At the conclusion of each burn additional data were collected in a post-burn evaluation and added to the plan prior to being archived: 1) date of the burn, 2) duration in hours, 3) weather parameters, as described above, observed during the burn, 4) acres burned, 5) names of personnel involved, 6) tree crown-scorch percent estimate, 7) number of spotovers, or escapes, and any damage, 8) positive or negative assessment of whether the objectives were met, and 9) comments. In most cases the burn manager also marked on the map included in the plan the specific area which was burned. This was important because many burn units were divided into smaller blocks and completed over a period of weeks or months. A number of burn units were only partially completed due to unforeseen constraints, while others were adjusted in area by logistical considerations. Temporal and spatial resolution of burn area was therefore increased by those records. Burn plans generated during the 1970s through the early 1990s contained maps consisting of blue-line aerial photos with hand-drawn fire boundaries while those from the mid-1990s through 2002 utilized maps created in a Geographic Information System (GIS) with relatively current digital ortho quarter-quadrangle (DOQQ) images. Data quality of plans executed before 1990 were judged as poor due to incompleteness or indiscernible mapping of fire perimeters. Burn plans of questionable quality were excluded from the analysis and only those dating from 1990 through December 2002 were utilized.

Each useable prescribed burn plan for the GSWP through 2002 was thoroughly inspected for specific burn dates and fire perimeters. The boundary of each burn was digitized over a DOQQ developed from aerial images taken in 1999. ArcGIS software (ESRI 1999) was utilized for all digitizing work and spatial data analysis. Burn perimeter mapping accuracy was judged as “high” since burn units were typically bounded by existing roads, firebreaks, streams or other water features which were readily visible on the DOQQ. Where the burn evaluation map indicated that fire perimeters differed from the proposed boundary, those changes were followed as closely as possible during the digitizing process and often aligned with dirt roads, old fencelines, or landscape type borders which were readily visible on the DOQQ. A total of 186 burn perimeters were digitized and stored in the GIS.

All prescribed burn perimeters were stored in a single polygon shapefile as a data layer in the GIS. Each burn perimeter was associated with an ID number in an attribute table. Data for each burn were stored in the attribute table and included date of burn and acres, as calculated by the GIS.

Wildfire Reports

Each detected wildfire on SWFWMD lands was recorded and archived by use of a wildfire report. All wildfire reports of wildfires on GSWP were pulled from archives and examined for this study. Dating back to 1979, these reports included wildfires caused by arson (19%, n = 11), escaped from prescribed burns (12.1%, n = 7), unknown (10.3, n = 6), miscellaneous (5.2%, n = 3), and lightning (53.4%, n = 31). Only lightning-ignited wildfires (hereafter referred to as lightning-fires) were analyzed in this study.

Each wildfire report contained; 1) date of fire, 2) location, 3) cause, if determined 4) origin of fire, if determined, 5) time fire was first reported, 6) time suppression was initiated, 7) weather parameters, 8) names of personnel involved, 9) acres burned, 10) damage assessment, 11) landscape type(s) burned. As with the prescribed burn plans, data quality improved over time. Reports from the 1970s through the early 1990s contained maps consisting of blue-line aerial photos with hand-drawn wildfire boundaries while those from the mid-1990s through 2002 utilized maps created in a GIS with relatively current DOQQ images. Overall map accuracy of wildfire boundaries was judged as "high" due to the heterogeneity of the landscape providing recognizable landmarks, visible in the field as well as on the maps, and to a high degree of familiarity of the land management personnel with the property. All lightning-fire records (n=31) were judged as adequate in terms of data quality and were included in the study. The boundary of each lightning-fire was digitized over a digital ortho quarter-quadrangle developed from aerial images taken in 1999. ArcGIS software was utilized for all digitizing work and spatial data analysis.

All lightning-fire perimeters were stored in a single polygon shapefile as a data layer in the GIS. Each fire perimeter was associated with an ID number in an attribute table. Data for each lightning-fire were stored in the attribute table and included date of burn and acres, as calculated by the GIS.

Fire Return Interval

Once all the prescribed burn perimeters and lightning-fire perimeters were digitized and their respective attribute tables were populated, the fire return interval for each lightning fire location could be determined. Overlaying the lightning-fire shapefile on top of the prescribed burn shapefile graphically depicted their spatial relationships. A query of the database or a simple point and click of the computer mouse was used to illustrate the date of the last burn on any chosen point across the landscape. The fire return interval for each lightning-fire was then calculated to the nearest whole number in months. The date of last burn as recorded on the wildfire report was used where those data could not be ascertained through a GIS query (n= 4). Lightning-fires which occurred in areas with no previous burn history (n=11) for example, swamps or flood-plain forests, were excluded from fire interval calculations.

Landscape Type

Landscape type in this study refers to relatively discrete vegetation assemblages existing on the landscape as defined by the Florida Land Use and land Cover Classification System (FLUCCS) data (FDOT 1999). Table 2-1 describes each landscape type used in the analyses. The data were imported into a GIS as a layer. Covering the entire state of Florida, this layer was clipped to the perimeter of the GSWP to reduce the size of the data file and to increase processing speed. The total acres of each landscape type were then calculated in the GIS for the entire GSWP. The prescribed burn layer and the lightning-fire layer were in turn overlayed onto the FLUCCS layer and total acres of each landscape type were subsequently calculated for both fire shapefiles. Landscape types were then grouped into eight distinct categories based on similar characteristics and based on ground-truthed verifications (Table 2-1).

Table 2-1. Description of landscape types

Landscape Type	Description and other FLUCCS categories included in the variable
Flatwoods	Longleaf and/or slash pine with palmetto, includes Shrub and Brushland
Wet Prairie	Same as Flatwoods but with canopy cover < 10%
Pasture	Non-native grassland, "improved pasture"
Freshwater Marsh	Herbaceous wetland, includes Emergent Aquatic and Herbaceous
Cypress	Forested wetland systems, includes Bottomland, Wetland Coniferous Forest, Wetland Forested Mixed, and Bay Swamp
Planted Pine	Commercial plantation of slash pine or longleaf pine
Upland Forest	Dense upland forest, includes Upland Coniferous, and Hardwood Conifer Mixed
Other	Disturbed lands, includes Utilities, Reservoir, Disturbed, Extractive

Rainfall

Rainfall data from one sensor, located at $28^{o}21'39.7''$ N, $82^{o}1'20.4''$ W, near the center of the GSWP, were obtained from the SWFWMD. No other rainfall sensors were located on the property during the study period. Though rainfall may have been significantly different from location to location, it was assumed that the data from the centrally located sensor accurately represented the general trend of rainfall. Those records dated back to April of 1981 and consisted of daily totals organized by month and year. Thirty-day rainfall totals (1-MO RAIN) were calculated for each lightning-fire occurrence by summing the rainfall for the 30 days previous to the burn date. Three-month (3-MO RAIN), 6-month (6-MO RAIN), and 12-month (12-MO RAIN) rainfall totals preceding each lightning-fire occurrence were also calculated. Rainfall accumulations on the day of a lightning-fire occurrence (0-D RAIN), on the day preceding an occurrence (1-D RAIN), and seven days preceding an occurrence (7-D RAIN) were also obtained. In addition, total rainfall for each calendar year from 1981 through 2002 was calculated (ANN RAIN). Table 2-2 provides a description of the weather related variables used in the study.

Lightning

Lightning strike data were collected through the use of the Lightning Location and Detection Network (Vaisala Inc.), covering all of central Florida from 1989 through 2002 (Hildebrand pers. comm.). Lightning strike data for a circular area with a radius of five miles, centered on the GSWP and covering its entire boundary were obtained for the study. The total number of flashes (NUM STRIKES) was determined for each date a lightning-fire occurred during that time period. Total number of flashes were also calculated for the two days previous to each lightning-fire (STRIKES 2d) and for the seven-day period preceding each lightning-fire occurrence (STRIKES 7d).

Table 2-2. Description of weather variables used in the study

Variable	Description of Variable
0-D Rain	Rainfall total on the day of a lightning-fire
1-D Rain	Rainfall total one day preceding a lightning-fire
7-D Rain	Rainfall total for seven days preceding a lightning-fire
1-MO RAIN	Rainfall total for the 30 days preceding a lightning-fire
3-MO RAIN	Rainfall total for the 90 days preceding a lightning-fire
6-MO RAIN	Rainfall total for the 180 days preceding a lightning-fire
12-MO RAIN	Rainfall total for the 360 days preceding a lightning-fire
ANN RAIN	Rainfall total for a calendar year
NUM STRIKES	Total number of strikes the day of a lightning-fire
STRIKES 2d	Total number of strikes 2 days preceding a lightning-fire
STRIKES 7d	Total number of strikes 7 days preceding a lightning-fire

Statistical Analysis

Descriptive Statistics

General descriptive statistics were developed from the prescribed burn records and the lightning-fire reports. Mean and standard deviation values were calculated for annual acres prescribed burned, for all individual prescribed burns, annual lightning-fire acres, and individual lightning-fires. As a descriptor of seasonality, prescribed burns were separated by date into lightning-season and non-lightning-season. All of the lightning-fires which occurred on the GSWP during the study period were within the time-period of May through August. Therefore, prescribed burns which were conducted between May 1 and August 31 were categorized as lightning-season burns and all others were non-lightning-season burns. Total acres of burns from both seasons were calculated for each year.

Landscape Type Proportion

Acreage data used in ratio calculations were transformed with the Freeman-Tukey method to avoid problems of unequal variance (Cressie and Read 1989):

$$Z_i = (1000(B_i)/a_i)^{1/2} + (1000(B_i + 1)/a_i)^{1/2}$$

where B_i is the acres burned in the $_i$th observation, and a_i is the total area of the $_i$th burn unit or landscape type. The yield from this transformation was a proportion of a given landscape type in a specific polygon layer (e.g. GSWP) to the total acreage of that layer. It is similar to a percentage, but which does not sum to 100.

Z_i values were calculated for the GSWP as a whole, for aggregated prescribed burns, and for aggregated lightning-fires. Differences between each set of landscape type proportions was tested with the Chi-square goodness-of-fit test (Ott and Longnecker, 2001) set to a 1:1 ratio. The test result indicates whether a statistical difference exists between the contrasted layers (e.g. prescribed burn vs. lightning-fire) for at least one landscape type proportion. Pair-wise comparisons to test which landscape type proportions were different were not conducted since the proportions were sums of the entire population (study area) rather than samples used to construct means and other statistics.

Fire Return Interval

The time since last burn (FI), in months, was calculated for each lightning-fire with a known fire history. Frequency distribution analyses (Minitab 2000) were performed on those data to test the fit with: 1) Weibull, 2) normal, 3) exponential, 4) logistic, and 5) lognormal base e, frequency distributions. The Anderson-Darling goodness-of-fit statistic and Pearson's correlation coefficient were used to evaluate the fit, and shape and scale parameters were calculated for each distribution where applicable.

Multiple Linear Regression

Regression analysis is used to investigate the relationship between a response variable (Y), and one or more predictor variables (X) as illustrated by the formula:

$$Y = B_0 + B_1X_1 + B_2X_2 + ... + e$$

where B_o is the y-intercept, B_1 is a coefficient, and e is an error term.

The coefficient for each predictor variable, as calculated by the regression model, represents the change in the response for each unit change in the predictor variable. The regression equation represents the best "fit" of a line through a plot of X versus Y which results in the smallest total sum of the squared differences of all of the plot points from the regression line.

Two key assumptions of regression analysis are that the regression related errors for each variable are normally distributed with constant variance. Plots of the residuals for each variable were examined for indications of departures from this. In addition, normality tests were conducted on all variables and those variables with non-normal distributions were transformed to achieve normality. Of those variables which required transformation, a natural log of the data accomplished that goal. As a dependent variable, FI did not require transformation.

Initially, all the data for each variable were entered into a spreadsheet for preliminary analysis. A Pearson's Correlation matrix was computed for the set of variables to detect significant relationships (Table 3-3). The matrix facilitated an examination of collinearity between variables and the strength and statistical significance of the correlation between the predictor and the response variable. Correlations with p-values < 0.10 were considered candidates for inclusion in the regression analysis.

Regression equations were computed for all possible sets of predictor variables (Tables 2-2 and 2-3) on the response variable, lightning-fire acres (ACRES). The same process was applied to the response variable, fire interval (FI). Preliminary model selection was based on several statistics generated with the regression including R^2, p-value, and mean square error. In addition, normal probability plots of the residuals, plots of the residuals versus the fitted values, and the residuals versus the variables were plotted to assess assumptions of normality of the residuals and to look for indications of non-linearities in the relationships between the variables. Finally, a set of candidate models was ranked by use of Akaike's Information Criterion, corrected for small sample size, (AICc) which balances the number of predictors in the model with its error variance (Burnham and Anderson 1998). The formula for AICc is written:

$$AICc = n[\ln(RSS)] + 2k + [2k(k + 1)/(n - k)],$$

where RSS = residual sum of squares (from the regression), and k = # variables.

Table 2-3. Description of variables, excluding weather-related, used in the regression

Variable	Description
ACRES	Total acres burned in an individual lightning-fire
FI	Time in months since an area last burned
JULIAN	Julian date of a lightning-fire
PB ACRES	Total acres burned by prescribed fire in a calendar year
L-F ACRES	Total acres burned by lightning-fires in a calendar year

CHAPTER 3
RESULTS

Prescribed Burns

General Description

Burn plans prior to 1990 were incomplete, and specific dates and exact burn boundaries were unclear, therefore data for burns were included only for years 1990 through 2002. During that time period 195 burns were conducted for a total of 94,359 ac, with an average of 7258 ac/yr (SE = 1415). Annual acreage ranged from a low of 111 ac in 1993 to a high of 15,630 ac in 1997 (Figure 3-1). Individually, prescribed burns ranged from 15 acres to 2767 ac with a mean size of 435.7 ac (SE = 38.3). Combined area of all individual burn units was 50,158 ac (Figure 3-2). The fire interval, (FI), for prescribed burns ranged from 31 mo to 96 mo with the average 45.5 mo. Burn unit landscape types (Table 3-1) consisted primarily of pine flatwoods (Z = 42.8), cypress/forested wetland systems (Z = 37.4), and pine plantation (Z = 17.4). Those landscapes comprised 70.0% of the total Z-score of transformed acres. The composition of landscape types of prescribed burns was different from the GSWP as a whole (X^2 = 22.56, df = 6, p-value = 0.001). Burn units were composed more of pine flatwoods than the GSWP and none in the upland hardwood or disturbed categories, which comprised Z-values of 13.0 and 7.9 respectively for the property as a whole (Figure 3-1).

Table 3-1. Composite transformed landscape type proportions of burn units

Landscape Type	FW	WP	P	FM	Cy	PP	UF	O	Category
Z-value	43	12	14	8	37	17	0	8	Prescribed
	50	19	3	4	29	26	0	0	Lightning
	41	10	13	7	42	11	10	5	GSWP

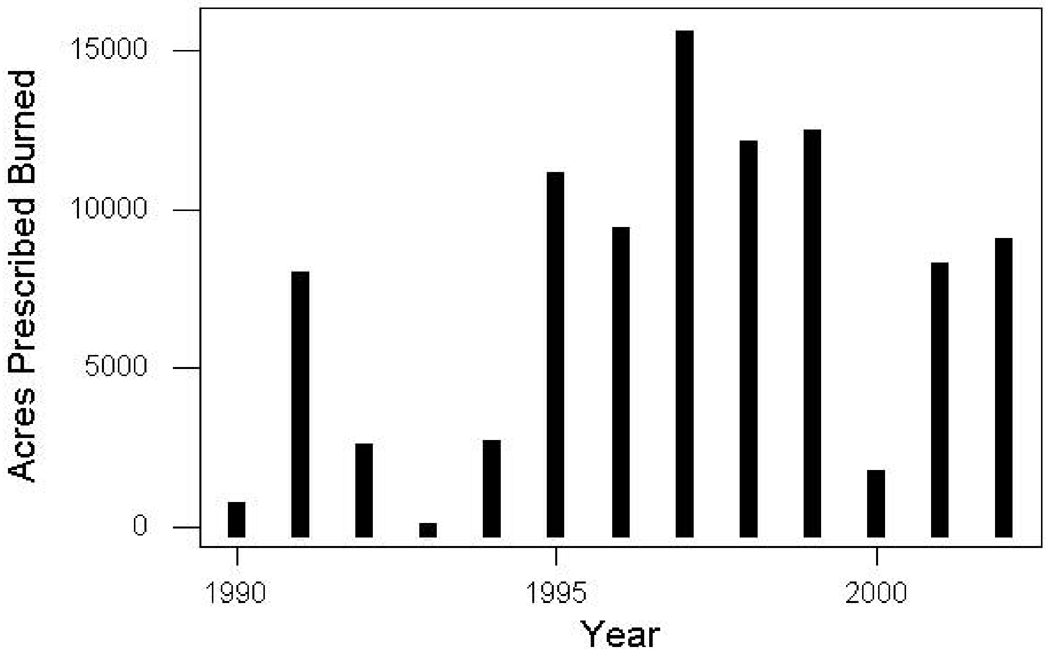

Figure 3-1. Total acres prescribed burned by year

Lightning-season Burns

Lightning-season burns (n = 36), defined as those burns occurring within the period May - August (based on lightning-fire occurrence dates in this study), averaged 1024 ac/yr (SE = 372) and ranged from 0.0 in five different years to 4858 ac in 1999. Individual lightning-season burns were smaller than non-lightning-season burns though the difference was not statistically significant (t = 1.10, p-value = 0.277) and averaged 367.0 ac (SE = 52.3). As a percentage of the total annual acres burned, lightning-season prescribed burns ranged from 0% in five different years to 38.8% in 1999.

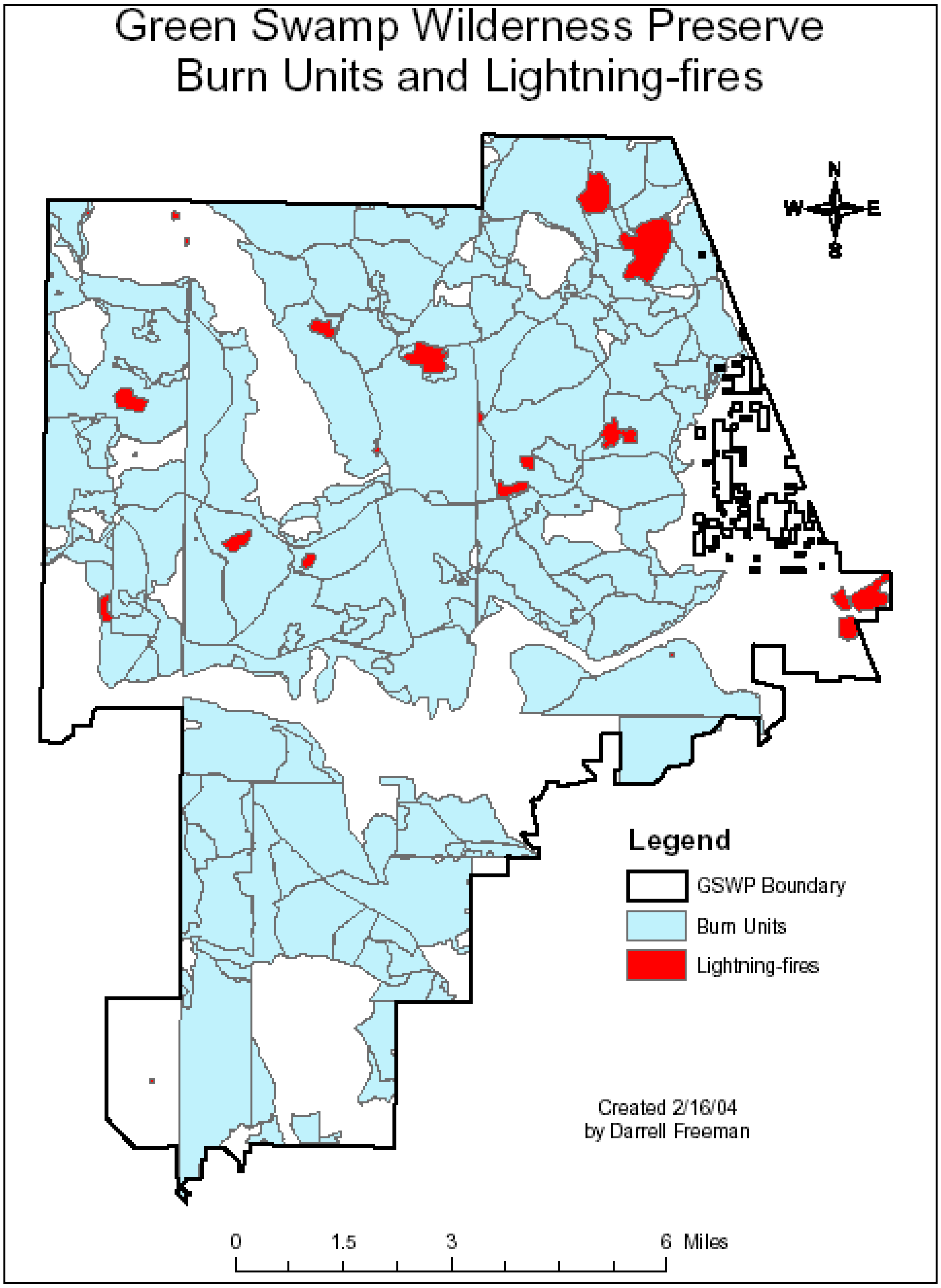

Figure 3-2. Prescribed burn units and lightning-fire locations in the GSWP

Lightning-Fires

A total of 31 lightning-fires were recorded during the period from 1981 through 2002 for an average of 1.48 fires/yr (Figure 3-3). Those fires burned 1040 ac combined and averaged 80.0 ac/yr (SE = 27.5) for the 13 years in which lightning-fires occurred.

The year 2000 had the greatest number of fires (n = 11) and the largest total acres burned in a year (317 ac). Individual fires were an average of 34.1 ac (SE = 9.85) though the median lightning-fire was 7.0 ac, and they ranged in size from 1 ac to 267 ac. Landscape proportions were different from the GSWP (X^2 = 33.28, df = 6, p-value<0.000) and from the burn units containing those lightning-fires (X^2 = 14.16, df = 5, p-value = 0.015). Lightning-fires were predominately pine flatwoods (Z = 50.4), cypress systems (Z = 29.1), and pine plantation (Z = 25.7). They included no upland hardwood forest or disturbed areas (Table 3-1).

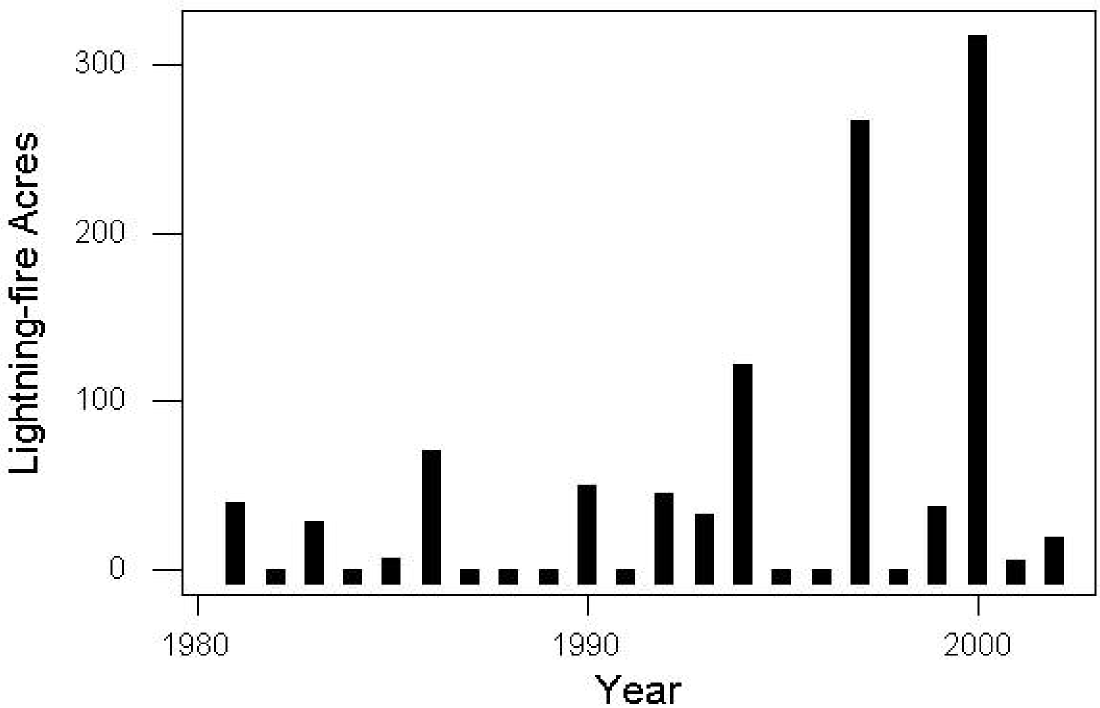

Figure 3-3. Total annual lightning-fire acres by year

Fire Interval

Fire Interval (FI) for the set of 31 lightning-fires ranged from as little as 7 mo to 114 mo (Figure 3-4). However, 11 of the fires occurred in locations with unknown history or no record of any previous burns, such as river floodplain and swamps, which historically remained wet year-round (Vanlerberghe pers comm). The remaining 20 lightning-fires with known previous burn histories were used in the analysis of FI. Mean fire interval was 37.1 mo (SE = 5.61), median FI was 30 mo, and the mode was 24 mo, indicating that those data were not normally distributed. It can be seen from Figure 3-4 that the distribution of FI was skewed to the right. The Anderson-Darling normality test confirmed that the data were non-normal (p-value = 0.036). The hypothesis that the distribution of FI values would be appropriately modeled by the Weibull frequency distribution was tested.

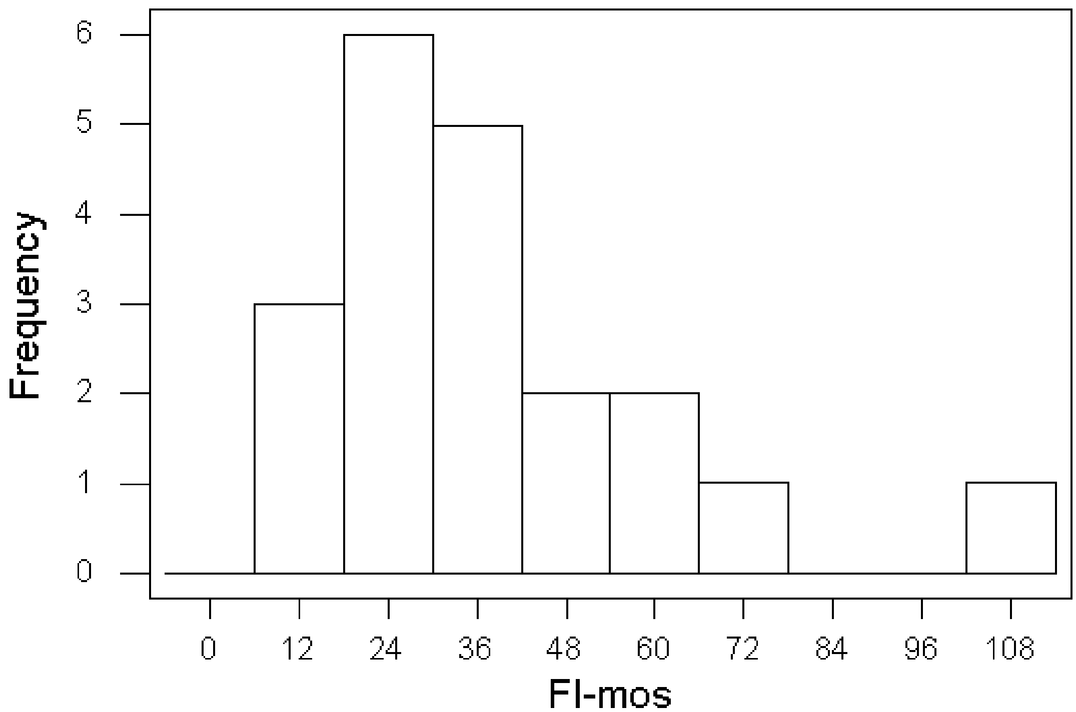

Figure 3-4. Fire interval frequency distribution of lightning-fires

Distribution function analyses were conducted to determine which frequency distribution fit the data best. The Anderson-Darling statistic and Pearson's Correlation Coefficient were the two statistical tests used. The Anderson-Darling statistic is a measure of how far the plot points fall from the fitted line in a probability plot (MINITAB Inc.2000). Smaller values indicate that the data fits the distribution better than those with larger values. Pearson's correlation measures the strength of the linear relationship between the X and Y variables on a probability plot. A correlation of 1.0 represents a perfect relationship between those variables and the plot points lie in a straight line on a probability plot. Therefore, a larger Pearson's correlation represents a better fit to the data than a smaller correlation.

The FI data fit well the Weibull distribution (Shape = 1.77, Scale = 41.13) with an Anderson-Darling statistic of 0.888 and a Pearson's correlation of 0.983 (Table 3-2) as compared to a Normal distribution with Anderson-Darling = 1.296 and Pearson's correlation = 0.926. However, the Lognormal distribution (base e and base 10) fit the data best with an Anderson-Darling = 0.759 and Pearson's correlation = 0.984. The Lognormal(e) distribution returned a 50th percentile value of 30.15 mo.

Table 3-2. Fire interval distribution Goodness-of-fit statistics

Distribution	Pearson's correlation	Anderson-Darling statistic
Exponential	N/A	2.716
Lognormal(e)	0.984	0.759
Normal	0.926	1.296
Weibull	0.983	0.888

Multiple Linear Regression

Multiple regression was used to develop a mathematical model which represents the linear relationship between two or more independent, or explanatory, variables and a dependent, or response, variable (Ott and Longnecker 2001). This general linear model is expressed as:

$$Y = B_o + B_1X_1 + B_2X_2 + \dots B_kX_k + e\ ,$$

where y is the dependent variable, B_o is the y-intercept, B_1 is the coefficient of X, an independent variable, and e is the error term. Regression calculates a "best fit" line through the plot of Y vs. the Xs as described by the resulting equation. The equation indicates the scale and direction of influence of each explanatory variable on the response. Values for Y may also be predicted by the equation in relation to changes in the X values.

Variable Selection

Correlation among variables

One of the first steps in regression analysis is determining which variables to include. Relationships between each of the variables were investigated by examining the correlation between each variable and all other variables in the dataset. A Pearson's correlation coefficient matrix was generated that contains all the variables and which displays the coefficients and their associated p-values for assessing statistical significance (Table 3-3). Coefficients, which may be negative or positive and range from -1 to 1, measure the strength of the correlation between two variables and are useful in determining if potential problems of collinearity may occur. A coefficient of 0.90 or above is considered a level where collinearity, or severe correlation between independent variables, is likely. In this case, one of the two variables should be removed from the analysis (Ott and Longnecker 2001). The correlation coefficient matrix generated with the study variables revealed no potential problems of collinearity.

Table 3-3. Correlation matrix of variables used in the regression analyses

	ACRES	0D RAIN	1D RAIN	7D RAIN	STR-PRV	STRIKES	1-MO RAIN	3-MO RAIN
0D RAIN	-0.193[a]							
	0.326[b]							
1D RAIN	-0.118	0.021						
	0.551	0.914						
7D RAIN	0.104	0.102	0.385					
	0.599	0.606	0.043					
STR PRV	-0.115	0.557	0.226	0.323				
	0.585	0.004	0.277	0.115				
STRIKES	-0.153	0.143	-0.137	-0.143	0.193			
	0.464	0.497	0.514	0.494	0.354			
1MO RAIN	0.482	-0.033	0.097	0.509	-0.057	-0.213		
	0.008	0.869	0.622	0.006	0.786	0.307		
3MO RAIN	0.307	-0.012	-0.126	0.423	-0.291	0.062	0.758	
	0.112	0.952	0.532	0.028	0.158	0.769	0.000	
6MO RAIN	0.264	-0.010	-0.135	0.456	-0.270	0.055	0.698	0.938
	0.175	0.960	0.500	0.017	0.192	0.794	0.000	0.000
12M RAIN	0.161	-0.130	-0.036	0.396	0.072	0.233	0.383	0.472
	0.412	0.518	0.860	0.041	0.731	0.262	0.044	0.011
ANN RAIN	0.503	-0.075	-0.166	0.280	-0.198	0.154	0.436	0.402
	0.006	0.710	0.409	0.157	0.343	0.464	0.020	0.034
FI	0.429	-0.308	-0.202	-0.071	-0.114	0.061	0.361	0.224
	0.059	0.186	0.394	0.767	0.632	0.798	0.117	0.342
PRV BRNS	-0.103	0.005	0.199	0.066	0.165	-0.269	-0.212	-0.361
	0.580	0.982	0.310	0.739	0.429	0.193	0.270	0.059
KBDI	0.114	0.401	0.117	0.211	0.615	-0.291	0.525	-0.641
	0.699	0.155	0.692	0.469	0.019	0.313	0.054	0.013
JULIAN	0.153	-0.134	-0.272	0.009	-0.585	-0.049	0.431	0.748
	0.410	0.495	0.161	0.964	0.002	0.815	0.020	0.000

[a] denotes correlation coefficient, r
[b] denotes p-value

The p-value associated with each correlation is also important since it indicates the statistical significance for the test of the hypothesis that the coefficient is different from 0. An alpha level of 0.10 was used as a standard for selecting potential variables for the regression analysis. ACRES, was correlated with FI (r = 0.429, p-value = 0.059) and 1-MO RAIN (r =0.482, p-value = 0.008). JULIAN was significantly correlated with several variables but not with the response variables of interest, ACRES or FI, and was not included in the regression analysis. Similarly, 3-MO RAIN, 6-MO RAIN, and 12-MO RAIN were all significantly correlated with each other and 1-MO RAIN but were not correlated with the response variables ACRES or FI. Correlations were also assessed on a dataset which contained variables associated with aggregated annual sums (Table 3-4). PB ACRES, the total acres prescribed burned in a year, was significantly correlated with NUM WILDFIRES (r = -0.507, p-value = 0.077) and ANN RAIN, or total annual rainfall (r = 0.506, p-value = 0.078).

Table 3-4. Variables used in the regression analysis of NUMFIRES

Variable	Description
NUMFIRES	Total annual number of lightning-fires
AC L-F	Total annual acres burned in lightning-fires
AC PB-LS	Total annual acres prescribed burned May 1-August 31
AC PB	Total annual acres prescribed burned
ANN RAIN	Total annual rainfall

Data transformations

Each selected variable was examined with a plot of the residuals versus the predicted values and normality plots of the residuals derived from an initial regression calculation. Residuals for ACRES, FI, and 1-MO RAIN were not normally distributed and the data were transformed by calculating the natural log of each value. The resulting residuals were normally distributed, thereby satisfying one of the assumptions of regression analysis.

Model Selection--FI

The selection of the "best" model was a step-wise process beginning with variable selection. Candidate variables identified in the correlation matrix were added to the regression model with FI as the response variable and the equation was calculated. Variables were removed one at a time from the model and the analysis was run again with each new set of variables. Models for which the regression was significant at $p < 0.10$ were retained for further assessment. Ultimately, Akaike's Information Criterion (AICc), corrected for small sample size (Burnham and Anderson 1998), was used as the final determination of the "best" model. The model with the lowest AICc is judged as "best". AIC is a model selection technique which serves to choose models with a balance of error variance and number of independent variables. Models with high error variance and/or more variables result in a higher AIC score.

Table 3-5 includes the resulting models with their associated p-values, R^2 value, and ranked by AICc. The "best" model (FI--1) describes FI of lightning-fires as a function of the size of those fires. The model estimated that FI increased as acreage of lightning-fires increased. The competing models include variables 12-MO Rain or 1-MO RAIN in the regression equation and approached statistical significance based on their p-values. These models indicate that with lightning-fire acreage held constant, FI increased as rainfall amounts increased. Statistically insignificant t-tests for the individual weather variables (12-MO $p= 0.503$, 1-MO $p = 0.689$) provided evidence that the size of the lightning-fire was a more important predictor of FI than weather parameters. Model FI-1 had a lower R^2 than the other two models, yet it exhibited the highest R^2(adjusted) value, indicating it possessed the greatest predictive strength of the three models. In addition, FI-1 had the most significant regression P-value (0.034). The R^2 of 22.6% for model FI-1 means the model explained 22.6% of the variation in FI.

Table 3-5. Regression models for FI ranked by AICc

Model		$P_{(model)}$	Coefficient	SE	p-value	$R^{2(\%)}$	AICc
FI-1	Constant (B_0)	0.034	24.33	7.53	0.005	22.6	184.84
	lnACRES		6.21	2.71	0.034		
FI-2	Constant	0.090	2.30	33.09	0.946	24.7	186.76
	lnACRES		6.09	2.76	0.041		
	12-MO RAIN		0.60	0.88	0.503		
FI-3	Constant	0.104	22.10	9.46	0.032	23.4	187.10
	lnACRES		5.74	3.01	0.073		
	ln1-MO RAIN		3.51	8.61	0.689		

Model Selection--Lightning-fire Acres

The same model selection process described above was used to determine the "best" model to describe size of lightning-fires. Plots of the residuals versus the variables and the residuals versus the predicted values indicated that transformation of the response variable, ACRES, was required. ACRES was natural log transformed (ln ACRES) and the plots of the residuals were deemed appropriate. Based on the lowest AICc score, the "best" model was AC-1 (Table 3-6) which included 1-MO RAIN and FI as predictors of lightning-fire size. The model revealed that ACRES increased as either 1-MO RAIN or FI increased. FI (p = 0.056) was a more significant predictor of lightning-fire size than 1-MO RAIN (p = 0.101). The competing models were significant at the alpha = 0.05 level, although model AC-1 had the highest R^2 value (31.7%).

Table 3-6. Regression models for ACRES ranked by AICc.

Model		$P_{(model)}$	Coefficient	SE	p-value	$R^{2(\%)}$	AICc
AC-1	Constant (B_0)	0.039	-2.78	1.98	0.178	31.7	82.01
	lnFI		1.15	0.56	0.056		
	ln 1-MO RAIN		1.00	0.58	0.101		
AC-2	Constant	0.050	-2.16	2.05	0.306	19.6	82.81
	LnFI		1.24	0.59	0.050		

Model Selection--Number of Lightning-fires

A single model of regression statistical significance ($p < 0.10$) was developed which explained the relationship between the response variable NUM FIRES and independent variables derived from annual sums. The model was estimated as:

$$\text{NUM FIRES} = 4.09 - 0.000278\ \text{AC PB} \qquad R^2 = 23.8\% \qquad p = 0.091$$

The model indicates that the annual number of lightning-fires decreased as the total annual acreage of prescribed burns increased. Addition of either variable annual rainfall or lightning-season prescribed burn acres to the model resulted in a statistically insignificant regression and substantially increased error variance. Logically, the annual total acres burned in lightning-fires was strongly correlated with NUMFIRES, but the variable was omitted from the regression analysis because no new knowledge would be gained by including it. The model's low R^2 of 23.8% is indicative of the wide variation in the occurrence rate of lightning-fires on an annual basis. Figure 3-4 illustrates that variability, expressed in annual lightning-fire acres, though the trend toward decreasing lightning-fire acres with increasing annual prescribed burn acres is evident.

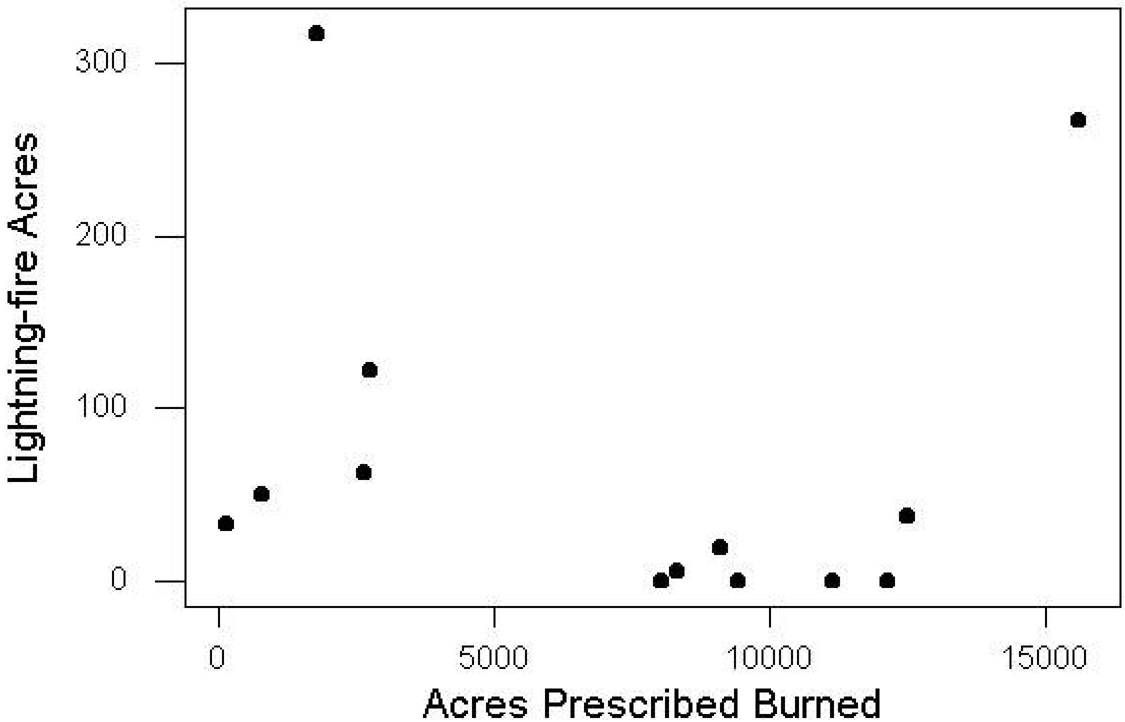

Figure 3-5. Annual acres prescribed burned by annual acres of lightning-fires.

CHAPTER 4
DISCUSSION

Prescribed Burns

Over 78% of the GSWP was included in a burn unit and burned at least once during the study period. The GIS provided a means to visualize the distribution of burns and to observe that essentially all of the property, except river floodplains and large swamps, was treated with prescribed fire. Pine flatwoods represented the greatest proportion of the landscape types in burn units which is not surprising given that pine flatwoods is the predominate upland habitat in the GSWP and is a fire-dependent ecosystem (Myers and Ewel, 1990). Though burn units also contained a large proportion of cypress and forested wetland systems, it is important to note that it was impossible to determine if those landscapes actually burned or whether water levels or moisture gradients prevented fire from entering those wetlands. Notes contained within many burn plan evaluations indicated that, in most cases, those wetlands were inundated or “damp” and therefore did not burn.

As established by this study, Prescribed burns tended to have occurred more outside of the lightning-season than within. Roughly 18.5% of the total number of burns, or 14.0% of average annual acreage, were conducted during the lightning-season. Certain landscapes were specifically burned outside the lightning-season to achieve planned objectives. For example, pine plantations were burned in winter to avoid mortality and the resulting economic loss in timber revenue (Elliot, pers. comm.). The smallest burn units (e.g. 15 ac) were pine plantation “pockets” which were separated out from surrounding landscapes and burned in winter. In most cases those small burns were conducted on the same date with several other burns.

Lightning-fires

Over one-third (n = 11) of the 31 lightning-fires which occurred during the study period were located outside of burn units. Four lightning-fires were located on sites which had reportedly either experienced a previous wildfire or prescribed fire (Elliott, pers. comm.), however those data were not available for verification. An average of 0.91 fires/yr were detected in areas known to have previously burned by prescription. Those 47.3 ac/yr were equivalent to 0.14 fires/10,000 ac/yr. Compared to north-Florida (Busby and Haines 1963), the GSWP experienced a lower rate of lightning-fire ignitions. They found a rate of 0.51 fires/10,000ac/yr (421.5ac/10,000ac/yr) for lightning-fires during their 4-year study period. Though the north-Florida study area was managed with prescribed fire, greater numbers and larger sizes of wildfires occurred on areas with a FI in excess of five years. The shorter average FI for prescribed burns on GSWP may explain the reduced lightning-fire occurrence rate experienced there. Davis and Cooper (1963) also reported that the probability of a wildfire occurrence and the acreage of the fire increased dramatically after five years since a previous burn. The results of this study indicated that lightning-fire size tended to increase over time but the probability of an occurrence appeared to peak at around 30 mo and declined thereafter. Rather than an inherent decrease in the flammability of the landscape >30 mo post-burn, however, prescribed burn frequency may have reduced the likelihood of a lightning strike contacting areas which had not burned in more than three years.

Hypothesis #2 ($H_{(2)}$) was that the FI distribution of lightning-fires would be best described by the Weibull frequency distribution. Though the data did fit the Weibull distribution well, the lognormal (base e) distribution fit the data best. This finding lends credence to the premise posed by McCarthy et al (2001) that the Weibull distribution should not be assumed a priori as the most accurate description of fire frequency for a given area. They argue that, biologically, it may make no sense to assume that FI would follow a distribution based on the probability of a wildfire as a power function of time since last burn ($h_{(t)} = ht^{\wedge b}$). In this study, FI appeared to have been strongly influenced by the frequency and the extent of prescribed burns. Were it possible to allow lightning-fires to burn unimpeded, over a significant time-period and in the absence of prescribed burns, a completely different FI distribution may emerge.

It is important to note that the wildfire reports pertaining to nearly all of the lightning-fires included some reference to fire suppression. This means that the size of those fires was influenced by human activity designed to stop fire spread. Correlations between fire size and FI or weather parameters were probably impacted as a result. Additional variation was induced by factors such as a) time from fire detection to suppression response and b) time required to suppress the fire. Those factors may help to explain the relatively low R-sq values (22.6%-31.7%) obtained in the regression analyses.

Lightning-fires occurred more frequently in pine flatwoods, wet prairie, and planted pine landscapes than those types existed across the GSWP. Planted pine areas were more than twice as likely, proportionately, to be associated with a lightning-fire than their availability would suggest. Pasture, mixed conifer and hardwood forest, and disturbed areas were under-represented as components of lightning-fires in relation to the GSWP as a whole. A lack of trees to act as lightning rods in pastures probably explains the reduced involvement of that landscape type.

Regression Analyses

Fire Interval

Fire interval was only significantly correlated with ACRES, and while the relationship was statistically important (p =0.059), the strength of the correlation was not strong (0.492). The regression equation with the lowest AICc score reflected that correlation in that ACRES was the only predictor variable included in the model. The regression was significant at the alpha = 0.05 level indicating that the model has predictive value and, therefore, the size of a lightning-fire was a function of FI. The model predicts that FI increases as the size of lightning-fires increase. This implies that the longer a given area goes without being burned the larger a wildfire will be when it occurs there.

Model FI-2, the second "best" model as determined by AICc, included 12-MO RAIN as the second predictor. The coefficient was positive (0.603) indicating that FI increased by 0.6 mo as 12-MO RAIN increased by one inch of rainfall. Statistical significance was approached (p = 0.090) but the R^2(adj) value of 15.8% meant that the model had low predictive value.

Only 22.6% of the variation in FI was explained by the FI -1 model. Fire suppression efforts, undertaken by the Florida Division of Forestry, which controlled the size of lightning-fires and were a function of time to begin and to complete fire control, probably accounted for much of the variation in FI not explained by the model. The actual effect of lengthened FI on the size of a lightning-fire was therefore distorted by fire suppression efforts and the effect could not be definitively ascertained from the available data.

Size of Lightning-fires

Hypothesis #3 ($H_{(3)}$) postulated that landscape type has greater influence on ACRES than time since last burn, which has greater influence than climate variables. The variable FWPROP, the proportion of Flatwoods in an individual lightning-fire, was used as an indicator of landscape type influence because it was the most prevalent category. This hypothesis was tested indirectly through the regression analyses. The regression coefficient and individual t-test for FWPROP were an indication of the influence and predictive significance, respectively, of FWPROP on ACRES. Those results indicate that $H_{(3)}$ was false and that FI and 1-MO RAIN had greater influence than landscape type.

ACRES was significantly correlated with FI and 1-MO RAIN. Both correlations were positive but were not strong and neither relationship exceeded a Pearson's correlation coefficient of 0.500. Model AC-1 included both of those variables and was statistically significant as a prediction equation ($p = 0.039$). This model explained 31.7% of the variation in ACRES and predicts that the size of a lightning-fire increases as FI increases - a conclusion already indicated in model FI-1. It is likely that the low R-sq. value was partly a result of the variability introduced due to fire suppression activities. Much of the variation in ACRES may have been a result of reduced distance to access roads, suppression tactics and other variables not accounted for in this study.

Surprisingly, this model also implies that the size of a lightning-fire increases with increasing 1-MO RAIN (indicated by the positive Pearson's correlation and regression equation coefficient). This finding would appear contrary to established fire behavior models and fire danger indices. Rainfall increases soil and vegetative fuel moisture levels which in turn reduce fire danger indices such as KBDI (Keetch and Byram 1968) and decreases predicted fire spread rates (Finney 1998). Together, both models predict that increased rainfall tends to decrease a fire's potential in terms of initial ignition and in acreage burned.

This anomaly of increased near-term rainfall correlating with increased ACRES may be related to the cause of the fires - lightning. Increased rainfall may have simply been an indicator of increased lightning, without which no lightning-fires would have occurred. Though lightning-fires are often thought to be a result of "dry" lightning strikes (strikes not associated with rainfall), the data show that rainfall was recorded in the month prior to all but one occurrence date (6/21/00). It is important also to note that lightning-fires tended to occur on days with little lightning activity as compared to the days preceding the occurrence. It is likely that during rain events lightning strikes may have resulted in an ignition of fuel which only smoldered as a result of high relative humidity and fuel moisture due to the rain. Smoldering may have continued for several days before conditions allowed the smolder to advance to flaming ignition and ultimately a lightning-fire occurrence.

Suggestions for Future Research

The use in this study of a GIS to develop a database of prescribed burns and lightning-fires on GSWP creates opportunities for further research. The database can be easily updated as prescribed burns are conducted and additional lightning-fires occur. Wildfires from other causes can be included and the database can be updated regarding additional management activities. Empirical fuel load descriptors could be incorporated as those data are collected. Spatial and temporal aspects of wildfires may then be investigated relative to a wider range of parameters than were examined in this study.

Future research should focus on the effects of human-related factors on lightning-fire size. Aspects such as response time to initiation of suppression and completion of suppression actions should be incorporated in the analysis. The suppression tactics used to control the fire could be captured as factors. Distance from the fire to main roads and secondary roads should be included as variables, an action easily accomplished with the GIS.

Incorporation of more spatially explicit weather and lightning strike data should be pursued. Whereas this study relied upon one rainfall-recording sensor, radar and other remote sensing technologies can produce rainfall estimates with much greater spatial resolution. Lightning strike data bearing polarity and amperage tied to geographic coordinates could be applied in the analysis of lightning-fire occurrences.

Alternative approaches to the study of lightning-fires may include the design and establishment of applied experiments. Various and replicated applications of specified prescribed fire return intervals and/or silvicultural treatments could be evaluated over time relative to lightning-fire occurrence. These experiments and the other suggested investigations could be accomplished with an expanded research association between the SWFWMD and the University system.

CHAPTER 5
MANAGEMENT IMPLICATIONS

Prescribed fire was used on the GSWP as the main management tool by the SWFWMD Land Management staff for the stated purposes of ecosystem enhancement and wildfire hazard reduction (Love pers comm). In comparison to the north Florida study done by Davis and Cooper (1963) on a national forest managed with prescribed fire, results indicate that the rate of lightning-fire ignitions and the acreage burned in lightning-fires was further reduced by the extent of the prescribed burn program on GSWP. Those results are notewothy given that the scope of this analysis was 20+ yr, including prolonged periods of drought, and the north Florida study was 4 yr. It appeared that one major difference in the two study sites was that 48.7% of the north Florida property consisted of landscapes unburned for over 5 yr. In contrast, the majority of the GSWP was maintained at less than 4 yr as indicated by the mean FI for prescribed burns of 3.8 yr. Continuation of the current prescribed burn program, in terms of the FI and extent across the landscape, will likely maintain lightning-fire ignitions and acreages at historic levels.

The benefits of properly executed prescribed fire to Florida's ecosystems are well documented, particularly for endangered plants (Breininger and Schmalzer 1990) and animals (Maehr et al 2001). Burns which occur during the lightning season, primarily May-August, are concurrent with the growing season for plants and have been shown to be especially beneficial in stimulating the flowering and fruiting of native species (Robbins and Myers 1992). Priority should be given to conducting more lightning-season burns on the GSWP. As a percent of the total acres burned annually, lightning-season burns comprised from 0% to a maximum of 38.8% in 1999. In addition, lightning-fires should be allowed to burn to their natural conclusions when possible. Those fires which occur under acceptable prescription parameters for prescribed fires, for example, could be monitored by trained fire managers to assure that objectives are met and suppression is applied only where necessary to prevent smoke problems or other perils.

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BIOGRAPHICAL SKETCH

Darrell Lee Freeman was born in Texarkana, Texas, on 26 May 1959. In 1981 he received a B.S. in wildlife and fisheries sciences from Texas A&M University. After graduation Darrell owned and operated a landscaping business in Florida until 1992 when he started a naturalist guiding and consulting operation in Arizona. In 1996 he began work as a land manager for the Southwest Florida Water Management District in Florida. In May 2004 he completed requirements for the Master of Science degree, at the University of Florida. Darrell is married to his wife, Trish, with no children.