EFFECT OF WILDFIRE AND SHELTERWOOD TIMBER-HARVESTING ON THE VEGETATED LANDSCAPE OF SAPELO ISLAND, GEORGIA, 1994 - 1999

by

DAVID ALLAN MARR

(Under the Direction of Thomas W. Hodler)

ABSTRACT

The effects of timber-harvesting and wildfires on the vegetated landscape were compared using 1999 color infrared Digital Orthophoto Quarter Quads (DOQQs) for Sapelo Island, Georgia. ERDAS Imagine 8.5 was used to sub-set and classify the DOQQ's for analysis using ArcView 3.2, the Patch Analyst extension and the FRAGSTATS interface. The landscape metric variables that were produced from FRAGSTATS were analyzed using a multiple one-way ANOVA, Tukey's multiple range test. The results from this study indicate that shelterwood timber-harvesting and wildfires are having a similar effect on the vegetated landscape of Sapelo Island. Both disturbances increase the landscape fragmentation, patch uniformity and core area edges but decrease the relative variation in patch size and interior core area.

INDEX WORDS: Timber-harvesting; Wildfire; Color Infrared Aerial Photography; Sapelo Island, Landscape Metrics.

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DEDICATION

I dedicate this thesis to my wife, Christy Deanne Marr, who has supported me through this entire endeavor and to my father, William F. Marr, Jr., who baby-sat my daughter, Morgan Marr, every weekday while I attended graduate school.

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TABLE OF CONTENTS

Page

LIST OF TABLES

Page

LIST OF FIGURES

Page

CHAPTER 1: INTRODUCTION

In most forested areas of the United States, the effects of naturally occurring disturbances, such as wildfires and un-naturally occurring disturbances, such as timber harvesting can be observed on the landscape. This thesis addresses the hypothesis that wildfires and timber harvesting are having similar effects on the vegetated (patch) landscape of Sapelo Island, Georgia. Numerous techniques involving an un-supervised computer classification and air photo-interpretation of digital, color infrared aerial photography will be used to quantify and analyze the vegetated landscape.

1.1 LANDSCAPE

The landscape may be defined as "a heterogeneous land area composed of a cluster of interacting ecosystems." (Forman and Godron, 1986, 11) Landscapes have a variety of characteristics. They may vary in size down to a few kilometers in diameter and the principles of landscape apply to mosaics at any level of scale. The landscape is measurable, defined by its recognizable and spatial clusters of ecosystems and disturbance regimes (Forman and Godron, 1986; Zonneveld, 1990). Additionally, "each individual ecosystem at the scale of a landscape can be recognized as a patch with significant width…determining these spatial distributions is to understand landscape structure." (Forman and Godron, 1986, 25).

Landscapes can generally be thought of by their land use and land cover characteristics. Land use is determined by categories of human use of the landscape, such as urban,

transportation, agricultural or industrial uses while land cover relates to the natural characteristics of the physical landscape, such as vegetation type, bare ground, water, etcetera. Landscapes studied form an applied landscape ecology perspective should be rigorous, quantitative and empirical (Wiens, 1992). Field-based studies and remote sensing techniques, such as aerial photograph interpretation are both capable of empirically quantifying the landscape (Naveh and Lieberman, 1984). Based upon the resolution of such aerial photography, the landscape can be sub-divided into many small polygons that are referred to as patches. Patches may be combined to form a mosaic, or a cluster of smaller patches which contain similar landscape features (McGarigal and Marks, 1995).

1.2 EFFECTS OF FIRE ON VEGETATION

Prescribed fires affect the vegetated landscape in different ways depending on the characteristics of the fire, time of year of the occurrence and the forest type (Kelly, 1998). The effects of fire on vegetation are highly variable and difficult to measure. Generally, fire tends to either reduce the amount of vegetation or simply kill the vegetation outright. There is a correlation between the intensity of the fire and tree mortality. Fires with higher intensities produce a higher tree mortality rate (18-30%), whereas, moderate to low intensity fires produced almost no change in the overstory (Elliott *et al*., 1999). As a result of high intensity wildfires, vegetation has either had its inner bark, nutrient-carrying layers destroyed or its roots damaged to the point that the tree will eventually die. Abrahamson (1984a) and Breininger and Schmalzer, (1990*)* found that fire creates gaps in the vegetated landscape, allowing other species to grow, affecting the ecological and biological diversity of the landscape.

1.3 COLOR INFRARED (CIR) AERIAL PHOTOGRAPHY

Large-scale CIR aerial photography has been used widely for vegetation mapping (Welch *et al*., 1992; Cousins and Ihse, 1998; Kadmon and Harari-Kremer, 1999; Nilsen *et al*., 1999; Coulter *et. al*., 2000; and Stow *et al*., 2000). Smith (2001) analyzed historic vegetation changes in two Georgia estuaries using aerial photography and geographic information systems (GIS). Results from these studies indicate that CIR aerial photography can be used successfully to map vegetation and to assess the health of vegetation. Vegetation that has been severely damaged or killed by fire typically appears as yellow on CIR aerial photography (Philipson, 1997). CIR aerial photography has been commonly used also to visually identify the different types of vegetation, such as distinguishing hardwoods from conifers (or even between species). Vegetation can be classified based on the aerial photo-interpretation of the visual elements of aerial photographs (tone, texture, size, shape, height, shadow and association of the vegetation). Such classifications can be made either manually via visual analysis or by using computer software that permit you to define land use/land cover characteristics and allow the software to classify those data in digital form.

Vegetation mapping can be performed using both aerial photographic interpretation and field-based measurements. Aerial photography provides the best measure of the canopy boundary extents while fieldwork provides information, such as the tree species, that may be difficult or impossible to obtain from aerial photography, depending on the scale of the photography (Fox *et al*., 2000).

1.4 STUDY SITE SELECTION

Sapelo Island was chosen as the study site for five reasons: (1) its well-documented history of wildfires and timber management practices; (2) its restricted access to the public and its limited commercial development; (3) its relatively close proximity to Athens, Georgia (about 402 kilometers); (4) its logistical support for researchers in the form of housing and vehicles at The University of Georgia Marine Institute (UGAMI); and (5) availability of financial support from the Georgia Department of Natural Resources (GDNR) for investigating the effects of wildfire on the vegetation of Sapelo Island. Sapelo Island has been an area of extensive research since the 1950's. There have been more than 800 scientific papers and articles published by resident and visiting researches at the UGAMI. Most of these publications address the ecology of the marshes.

1.5 RESEARCH OBJECTIVE

The objective of this study was the comparison of the effects of wildfire and timber harvesting on the vegetated landscape of Sapelo Island using CIR aerial photography. Analysis of digital CIR aerial photography provided the data needed to statistically determine differences between wildfire and timber harvesting disturbances of the vegetation. Four classification categories of disturbance types were used to assess the effects of wildfire and timber harvesting using CIR aerial photography (Table 1-1). These categories consisted of four combinations of timber harvesting and/or wildfire conditions.

Table 1-1. Vegetation disturbance classification categories for study sites on Sapelo Island, Georgia, 1994 to 1999[1]

	Wildfire	No Wildfire
Timber Harvest	**WT**	**NWT**
No Timber Harvest	**WNT**	**NWNT**

[1] WT= Wildfire and timber harvest; NWT= No wildfire, timber harvest; WNT= Wildfire, no timber harvest; NWNT= No wildfire, no timber harvest.

These four disturbance categories were determined based upon both fieldwork (conducted during the summer of 2002) and analysis of aerial photographs for the years 1994 and 1999. On-site analysis, identification and mapping of the vegetation produced land cover characteristics (see Chapter 3) that were used in defining the four categories.

Category WT contained areas that had been both burned by wildfire and timber harvested between 1994 and 1999, based on existing wildfire and timber harvest records. This category assessed the combined effects of both wildfires and timber harvesting on the vegetation.

Category NWT contained areas that were timber harvested but not burned by wildfire. By comparing Category WT to Category NWT an analysis of the effects of wildfire on areas that had also been timber harvested could be made.

Category WNT contained areas that had been burned by wildfire but not timber harvested, from 1994 to 1999. This category would help determine the effects of timber harvesting on areas that had been burned by wildfire.

Category NWNT contained sites that had neither been burned by wildfire nor timber harvested. This category was a control group.

1.6 RESEARCH HYPOTHESES

Six statistical hypotheses were formulated for analysis. These hypotheses were:

1. Wildfire will not produce different patches in the vegetated landscape of Sapelo Island that has been timber harvested. (Note: H_0 is null hypothesis, H_A is alternate or research hypothesis)

H_0: Category WT = Category NWT
H_A: Category WT ≠ Category NWT

2. Wildfire will not produce different patches in the vegetated landscape of Sapelo Island that has not been timber harvested.

H_0: Category WNT = Category NWNT
H_A: Category WNT ≠ Category MWNT

3. Timber harvested areas will not produce different patches in the vegetated landscape of Sapelo Island that have been burned by wildfire.

H_0: Category WT = Category WNT
H_A: Category WT ≠ Category WNT

4. Timber harvested areas will not produce different patches in the vegetated landscape of Sapelo Island that have not been burned by wildfire.

H_0: Category NWT = Category NWNT
H_A: Category NWT ≠ Category NWNT

5. There will not be different patches in the vegetated landscape that: 1) have not been burned by wildfire; and 2) timber harvested versus areas that: 1) have been burned by wildfires; and 2) not been timber harvested.

H_0: Category NWT = Category WNT
H_A: Category NWT ≠ Category WNT

6. There will not be different patches in the vegetated landscape that: 1) have been both burned by wildfire; and 2) timber harvested versus areas that: 1) have not neither been burned by wildfire; nor 2) timber harvested.

H_0: Category WT = Category NWNT
H_A: Category WT ≠ Category NWNT

CHAPTER 2: LITERATURE REVIEW

2.1 LOCATION AND CLIMATE

Sapelo Island is located 96 km southwest of Savannah, Georgia (Figure 2-1). This barrier island is approximately 4.8 x 16 km in dimension and covers 76.8 km^2 of land. Its climate is humid sub-tropical with short, mild winters and long, hot humid summers. The temperatures are moderated by a maritime influence. Rainfall is heaviest during the summer months with an average total annual rainfall of 1300 mm. On average, none of the months receive less than 25 mm of precipitation (Chalmers, 1997).

2.2 HUMAN INFLUENCE

In the early 1800s, Thomas Spalding became the owner of all but a small portion of the island and cleared much of the land for cultivation or pasture. A network of ditches and canals, still evident today, were dug to drain the swampy interior of the island. Most of the original forests of Sapelo Island were harvested and disappeared during the 1800s. By the early 1900s, many of the cultivated fields had reverted back to forest. Howard E. Coffin purchased most of Sapelo Island from its various owners in 1912 and then sold the island to Richard J. Reynolds in 1934. In 1969, Anne Marie Reynolds negotiated the sale of Sapelo Island to the State of Georgia (Georgia Dept. of Natural Resources, 1999). Presently, the State of Georgia owns the entire island with the exception of Hog Hammock, a community covering approximately 175 ha (Chalmers, 1997).

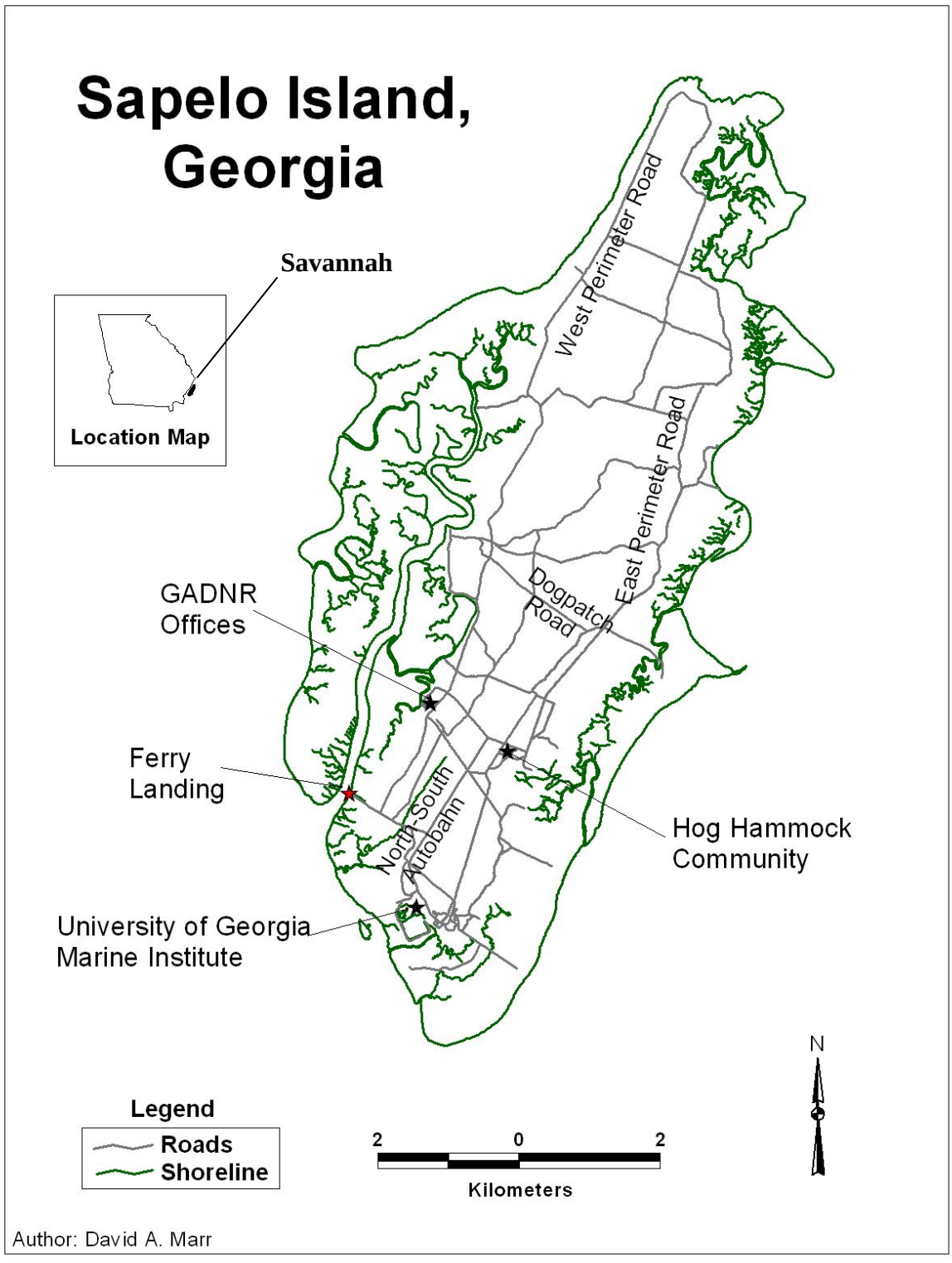

Figure 2-1. Location of Sapelo Island, Georgia, 2003. Source: GDNR data.

The main shift from private to public ownership occurred when the R.J. Reynolds Wildlife Refuge, comprising roughly the northern two-thirds of the island, was purchased using funds from the federal government Pittman-Robertson Wildlife Restoration Act (75% federal/25% state contribution). The Sapelo Island National Estuarine Research Reserve (SINERR) was established in 1976 on marsh lands in the southern and western sections of the island with funds contributed equally from the National Oceanic and Atmospheric Administration (NOAA) and the State of Georgia. The primary purpose of the SINERR is to protect the natural and cultural resources of the island and to provide research opportunities (Georgia Dept. of Natural Resources, 1999).

2.3 LAND USE/LAND COVER/DATA SOURCES

The term land use commonly refers to "human activity or economic function associated with the land" (Lillesand and Keifer, 2000: 208). Land use is inferred indirectly from the aerial photography, based upon the direct observations of land cover types (Philipson, 1997). A well-known classification scheme used in land use/land cover mapping is the Anderson classification system developed by the United States Geological Survey (USGS) in the 1970s (Anderson *et al.*, 1976). The system has four levels (or categories) of classification titled Level I to Level IV (Table 2-1).

Whereas land use is indirectly inferred from the land cover on aerial photography, land cover is identified from direct observation of the aerial photography. The term land cover refers to the type of feature present on the surface of the earth (Lillesand and Keifer, 2000). Examples of land cover include the type of vegetation, such as grasslands or forest such as pine or hardwood. Also, land cover lacks emphasis upon its role in serving human needs. For example,

when viewing a four-lane highway on an aerial photograph, we can see from direct observation that the land cover is roadway. From indirect observation or inference, we would say that the land use is transportation. The land cover type can be determined based on such photographic elements as object texture, tone, size, height, shadow, shape, pattern and association (Philipson, 1997). An essential component of this study is the production of land cover maps for each of the 48 sample sites identified in this research.

Table 2-1. Anderson Classification System. Source: Anderson *et al.*, 1976

Land use/land cover	Level I	Level II	Level III	Level IV
Example	4. Forest	4.1 Deciduous 4.2 Evergreen 4.3 Mixed	User-specific	User-specific
Suitability	Very-high altitude, Satellite data (LANDSAT)	High-altitude, Small scale aerial photos	Medium-altitude, Medium-scale aerial photos	Low-altitude, Large-scale aerial photos
Map scale	1: 500,000	1: 500,000 to 1: 80,000	1: 80,000 to 1: 24,000	1: 24,000 and larger

As the spatial resolution (or level of detail of the photography) increases, the vegetation can be classified to a higher level. This multilevel classification system has been designed based on the different flying heights of the aircraft (or altitude) and the resulting scale of the aerial photographs. For example, the principle source for Level III classifications is medium-altitude, CIR aerial photography, with scales from 1:24,000 to 1:80,000 (Anderson *et al.*, 1976). The land use/land cover classes for Anderson's Level I and Level II classification are provided in Appendix A, for illustrative purposes only. At the Level II classification, reliable photo-interpretation becomes a problem, especially when interpreting aerial photographs with highly complex land-use/land covers, such as dense urban areas or cities. Even at Level III and IV, use

of substantial amounts of supplemental information should be anticipated (for example, detailed field checks or inventories). The 1:40,000-scale CIR aerial photographs taken as part of the USGS National Aerial Photography Program (NAPP) are well-suited for a Level I through Level III classification scheme. Based on Table 2-1, NAPP aerial photographs could be used to classify vegetation on Sapelo Island into Level I (Forest), Level II, (Deciduous, Evergreen or Mixed) or Level III (perhaps specific types of Evergreens, such as Loblolly pine or Slash pine). Even though software programs, such as ERDAS Imagine 8.5 (Leica-Geosystems), can produce land use/land cover classes, based on the radiometric properties (colors or tones) of the aerial photographs, human photo-interpreters are still needed to assign the classes to one of the Anderson classes, such as Deciduous or Evergreen. At any level, the reliability of the classification must be checked by a photo-interpreter and this requires specific knowledge of the types of land use/land cover found on the aerial photographs or on the ground. Even though the Anderson classification system does combine both land use and land cover, it provides a good starting point for designing a user-specific classification system.

Vegetation classification systems should be designed according to the researcher's needs (Madden, 2003). The classification system should take into account the research objectives and be appropriate for the scale of the aerial photography. Since the aerial photography used for this study was based on the 1:40,000 NAPP photos, any level of classification up to and including Level III, would be appropriate. The USGS Digital Orthophoto Quarter Quads (DOQQ's) used for this study were based on these NAPP photos (Table 2-2). Even though the level of spatial detail in an aerial photograph may allow a Level III classification, the limited experience and knowledge of the photo-interpreter may reduce the reliability of the classification to Level II or

even Level I classification. Fieldwork, used in conjunction with the photo-interpretation, improves the accuracy of the classification.

The NAPP CIR aerial photographs that show Sapelo Island were flown in February, 1999. The CIR aerial photographs that were also used for this study were flown in February, 1992 for the GDNR (Georgia Dept. of Natural Resources). These photos were flown at a scale of 1:16,000 for the use of the UGAMI to map the vegetation on and the estuaries around Sapelo Island. The aerial photography contractor that flew the mission for the 1992 aerial photographs could not be determined from available records. The digital, photo-mosaic produced by the author was created by scanning and rectifying the paper contact prints of the 1992 aerial photographs.

Land use mapping involves partitioning an image into discrete areal units, often referred to as polygons, each assigned to a subdivision within a classification (Philipson, 1997). Despite combining land use/land cover in the USGS classification system, a land use/land cover classification map should be designed with the following requirements: (1) repeatable results obtained by different interpreters; (2) valid for extensive areas; (3) the inference of land use from the land cover class; and (4) the potential for sub-dividing categories into more detailed categories (Lillesand and Keifer, 2000). In addition to these requirements, land use maps should also meet the following criteria: 1) the land use map must encompass all regions within the area to be examined; 2) the vegetation within each class must be clearly defined; and 3) the groups of vegetation to be mapped must be able to be categorized into only one, mutually-exclusive class (Philipson, 1997).

Welch *et al.* (1992) created a series of maps of Sapelo Island that have proven to be a valuable resource for resource managers and conservationists. These maps were created directly

from aerial photography and present the land use/land cover of the island. Figure 2-2 is a representation of this land cover in 1987 depicting the diversity of vegetation found on the island. The legend in Figure 2-2 illustrates a user-specific classification scheme that was designed specifically for Sapelo Island, with a particular emphasis on the marsh vegetation surrounding Sapelo Island. There are conceivably an infinite number of classes and classification schemes that could be designed to represent a study area, based on the research design and focus of the study.

In order to appreciate the overall vegetative landscape on Sapelo Island, the land cover present for the upland portion of Sapelo Island (or areas without the marsh) was included in this study. Table 2-2 displays data from a study conducted in 1995 by the GDNR which encompasses 12 habitat types covering areas ranging from <1 to 1332 hectares or up to 31 percent of land use (Table 2-2). Such land cover and area are based on the assessments begun in the 1970's by the Georgia Forestry Commission.

Table 2-2. Habitats of Sapelo Island in 1995. Source: *SINERR Management Plan,* 1999.

Habitat Type	Hectares	Percent Cover
1. Loblolly-Slash Pine	1332	31
2. Oak	763	18
3. Beaches and Dunes	734	17
4. Pond Pine	538	13
5. Openings/Food Plots	342	8
6. Longleaf Pine	165	4
7. Oak-Pine Mixture	140	3
8. Pine-Oak Mixture	106	2
9. Freshwater Ponds	91	2
10. Lowland Hardwood	42	1
11. Cypress	1	<1
12. Sedge Grass Ponds	24	<1
Total	4278	100

A description of the land cover on Sapelo Island in 1995 was based on the Georgia Forestry Commission classification system "General Description of the Eight Major Habitats" (Georgia Department of Natural Resources, 1999). Within the forested areas, the trees are primarily a mix of conifers (slash, loblolly, longleaf, pond pines) and oaks (live, laurel oak). In terms of water, there are man-made dikes, naturally occurring freshwater ponds, and saltwater marshes on the island. The north eastern edge of Sapelo Island is bordered by Blackbeard Island while south eastern Sapelo Island is bordered by the Atlantic Ocean. The Duplin River borders the western edge of Sapelo Island. Beaches and dunes cover the lower half of Sapelo Island along the Atlantic Ocean. The three main residential or commercial areas are: (1) the Hog Hammock Community (residential); (2) the GDNR offices and Post Office (commercial); and (3) the UGAMI (commercial). With the exception of two or three vacation homes at Raccoon Bluff, all three residential or commercial areas occur in the southern third of the island (see Figure 2-1).

The average size of a timber harvest area ranges from 8 – 60 hectares. Commercially mature, 20-25 meters tall, stands of pine saw-timber are harvested when their crowns have closed. Within these pine stands, only loblolly and slash pines are harvested for timber (Belcher, 2003). Twenty-five areas (often referred to as compartments) were timber harvested for 1994, 1996 and 1997 combined. (Figure 2-3). These timber harvest areas were identified from digital maps provided by the GDNR. These maps indicate that no significant timber harvest activities occurred on Sapelo Island for the years 1995 and 1998.

2.4 WILDFIRES (CROWN FIRES)

Crown fires, also known as wildfires, travel rapidly through a forest canopy. They burn extremely hot, killing almost everything above ground (Page, 1983). Crown fires may start

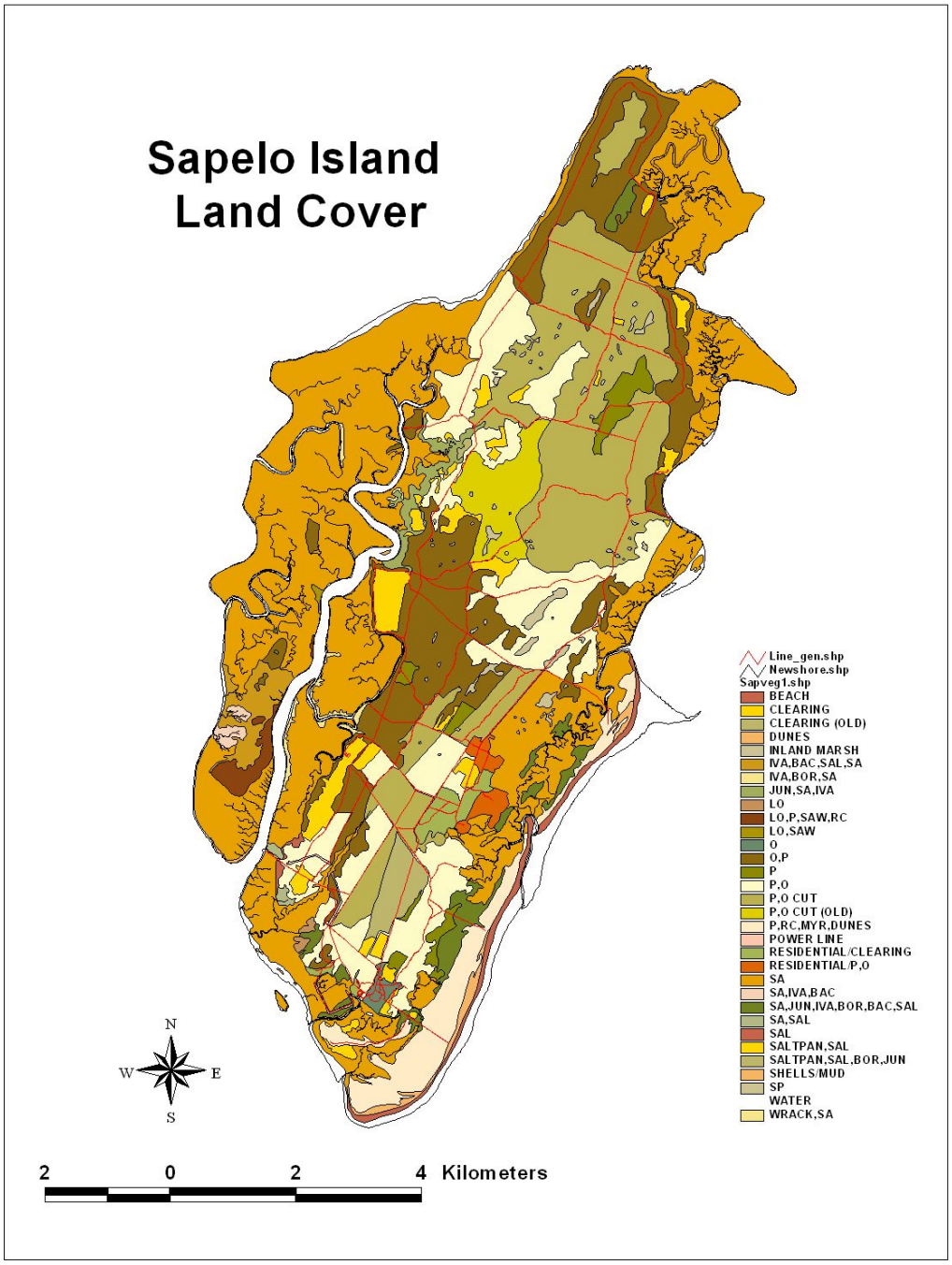

Figure 2-2. Land cover map, Sapelo Island, Georgia, 1987. Source: Center for Remote Sensing and Mapping Science (CRMS). The legend to the right represents the different land cover classes identified by Welch *et al.* (1992). BEACH: beach; CLEARING: open area/grass; DUNES: sand dunes; INLAND MARSH: inland marsh; IVA, BAC, SAL, SA, BOR, JUN, WRACK: marsh vegetation; LO: live oak; O: oak; P: pine; CUT: cleared; MYR: wax myrtle; RC: red cedar; SAW: saw palmetto; SHELLS/MUD: shell and mud deposits; POWER LINE: utility clearing; RESIDENTIAL: urban area; WATER: ocean, creeks; Line_gen: roads; Newshore: shoreline;

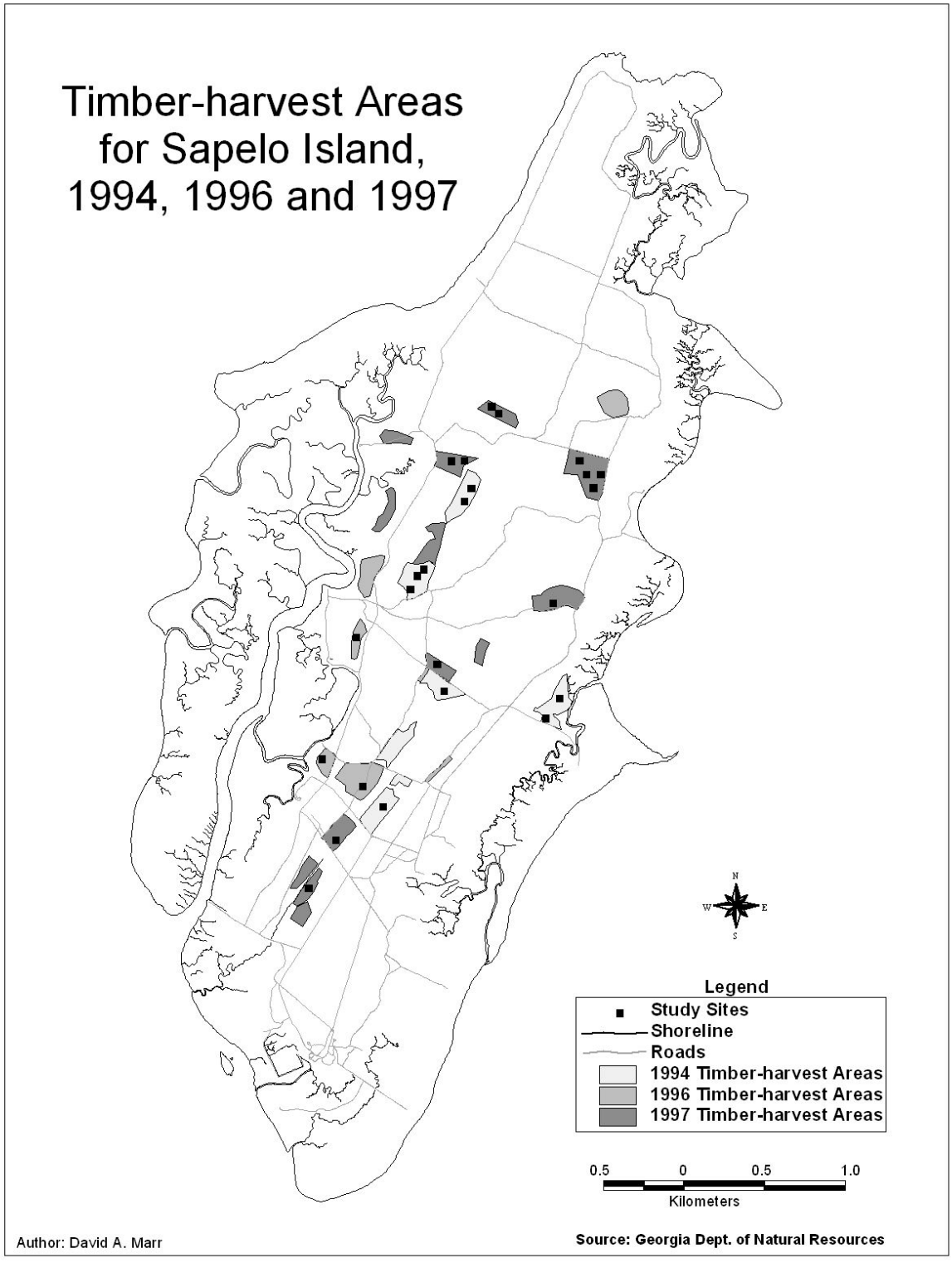

Figure 2-3. Timber harvested areas during 1994, 1996 and 1997, Sapelo Island, Georgia.

naturally as a result of lightning strikes during thunderstorms or from un-controlled, prescribed burns that have become intense surface fires, fueled by heavy accumulations of liter or debris. Crown fires may occur in conjunction with surface fires. A surface fire is generally a less intensive fire than a crown fire and can occur either naturally or as a prescribed fire set and managed for desired fire effect. Prescribed fires are set deliberately in order to reduce the understory, litter or debris that could provide fuel for a crown fire. Prescribed burns also control the growth of sapling hardwoods and promote the growth of fire-intolerant pines, keeping the woodlands more open (DeVos, 2004). To reduce the likelihood of a wildfire and protect the residential areas on Sapelo Island, prescribed fires are frequently set over large areas by the GDNR to burn large areas. Even though one 1998 wildfire started as the result of prescribed burning, the majority of wildfires that have occurred on Sapelo Island began as lightning strikes (Meyers, 2003). Fire records provided by D. Hurley (GDNR), M. Price (UGAMI) and J. Meyers (USGS) were compiled and plotted, creating wildfire maps for areas of Sapelo Island that were burned by wildfires in 1997 and 1998 (Figure 2-4).

2.5 LANDSCAPE HETEROGENEITY AND DIVERSITY

Landscapes have been categorized as being either homogenous or heterogonous. A landscape is homogenous if adjacent groups of elements (or patches) are not significantly different throughout the landscape. Homogenous areas are associated with undisturbed and minimally fragmented landscapes (Forman and Godron, 1986; Turner, 1989). Heterogeneous landscapes are associated with disturbed and fragmented landscapes.

> Heterogeneous landscapes provide more stable dynamics for species sensitive to disturbances and leads to generalist species…the edges of these patches also become more important for the persistence and recovery of

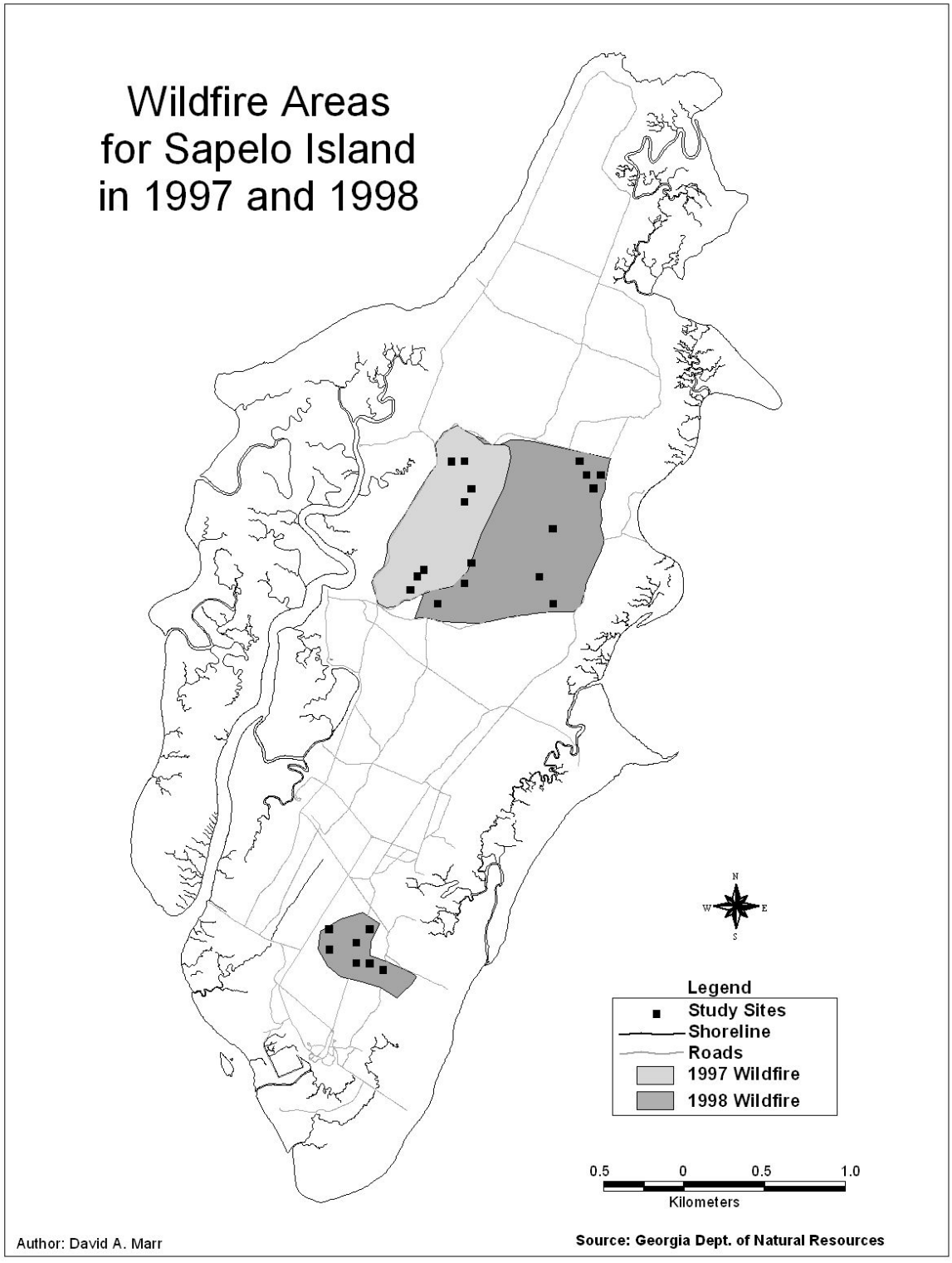

Figure 2-4. Wildfire areas during 1997 and 1998, Sapelo Island, Georgia.

> fluctuating populations, keeping populations on an even density level" (Hansson, 2000, 84).

Heterogeneity can have a significant yet variable effect on different species within the overall population being examined.

> A high degree of heterogeneity in a landscape results in few forest interior species…contains extensive edge habitat with edge species…total species diversity is high (Forman and Godron, 1986, 26).

Severe disturbances, from either wildfires or possibly timber harvesting, may either rapidly increase or decrease heterogeneity (Forman and Godron, 1986).

Biological diversity or 'biodiversity' refers to the amount and variety of animal and plant species living on earth, including all of their complex ecosystems and landscapes. The definition of landscape diversity is often included in this definition of biodiversity (www.biodiv.org). Landscape diversity

> refers to the number of landscapes in the geographical area being studied…a landscape is a collection of elements which consists of defined assemblages of plants, animals and land-use patterns…the boundary of the landscape will vary according to the scale being used and the purpose of the investigation (Convention on biological diversity).

Landscape diversity is important because two-thirds of the world's biodiversity is located in developing countries. To properly conserve global biodiversity and prevent the loss of biodiversity, often occurring in landscapes that are managed for human benefit, one must understand the specific components of landscape diversity, such as richness and evenness (Tillman, 1999). The term richness typically refers to the number of patch types present in the landscape while the term evenness typically refers to the distribution of area among patches types in the landscape (McGarigal and Marks, 1995). Several indices that measure diversity by incorporating richness and evenness values are Shannon's evenness index (SHEI), Simpson's evenness index (SIEI) and modified Shannon's evenness index (MSIEI). Each index isolates the

evenness component of diversity by controlling for the richness. As each evenness index approaches its maximum value of 1, the observed diversity approaches perfect evenness. That is, the total area is evenly distributed among all types of patch types. However, these diversity indices: 1) convey no information on species composition; 2) do not equate large evenness values with a greater richness values (a landscape with greater evenness may have lower richness); 3) does not indicate which types of patch are more or less abundant or ecologically significant; and 4) do not isolate richness and evenness into their respective components (McGarigal and Marks, 1995). Another landscape measure of diversity, stability, involves not just the number of different patch types in an ecosystem but the number of species present.

Stability, as it relates to species diversity, occurs at two levels: community and population. As diversity increases, community stability increases but population stability decreases. Also, increased diversity leads to increased productivity. The assumptions are two-fold: 1) that species are in their natural environment; and 2) the scaling coefficient, z, is between 1 and 2 (Appendix B). Studies conclude that species in their natural environment have a scaling coefficient between 1 and 2 (Tillman, 1999).

Sapelo Island is an excellent study area for research comparing the effects of disturbances, such as wildfires and timber-harvesting, because of the limited commercial development or urbanization and extensive timber-management activities. Wildfires have also occurred on Sapelo Island, which allow meaningful comparisons between a human disturbance, timber-harvesting, and a natural disturbance, wildfire. Quantifying the effects of these disturbances, through the analysis of aerial photography, should yield results that can be interpreted ecologically, in such terms as landscape heterogeneity, diversity, richness, evenness and stability.

CHAPTER 3: METHODOLOGY

The proposed methods for this study were designed to compare the effect that both a human disturbance (timber harvesting) and a natural disturbance (wildfires) have had on the vegetated landscape of Sapelo Island. Twelve sample sites per category (WT, NWT, WNT and NWNT) were randomly selected and classified from the DOQQ's. An un-supervised, computer classification was used to produce eight possible land covers from the DOQQ imagery (Thomson *et al.*, 1998). The spatial patterns of the land cover classes were analyzed and quantified using the spatial pattern analysis program, FRAGSTATS (McGarigal and Marks, 1995). With more than 40 landscape metrics available for each of the 48 sample sites (12 sites per category), statistical comparisons were made between each of the four categories. The methods involved in this process included sample site selection, sample site preparation, sample site classification, landscape metric production and multiple ANOVA comparisons with Tukey's post-hoc tests (Figure 3-1).

3.1 SAMPLE SITES

Sample sites were prepared or spatially defined on the DOQQ's by creating different size grids and determining which grid cell size best fit the study. As the size of the grid cell decreased, the potential number of cells that fit inside the disturbed areas increased. After experimenting with a number of grid sizes, a 100 x 100 m grid cell or sample site was finally

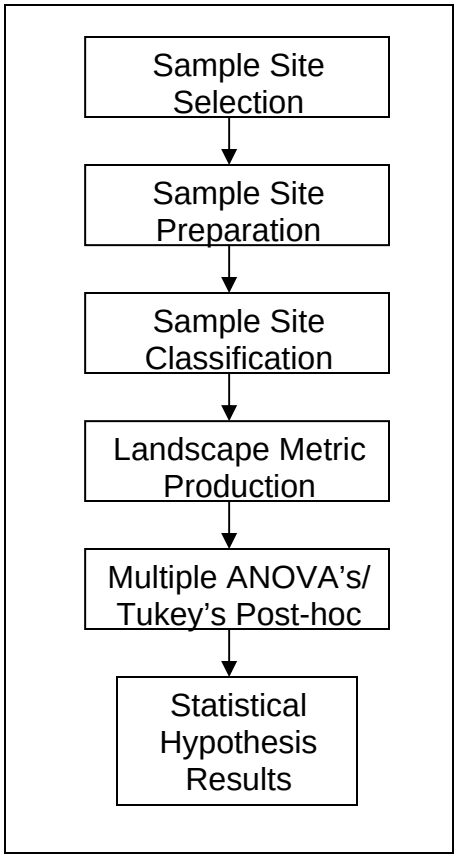

Figure 3-1. Flowchart of the methods, Sapelo Island, Georgia, 2003.

chosen to represent each possible sample site. The 100 x 100 m grid created many potential one hectare sampling grid cells that were large enough to fit entirely inside the disturbed areas. Due to the 1-m spatial resolution of the DOQQ's, each sample site contained 10,000 pixels (or picture elements), adequately representing the vegetation. The boundary of each sample site or grid cell was prepared through this gridding process.

Using ArcView 3.2 (ESRI, 1996), 1,000 randomly generated points were created, which covered Sapelo Island. If a point fell within a 100 x 100 m cell, that cell was retained as a potential sample site. The areas of wildfire and timber harvest disturbances were plotted using the ArcView software. Each retained cell fell completely within the disturbed areas. Each cell was sequentially assigned a number and a random number generator in EXCEL was used to select the sample sites. This process of random stratification created 12 sample sites for each of the four disturbance categories (Figure 3-2).

Using the ArcView, four polygon themes (or data layers) were created, one polygon theme for each disturbance category. Each theme contained the 12 polygon boundaries for each of the 12 sample sites. ERDAS Imagine 8.5 (Leica-Geosystems, 2000) was used to define the boundaries of each sample site on the DOQQ imagery (Figure 3-3) (Thomson *et al.*, 1998).

An un-supervised, maximum likelihood classifier was used in ERDAS Imagine to classify each sample site subset from the DOQQ into eight land cover classes, created by the author, to represent the vegetated landscape of Sapelo Island. The land cover classes used to classify the vegetated landscape were pine, hardwood, shadow, grey/vegetation, shrub/ understory, bare ground, water/wetland and un-classified. The following colors were also arbitrarily assigned by the author and did not represent spectral reflectance: pine (pink), hardwood (red), shadow (black), grey/vegetation (grey), shrub/understory (gold), bare

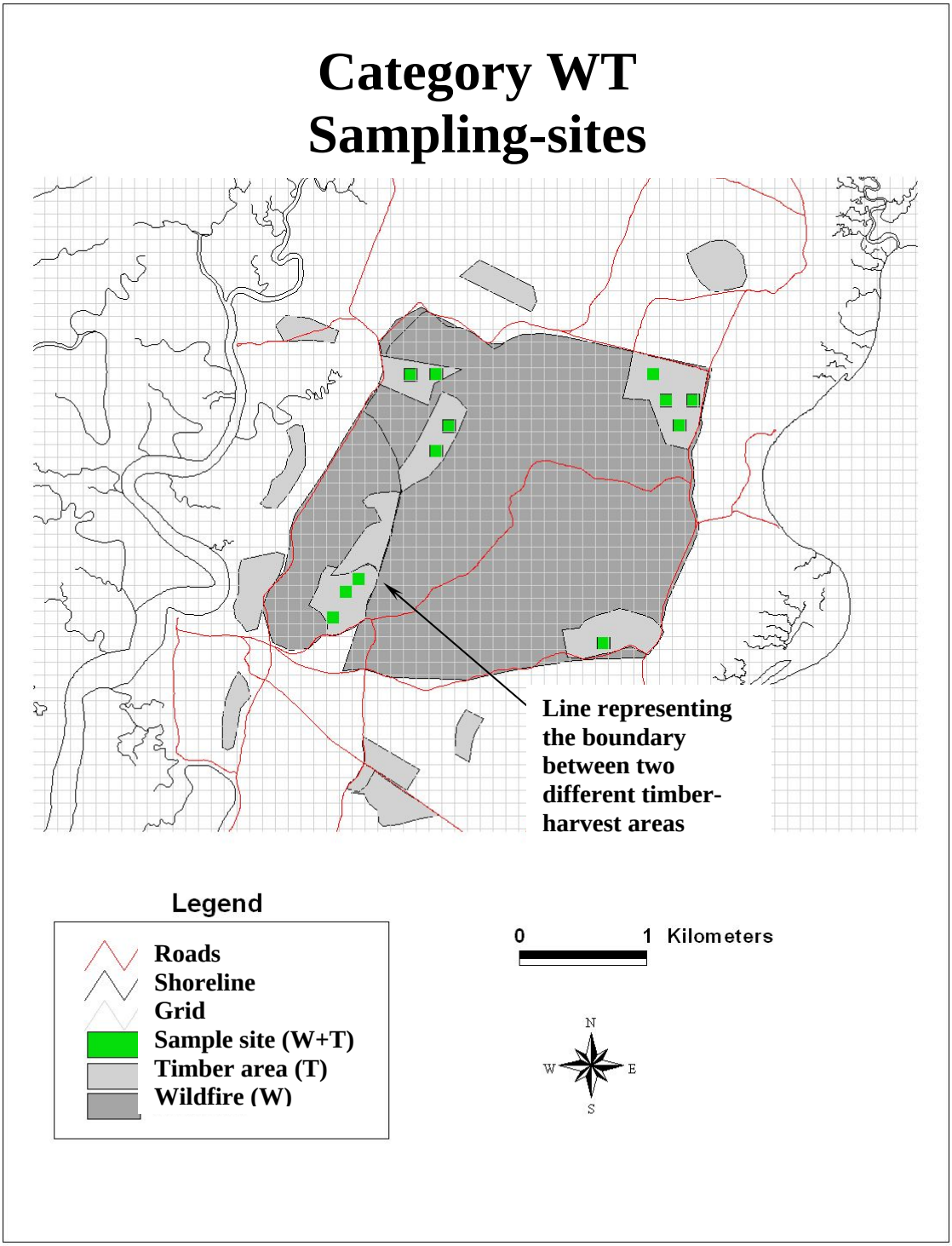

Figure 3-2.The twelve 100m x 100m sample sites of timber-harvest areas (T) overlaid onto the area burned by wildfire (W), representing the combined effects of both disturbances (Category WT), Sapelo Island, Georgia, 2003.

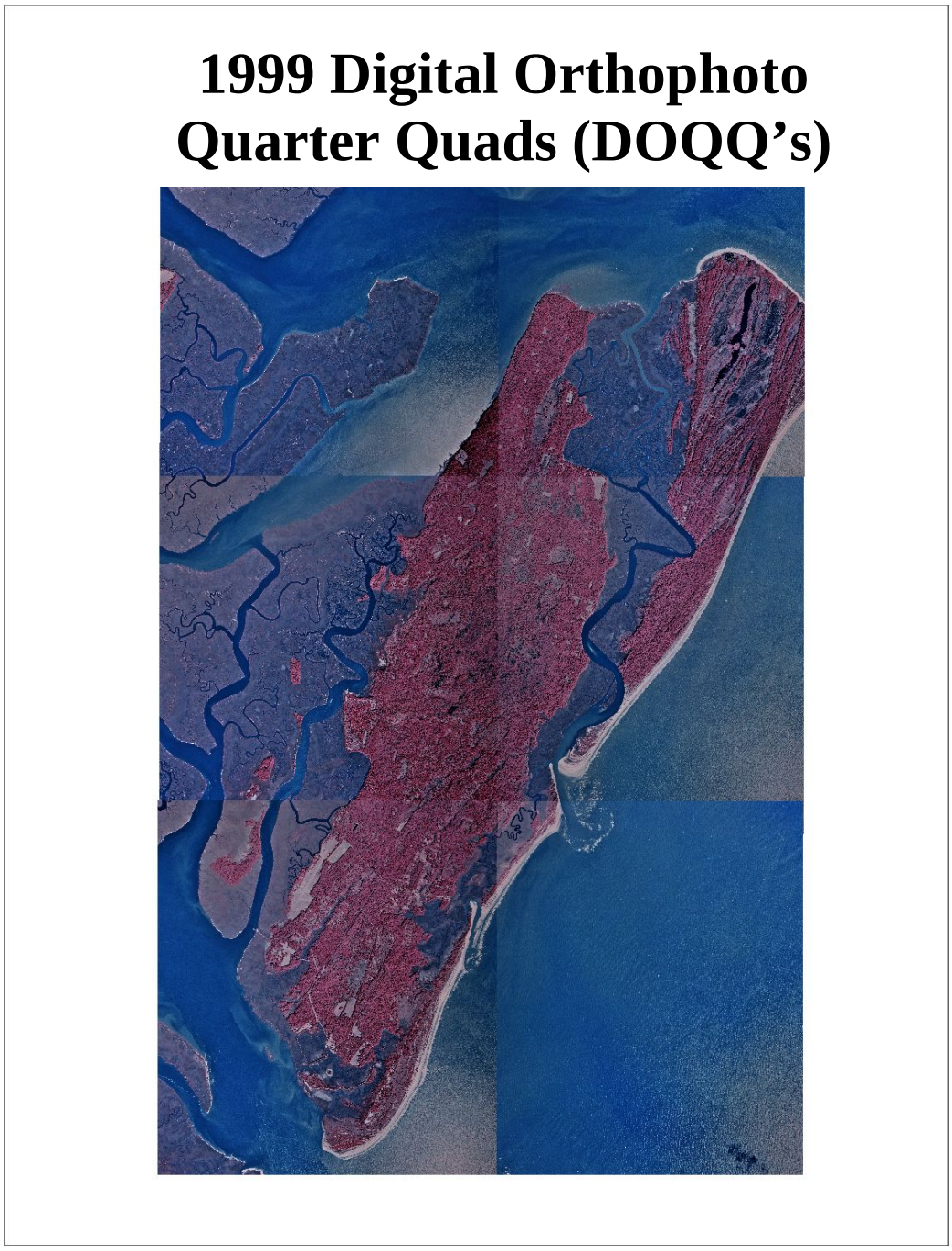

Figure 3-3. Sapelo Island, Georgia, (Blackbeard Island in NE corner), Digital Orthophoto Quarter Quads, 1999.

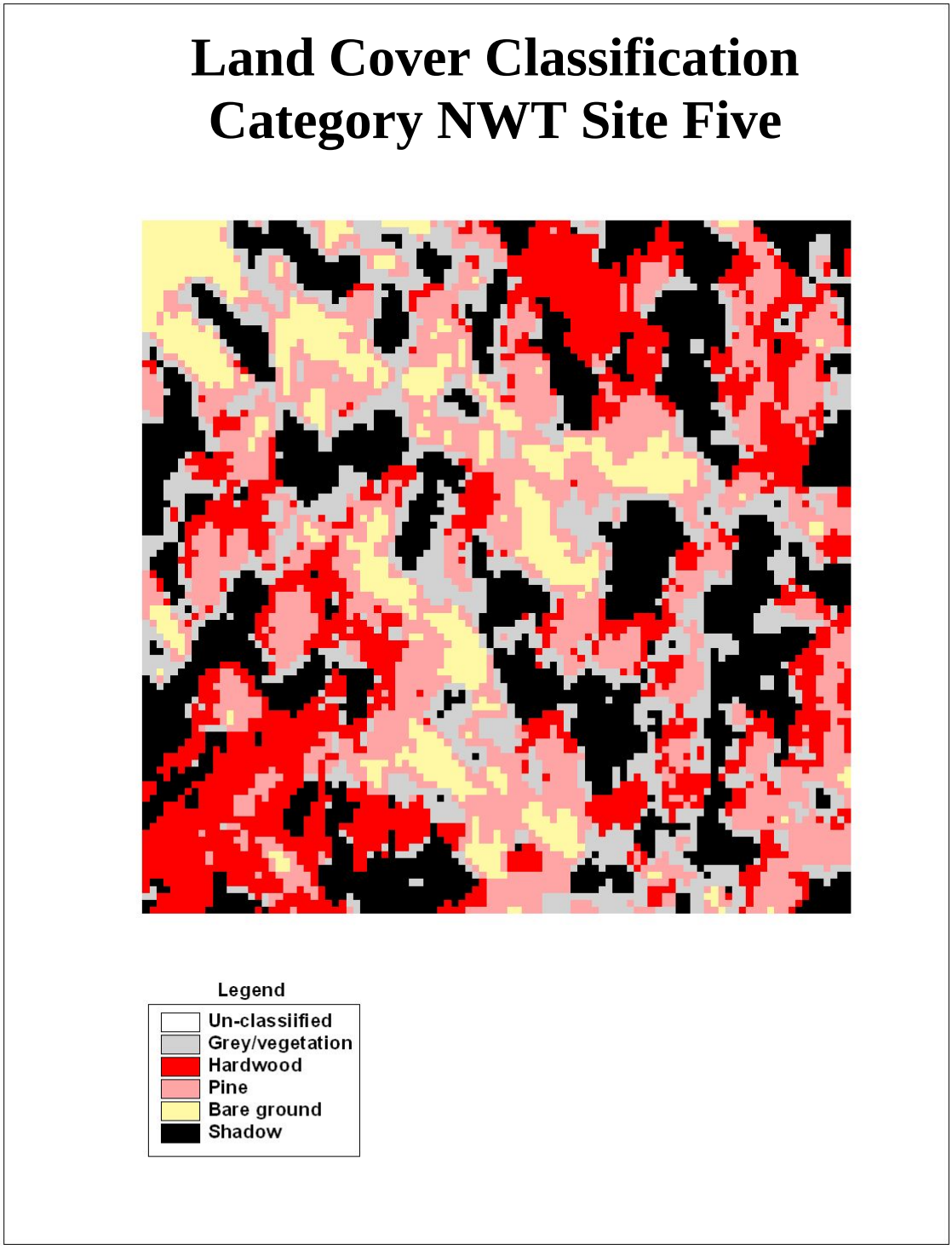

Figure 3-4. Land cover for Category NWT, Sample site #5, Sapelo Island, Georgia, 1999. The class 'Shrub/Understory' was omitted from the legend due to none being present in the sample site. The class 'Bare ground' includes grass.

ground (light yellow), water/wetland (blue) and un-classified (white) (Figure 3-4). The pine appeared as a light-pink color on both the 1992 CIR aerial photography, the USGS DOQQ's and exhibited a circular, even-textured crown. Hardwood classes typically appeared as a darker-red color and had an uneven textured, semi-circular crown. The areas that were classified as shadow appeared as dark grey or black on the CIR aerial photography. Although water also appeared as black on the CIR aerial photography, the presence and proximity of large trees near the shadows and to a lesser extent, the shape of the shadow itself, indicated that the shadows were actually a result of the height of the trees and the sun's angle. These tree-shadows masked the vegetation under them making interpretation of the understory impossible. Grey/vegetation class contained areas of vegetation that actually appeared as light grey on the CIR aerial photography and indicated that vegetation had been either killed or severely damaged. The shrub/understory class contained shrubs that had similar hues, ranging from a light-pink to a dark-red, as the vegetation classified as trees canopies, on both the DOQQ's and the aerial photography. The shrub/understory class had to be differentiated from the pine and hardwood classes by determining their height through the use of a 4X Abrams stereoscope and the positive contact prints of the aerial photographs. Bare ground class represented areas of the ground that were devoid of trees or shrubs, although it could contain grass. These areas had a high spectral reflectance in all three bands (red, green and blue) and typically appeared as white on the CIR aerial photography (Figure 3-5). Water/wetland class typically appeared as dark blue on the CIR aerial photography and could be differentiated from shadow through air photo interpretation. This class also contained man-made dikes, ponds and naturally occurring inland-marshes. The unclassified class was designed to include any possible cells that could not be classified into one of the eight land cover classes but actually consisted of a narrow border of cells at the edge of the

Figure 3-5. Photo-mosaic of 1992 CIR aerial photographs, Sapelo Island, Georgia. Source: Author.

sample sites. Although the reason behind the production of the unclassified cells could not be determined, the cells represented less than two percent of the entire set of pixels and were deemed acceptable by the author.

In ERDAS Imagine, three viewers (or windows) were viewed simultaneously to classify each of the ten un-supervised classes into one of the eight land cover classes. Based on previous trials, ten un-supervised classes yielded the best classification results. Viewer 1 contained the clipped sampling-site from the DOQQ. Viewer 2 contained the un-supervised, classified image of sample site. Viewer 3 contained the 1992 photo-mosaic of the sampling-site area, created by the author, and aided in the classification. All three of the viewers were 'geo-linked' so that the cross-hair in each of the viewers was centered over the same geographic coordinate and all three cross-hairs were linked together to move identically. By interpreting the imagery in Viewer 1 and Viewer 3, the un-supervised classes in Viewer 2 were assigned to one of the eight land cover classes, using the land cover signatures (Figure 3-6). The land cover signatures created by the classification process were color coded according to the land cover scheme mentioned earlier. Since a relatively small area (1 ha) was being classified, most of the sampling-sites only contained four or five of the eight land cover classes.

3.2 FRAGSTATS

FRAGSTATS facilitates landscape structure characterization by computing measures referred to as landscape pattern metrics for classified grid and image data. "Landscape pattern metrics are measurements designed to quantify aspects of landscape pattern such as fragmentation, patch shape or percentage of land cover" (Griffith *et al.*, 2000, 45). These metrics are used to test statistical hypotheses, such as those stated in the research objectives (see

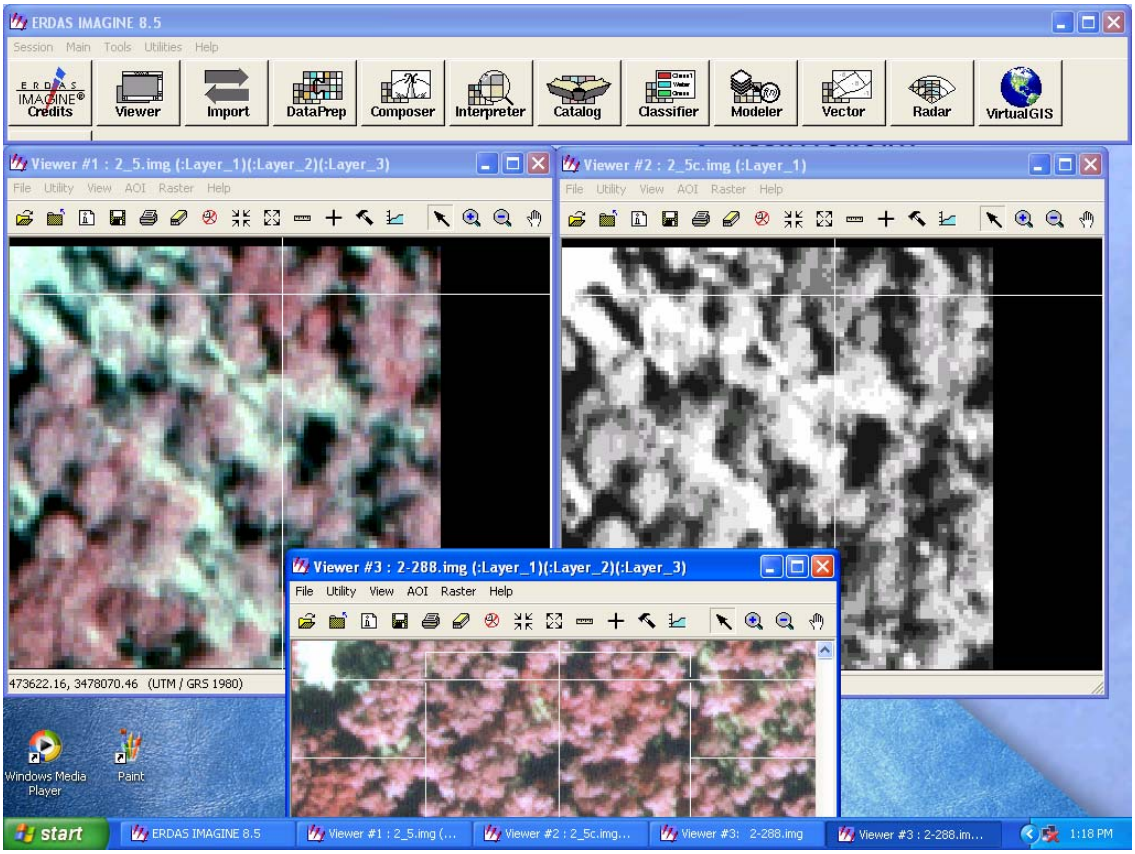

Figure 3-6. Three linked viewers in ERDAS Imagine 8.5. Sample site#5, Category NWT, Sapelo Island, Georgia, 1999. Viewer 1 is located in the upper left, Viewer 2 in the upper right and Viewer 3 is seen in the lower center.

Section 1.5) concerning the relationship between ecological processes (wildfire), human activities (timber harvesting) and vegetation patterns.

Each classified sample site, produced using ERDAS Imagine, was converted to a 'grid' theme using the Spatial Analyst extension in ArcView 3.2 (Elkie *et al.*, 1999). Using the Patch Analyst ArcView extension and the FRAGSTATS software, 40 landscape metrics were calculated for each sample site (Appendix C). Figure 3-4 is typical of the product generated from the unsupervised classification in ERDAS Imagine then converted to a GRID data format using the Spatial Analyst extension in ArcView 3.2. The Patch Analyst created landscape metric data for 40 FRAGSTATS variables. A table containing a partial Patch Analyst output is included in Appendix D. Each sample site contained similar tabular data quantifying the vegetated landscape in terms of landscape metrics. Thirteen of the 40 potential landscape metrics were removed because they either contained a zero, such as the percentage of landscape (ZLAND) or the data were extraneous, such as total landscape area (TLA). In the TLA case, all of the sample sites were the same size (1 ha). Four new class variables (shrub/ understory, grey/veg., pine and hardwood) were added, providing a total of 31 landscape metrics for statistical analysis, using an ANOVA with Tukey's Post-hoc test.

An ANOVA tests whether the means for two separate populations are significantly different with respect to only one factor, such as the number of patches (NUMP). As long as the sample sizes are equal and the sample sizes are fairly large in number (>10) then the *F* statistic is reliable (Witte, 1993). Although a statistical test for a normal distribution was not done, a review of the results' descriptive statistics appeared suitable for an ANOVA parametric test (Holloway, 2003). ANOVA assumes a normal distribution and an equal variance among all populations. Tukey's Post-hoc test allowed multiple comparisons of the means between

categories and the determination of which categories had significantly different means. Appendix E has a further discussion of Tukey's Post-hoc test.

CHAPTER 4: RESULTS

Out of the 31 landscape metrics used for statistical analysis, seven landscape metrics had significantly different means ($P<.05$) between treatments (NWT, WT, NWNT, and WNT). The significant landscape metrics were patch size coefficient of variation (PSCOV), area weighted mean patch fractal dimension (AWMPFD), patch core area coefficient of variation (CACV1), mean core area index (MCAI), Shannon's evenness index (SHEI), Simpson's evenness index (SIEI) and modified Simpson's evenness index (MSIEI) (Appendix F). The null hypothesis that all samples are drawn from the same population was rejected and concluded that at least one sample is drawn from a different population than the other samples. Tukey's multiple means comparison identifies the significantly different categories (Table 4-1). The level of significance was $\alpha = 0.05$ and the degrees of freedom were 1 and 44. The decision to reject or fail to reject the null hypothesis was non-directional or two-tailed.

The means of the significantly different landscape metrics were identified (Table 4-2) and according to the Tukey's Post-hoc test, there was a difference of means between the following categories treatments: WT and NWNT (PSCOV, SHEI, SIEI and MSIEI); NWT and NWNT (PSCOV, CACV1 and MCAI); and, WT and NWT (AWMPFD). Each significant landscape metric was then interpreted in terms of their landscape structure (Tables 4-3 to 4-7).

1) The first statistical hypothesis stated that wildfire would not produce a difference in areas that have been timber-harvested (H_0: Category WT = Category NWT). All FRAGSTATS landscape metrics, except the area weighted mean patch fractal dimension (AWMPFD), failed to

Table 4-1. One-way ANOVA and Tukey's multiple means summary

	Between All Categories		Comparisons		Decision for Null Hypothesis
Variable[1]	F	*p*	Categories	*p*	
PSCOV	4.310	.009	NWT and NWNT	0.009	Reject
			WT and NWNT	0.04	Reject
			WNT and NWNT	0.091	Fail to Reject
			NWT and WNT	0.789	Fail to Reject
			WT and NWT	0.941	Fail to Reject
			WT and WNT	0.984	Fail to Reject
AWMPFD	3.266	0.30	WT and NWT	0.025	Reject
			NWT and NWNT	0.101	Fail to Reject
			NWT and WNT	0.236	Fail to Reject
			WT and WNT	0.727	Fail to Reject
			WT and NWNT	0.931	Fail to Reject
			WNT and NWNT	0.972	Fail to Reject
CACV1	3.623	.020	NWT and NWNT	0.013	Reject
			WNT and NWNT	0.13	Fail to Reject
			WT and NWNT	0.311	Fail to Reject
			WT and NWT	0.467	Fail to Reject
			NWT and WNT	0.76	Fail to Reject
			WT and WNT	0.963	Fail to Reject
MCAI	4.023	.013	NWT and NWNT	0.008	Reject
			WT and NWT	0.095	Fail to Reject
			NWT and WNT	0.284	Fail to Reject
			WNT and NWNT	0.405	Fail to Reject
			WT and NWNT	0.753	Fail to Reject
			WT and WNT	0.939	Fail to Reject
SHEI	3.169	.033	WT and NWNT	0.037	Reject
			WT and NWT	0.089	Fail to Reject
			WNT and NWNT	0.436	Fail to Reject
			WT and WNT	0.582	Fail to Reject
			NWT and WNT	0.668	Fail to Reject
			NWT and NWNT	0.981	Fail to Reject
SIEI	3.210	.032	WT and NWNT	0.035	Reject
			WT and NWT	0.155	Fail to Reject
			WNT and NWNT	0.22	Fail to Reject
			NWT and WNT	0.58	Fail to Reject
			WT and WNT	0.822	Fail to Reject
			NWT and NWNT	0.905	Fail to Reject
MSIEI	4.272	.010	WT and NWNT	0.011	Reject
			WT and NWT	0.075	Fail to Reject
			WNT and NWNT	0.131	Fail to Reject
			NWT and WNT	0.47	Fail to Reject
			WT and WNT	0.73	Fail to Reject
			NWT and NWNT	0.868	Fail to Reject

[1]For the seven landscape metrics: PSCOV: patch size coefficient of variation; AWMPFD: area weighted mean patch fractal dimension; CACV1: patch core area coefficient of

variation; MCAI: mean core area index; SHEI: Shannon's evenness index; SIEI: Simpson's evenness index; MSIEI: modified Simpson's evenness index; For the four disturbance categories: WT: wildfire and timber harvest; NWT: no wildfire, timber harvested; WNT: wildfire, no timber harvest; NWNT: no wildfire and no timber harvest;

Table 4-2. Means for significant FRAGSTAT variables.

Variable	Category WT	Category NWT	Category WNT	Category NWNT
PSCOV	439.64	402.39	463.14	620.36
AWMPFD	1.45	1.41	1.44	1.44
CACV1	644.26	528.99	606.27	782.03
MCAI	7.26	10.74	8.10	5.81
SHEI	0.90	0.84	0.87	0.83
SIEI	0.93	0.88	0.91	0.87
MSIEI	0.85	0.77	0.82	0.75

PSCOV: patch size coefficient of variation; AWMPFD: area weighted mean patch fractal dimension; CACV1: patch core area coefficient of variation; MCAI: mean core area index; SHEI: Shannon's evenness index; SIEI: Simpson's evenness index; MSIEI: modified Simpson's evenness index;

Table 4-3. Patch size coefficient of variation (PSCOV)

Characteristics	Category	Category
	NWT	NWNT
Mean	402.39	620.36
Patch uniformity	More	Less
Relative variation in patch size	Less	More
Timber harvested	Yes	No
Wildfire	No	No
	WT	NWNT
Mean	439.64	620.36
Patch uniformity	More	Less
Relative variation in patch size	Less	More
Timber harvested	Yes	No
Wildfire	Yes	No

WT: wildfire and timber harvest; NWT: no wildfire, timber harvested; NWNT: no wildfire and no timber harvest;

Table 4-4. Area weighted mean patch fractal dimension (AWMPFD)

Characteristics	Category	Category
	WT	NWT
Mean	1.45	1.41
Fragmentation	More	Less
Shape complexity	More	Less
Edges	More	Less
Timber harvested	Yes	Yes
Wildfire	Yes	No

WT: wildfire and timber harvest; NWT: no wildfire, timber harvested;

Table 4-5. Patch core area coefficient of variation (CACV1)

Characteristics	Category	Category
	NWT	NWNT
Mean	528.99	782.03
Fragmentation	More	Less
Core area variability	Less	More
CACV1 value	Smaller	Larger
Timber harvested	Yes	No
Wildfire	No	No

WNT: wildfire, no timber harvest; NWNT: no wildfire and no timber harvest;

Table 4-6. Mean core area index (MCAI)

Characteristics	Category	Category
	NWT	NWNT
Mean	5.81	10.74
Interior	Less	More
Edge	More	Less

NWT: no wildfire, timber harvested; NWNT: no wildfire and no timber harvest;

Table 4-7. Simpson's evenness index (SIEI)

Characteristics	Category	Category
	WT	NWNT
Mean	0.93	0.87
Diversity of patch types	Less	More
Evenness of distribution of area among patches	More	Less
Timber harvested	Yes	No
Wildfire	Yes	No

WT: wildfire and timber harvest; NWNT: no wildfire and no timber harvest;

reject the null hypothesis. In the areas that have been timber harvested**,** wildfire is having an influence on the landscape, in terms of fractal dimension**.** The sites in Category WT are more fragmented, have a greater shape complexity and more edges than the sites in Category NWT. In timbered areas then, this would indicate that wildfires create more fragmentation, increase the complexity of the patches (shape) and create more patch edges on the landscape of Sapelo Island.

2) The second statistical hypothesis stated that wildfire would not produce a difference in areas that have not been timber-harvested (H_0: Category WNT = Category NWNT). All FRAGSTATS landscape metrics failed to reject the null hypothesis. No significant differences in means existed between Category WNT and Category NWNT.

3) The third statistical hypothesis stated that timber-harvesting would not produce a difference in areas that have been burned by wildfire (H_0: Category WT = Category WNT). All FRAGSTATS landscape metrics failed to reject the null hypothesis. No significant differences in means existed between Category WT and Category WNT.

4) The fourth statistical hypothesis stated that timber-harvesting would not produce a difference in areas that have not been burned by wildfire (H_0: Category NWT = Category NWNT). All FRAGSTATS landscape metrics, except patch size coefficient of variation (PSCOV), patch core area coefficient of variation (CACV1) and mean core area coefficient index (MCAI), failed to reject the null hypothesis. In areas that have been not been burned by wildfire, timber harvesting was having an influence on the landscape. The sites in Category NWT have lower CACV1, PSCOV and MCAI values than the sites in Category NWNT. Overall, this indicates that the sites that were timber harvested had more fragmentation, less core

area variability, less relative variation in patch size, more patch uniformity, more edges and less interior core area than the non-timbered harvest sites.

5) The fifth statistical hypothesis stated that there would not be a difference in areas that have not been burned by wildfire but timber harvested versus areas that have been burned by wildfires but not timber harvested (H_0: Category NWT = Category WNT). All FRAGSTATS landscape metrics failed to reject the null hypothesis. The results imply that shelterwood timber-harvesting and wildfires are having a similar effect on the vegetated landscape of Sapelo Island.

6) The last statistical hypothesis stated that there would not be a difference in areas that had been both burned by wildfire and timber-harvested versus areas that were neither burned nor timber-harvested (H_0: Category WT = Category NWNT). All FRAGSTATS landscape metrics, except (Patch Size Coefficient of Variation) PSCOV, (Shannon's Evenness Index) SHEI, (Simpson's Evenness Index) SIEI and (Modified Simpson's Evenness Index) MSIEI, failed to reject the null hypothesis. The combined effects of both timber harvesting and wildfires produce a landscape of uniform patches that are more evenly distributed but with less relative variation in patch size. Also, according to the evenness indices, there is more evenness of distribution of area among patches for areas that have been both burned by wildfire and timber-harvested.

As landscapes become more fragmented, landscape heterogeneity increases. In this study, landscape disturbances, such as wildfire or timber harvesting, produced heterogeneous landscapes. Heterogeneous landscapes were characterized by more stable dynamics and a more even distribution of population densities than homogeneous landscapes, especially for species sensitive to disturbances (Forman and Godron, 1986). These heterogeneous landscapes created by the management of Sapelo Island benefit certain grassland-shrub bird species at-risk, such as the painted bunting. Painted buntings were associated with smaller more numerous and more

heterogeneous stands of trees which had a high ratio of edge to area (Kopachena and Crist, 2004). On Sapelo Island, pine-oak forests should have less than 75% of canopy cover and open grass/shrub patches within the forest (Springborn, 1999). This study suggests that wildfires and timber-harvesting create more patch edges and more core area edges which are beneficial to the painted bunting but decreases the relative variation in patch size and interior core area, which may negatively affect other interior forest bird species.

CHAPTER 5: SUMMARY AND CONCLUSION

5.1 SUMMARY

This thesis involved the processing of digital imagery (DOQQ's) and the production of landscape metrics to compare the effects of wildfire and timber-harvesting disturbances on the vegetated landscape of Sapelo Island. From the results of the one-way ANOVA with Tukey's Post-hoc test, several landscape metrics had significant differences of means: 1) PSCOV, 2) CACV1, 3) MCAI, 4) AWMPFD, 5) SHEI, 6) SIEI, and 7) MSIEI. Each variable is related to the degree of disturbance (Figure 5-1). Numerous computer techniques and software programs, including ArcView 3.2, ERDAS Imagine 8.5, SPSS 10.0, FRAGSTATS, Patch Analyst and Pathfinder Office GPS software were needed to accomplish the analysis. The DOQQ's were a readily available, cost-effective source of landscape data for assessing the effects of disturbances on the vegetated landscape. Despite the quality imagery, extensive fieldwork was needed to identify the different types of vegetation present on Sapelo Island and, most importantly, acquire the knowledge necessary to interpret and classify the imagery.

In timbered areas, wildfires had an influence on the fractal dimension of the vegetated landscape. Wildfires created more fragmentation, more patch edges and increased the complexity of the patches (shape). In non-wildfire areas, timber harvesting increases the landscape fragmentation, patch uniformity and core area edges but decreases the relative variation in patch size and interior core area. The landscape-level patch size coefficient of variation (PSCOV) measuring the relative variation in patch size could be misinterpreted unless the number of patches (NUMP) or other similar landscape metrics is examined. For example,

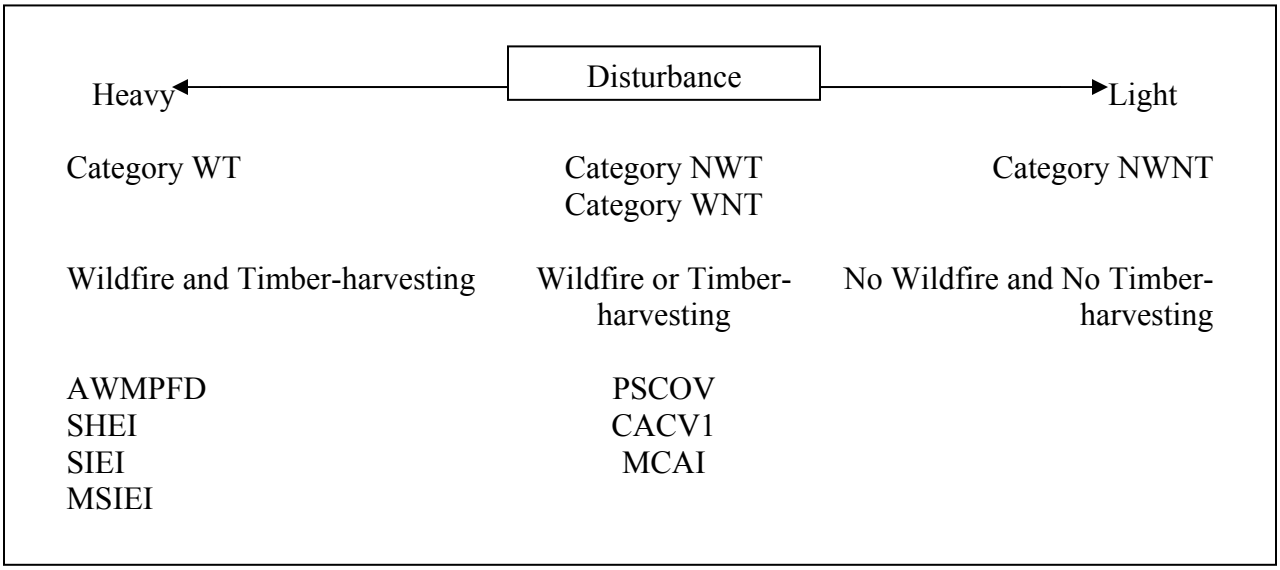

Figure 5-1. Significant variables by category. For the seven landscape metrics: PSCOV: patch size coefficient of variation; AWMPFD: area weighted mean patch fractal dimension; CACV1: patch core area coefficient of variation; MCAI: mean core area index; SHEI: Shannon's evenness index; SIEI: Simpson's evenness index; MSIEI: modified Simpson's evenness index; For the four disturbance categories: WT: wildfire and timber harvest; NWT: no wildfire, timber harvested; WNT: wildfire, no timber harvest; NWNT: no wildfire and no timber harvest;

two landscapes could have the same PSCOV but one landscape could have 100 patches with a mean patch size (MPS) of 10-ha while the other landscape could have 10 patches with a MPS of 100-ha. For this study, areas that have been both burned by wildfire and timber harvested have more patch uniformity and less relative variation in patch size. These areas also had the most number of patches (NUMP) although this may not indicate the most fragmentation, as shown in the example above. Also, according the evenness indices (SHEI, SIEI and MSIEI), these areas had the most evenness of distribution of area among patches.

5.2 CONCLUSION

For this study, individual disturbances, such as either wildfire or timber harvest, increased the landscape fragmentation, creating a more heterogeneous landscape. Due to the increase of edges and decrease of interior in core areas, rare interior species would be expected to decrease and edge species increase. These disturbances are known to increase the abundance of species that require multiple patch types in close proximity to each other. Ideally, the landscape dynamics become more stable, resulting in more evenly distributed population densities. Joint disturbances, such as those from both wildfire and timber harvesting, have effects similar to single disturbances but with an additional increase in the evenness of the vegetated landscape. The landscape becomes more fragmented and heterogeneous, exhibiting less diversity among patch types and exhibiting more evenness of distribution of area among patches (Forman and Godron, 1986). Before human disturbances, natural wildfires modified the vegetated landscape of Sapelo Island. In terms of patch size, core area and evenness, shelterwood timber-harvesting and wildfires are having a similar effect on the vegetated landscape. Resource managers could duplicate the effects of wildfire through a timber-management program that

matched the frequency, timing and spatial extent of wildfires that occurred ‘naturally’ on Sapelo Island. The challenge then is to determine the ‘natural’ wildfire regime that occurred on Sapelo Island. Furthermore, time-series studies could aid in further assessing the impact of disturbances on the vegetated landscape.

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APPENDICES

APPENDIX A: ANDERSON CLASSIFICATION SYSTEM, LEVEL I AND LEVEL II. Source: Anderson *et al.*, 1976.

Level I		Level II	
Number	Class	Number	Class
1	Urban or Built-up land	11	Residential
		12	Commercial
		13	Industrial
		14	Transportation, Communication or Utilities
		15	Industrial and Commercial Complexes
		16	Mixed Urban or Built-up Land
		17	Other Urban or Built-up Land
2	Agricultural	21	Cropland and Pasture
		22	Orchards, Groves and Vineyards
		23	Confined Feeding Operations
		24	Other Agricultural Land
3	Rangeland	31	Herbaceous Rangeland
		32	Shrub and Brush Rangeland
		33	Mixed Rangeland
4	Forest Land	41	Deciduous Forest Land
		42	Evergreen Forest Land
		43	Mixed Forest Land
5	Water	51	Streams and Canals
		52	Lakes
		53	Reservoirs
		54	Bays and Estuaries
6	Wetland	61	Forested Wetland
		62	Nonforested Wetland
7	Barren land	71	Dry Salt Flats
		72	Beaches
		73	Sandy Areas other than Beaches
		74	Bare Exposed Rock
		75	Quarries and Gravel Pits
		76	Transitional Areas
		77	Mixed Barren Land

APPENDIX A (cont.)

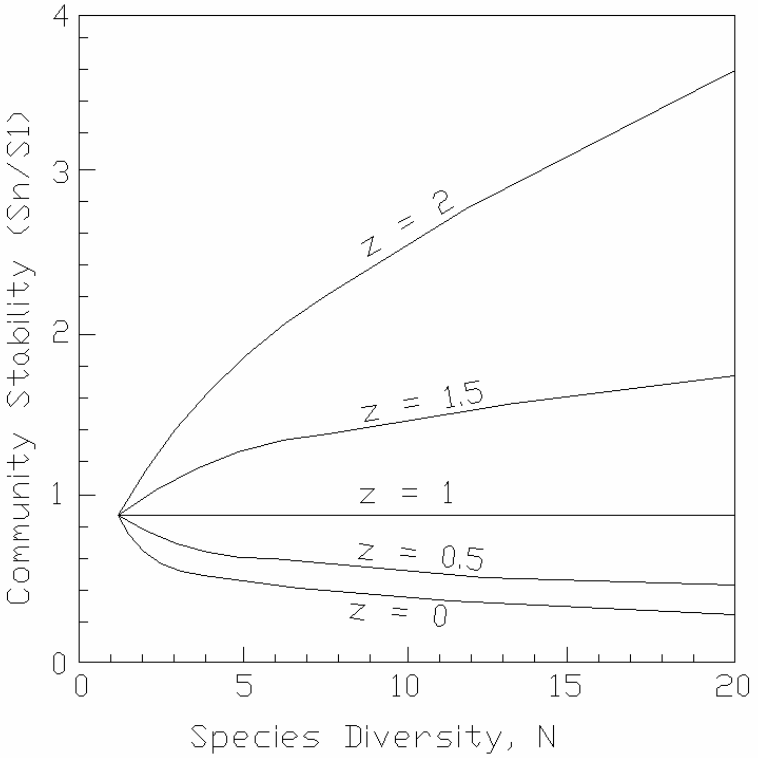
Level I		Level II	
8	Tundra	81	Shrub and Brush Tundra
		82	Herbaceous Tundra
		83	Bare Ground Tundra
		84	Wet Tundra
		85	Mixed Tundra
9	Perennial Snow or Ice	91	Perennial Snowfields
		92	Glaciers

APPENDIX B. TILMAN EQUATION.

$$\frac{S_N}{S_1} = N^{(Z-1)/2} \qquad \text{(Equation 3-2)}$$

S_N = the temporal stability of a community containing N species
S_1 = the temporal stability of a one-species community
N = number of species in a community e.g. community diversity
z = the scaling coefficient

The ratio of S_N to S_1 gives the temporal stability of a community containing N species relative to a community containing only one species. The critical value of z is 1. If z >1 the temporal stability of total community abundance increases as diversity increases. If z <1 total community abundance is destabilized. If z =1 stability is unaffected by diversity (see Figure) (Tilman, 1999).



APPENDIX C: LIST OF SELECTED FRAGSTAT VARIABLES. Source: McGarigal and Marks, 1995.

Abbreviation	Full Name	Unit of Measure (metric)
AWMPFD	Area Weighted Mean Patch Fractal Dimension	n/a
AWMSI	Area Weighted Mean Shape Index	n/a
BARE	Bare Ground	percent
CACOV	Core Area Coefficient of Variation	percent
CACV1	Patch Core Area Coefficient of Variation	percent
CAD	Core Area Density	number/100 ha
CASD	Core Area Standard Deviation	ha
DLFD	Double Log Fractal Dimension	n/a
ED	Edge Density	m/ha
GREY	Grey	percent
HARDWOOD	Hardwood	percent
IJI	Interspersion Juxtaposition Index	percent
LPI	Largest Patch Index	percent
LSI	Largest Shape Index	n/a
MCAI	Mean Core Area Index	percent
MNN	Mean Nearest Neighbor Distance	m
MPFD	Mean Patch Fractal Dimension	n/a
MPI	Mean Proximity Index	n/a
MSI	Mean Shape Index	n/a
MSIDI	Modified Simpson's Diversity Index	n/a
MSIEI	Modified Simpson's Evenness Index	n/a
NCA	Number of Core Areas	number
NUMP	Number of Patches	number
PINE	Pine	percent
PRD	Patch Richness Density	number/100 ha
PSCOV	Patch Size Coefficient of Variance	percent
SDI	Shannon's Diversity Index	n/a
SEI	Shannon's Evenness Index	n/a
SHEI	Shannon's Evenness Index	n/a
SIEI	Simpson's Evenness Index	n/a
TCA	Total Core Area	ha
TCAI	Total Core Area Index	percent
TE	Total Edge	percent

APPENDIX D: PARTIAL TABLE OF PATCH ANALYST OUTPUT

	Class	Name	ZLAND	TLA	NumP	MPS
1_1	All	All	0	1.02	391	0
1_1	0	Unclassified	1.97	1.02	1	0.02
1_1	1	Shrub/Understory	24.76	1.02	127	0
1_1	2	Grey/Veg	18.35	1.02	146	0
1_1	3	Pine	23.47	1.02	79	0
1_1	11	Shadow	31.45	1.02	38	0.01

Grey/veg: grey/vegetation; ZLAND: percent land; TLA: total landscape area; NumP: number of patches; MPS: mean patch size.

APPENDIX E: TUKEY'S POST-HOC TEST.

Tukey's test controls for compounding error rates during multiple comparisons and reduces the chance for committing a Type I error (rejecting a true null hypothesis) (Ott, 1993). Formula 3-1 indicates how large an observed difference must be for it to be called significant. Any absolute difference in means has to exceed the value of HSD to be statistically significant (Krus, 2003).

$$HSD = Q\sqrt{\frac{MS}{n}} \qquad \text{(Equation 3-1)}$$

HSD = Tukey's Honestly Significant Difference
Q = the listed range (from a table)
MS = the square root of the within group mean
n = number of observations in each group

Tukey's post-hoc test is one multiple comparison test which uses a Simultaneous Test procedure (STP). Simultaneous Test procedure controls for the likelihood of committing a Type I error using either an error rate per family (ERPF) or error rate familywise (ERFW) for a set of comparisons. A familywise error refers to the probability of committing Type I errors for a set of statistical tests. Simultaneous Test procedure is not done in steps and has one critical value for all of the comparisons in the set (Toothaker, 1993).

APPENDIX F: SIGNIFICANT FRAGSTAT METRICS BASED ON A ONE-WAY ANOVA AND TUKEY'S POST-HOC TEST. Source: McGarigal and Marks, 1995.

Abbreviation	Name (units)	Description
Patch		
PSCOV	Patch Size Coefficient of Variation (%)	Equals the standard deviation in patch size divided by the mean patch size; It represents the variability of the patch size relative to the mean patch size.
Shape		
AWMPFD	Area Weighted Mean Patch Fractal Dimension	Equals the average patch fractal dimension weighted by patch area so that larger patches weigh more than smaller patches;
Core Area		
CACV1	Patch Core Area Coefficient of Variation (%)	Equals the standard deviation in core area patches divided by the mean core area per patch, multiplied by 100; population coefficient of variation;
MCAI	Mean Core Area Index (%)	Equals the average percentage of a patch in the landscape that is core area; MCAI approaches 100 when the patches contain mostly core area;
Diversity		
SHEI	Shannon's Evenness Index	Equals minus the sum, across all patch types, of the proportional abundance of each type multiplied by that proportion, divided by the logarithm of the number of patch types;
SIEI	Simpson's Evenness Index	Equals the observed Simpson's Diversity Index divided by the maximum Simpson's Diversity Index; SIEI equals one when distribution of area among patch types is perfectly even;
MSIEI	Modified Shannon's Evenness Index	Equals minus the logarithm of the sum, across all patch types, of the proportional abundance of each patch type squared, divided by the logarithm of the number of patch types;