PLACING A HISTORICAL PLANTATION IN AN ECOLOGICAL CONTEXT: EVALUATING EFFECTS OF LAND USE LEGACIES ON VEGETATION PATTERNS USING DISCRETE RETURN LIDAR

by

CAREY BURDA

(Under the Direction of Marguerite Madden)

ABSTRACT

Land use legacy effects on forest structure in 33 coastal Georgia maritime forest plots were examined using discrete return airborne lidar data at Wormsloe State Historic Site. Historical maps, color, black and white, and color infrared aerial photography, and historical manuscripts were used to determine land use/land cover (LULC) in the plots over a 200-year time span. Plots were classified into low, moderate, and high levels of disturbance and transition based on LULC changes. Lidar metrics used to describe canopy structural characteristics within individual plots were ordinated using Detrended Correspondence Analysis. Disturbance and transition levels were overlaid onto the plots in ordination space and inspected for patterns. Transition levels produced statistically different patterns on canopy structure among the plots. Lidar-derived visualizations were incorporated into the Wormsloe Institute for Environmental History website, which was redesigned as part of this project.

INDEX WORDS: Discrete return lidar, land use legacy, maritime forest structure, coastal Georgia, historical plantations

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CHAPTER 1

INTRODUCTION

Entering a typical antebellum plantation in the Southern United States is like stepping back in time. The visitor is often greeted with an iconic drive lined with moss-draped live oak trees that elicits emotions of a bygone era. Driving down the avenue of oaks at the Wormsloe State Historic Site on the Isle of Hope, Georgia, one may experience just such emotions. It is as if time, history and processes on the Wormsloe Plantation stopped after the Civil War. If the visitor cares to look beyond the oak-lined drive, she will see a forest that reflects that antebellum era. She will also see a forest that reflects other eras, including colonial and pre-European settlement, and the 20th century. The forest brings these bygone eras alive to the present day, by reflecting the land use through species composition and structure. And unlike the antebellum era, the forest is anything but stagnant. It continues to grow, die, and shift in composition in ways that are influenced by its past land use. This research seeks to understand how past land use has influenced current vegetation structure on Wormsloe Plantation using light detection and ranging (lidar) data for the purposes of: 1) comparing vegetation structure related to different land use legacies; and 2) communicating these differences through visualization techniques.

Research Justification

Indirect impacts of human activity on the environment, such as acid rain, exotic organisms, and climate change, are significant contributors to ecological processes and functions. In addition to identifying physiological characteristics as a basis for understanding such processes, it is also imperative to investigate the land use history of an area in order to understand the influence of historic anthropogenic activities. Scientists and land use managers now recognize that the legacies of land use activities can influence ecosystem structure and function for decades and centuries to come (Maloney et al., 2008; Schulp and Verburg, 2009). This historical and scientific perspective can inform policy decisions and help design long term natural resource management plans. Foster et al. (2003, p. 77) argue "...site history is embedded in the structure and function of all ecosystems, that environmental history is an integral part of ecological science, and that historical perspectives inform policy development and the management of systems ranging from organisms to the globe." Studying how past land uses affect current plant communities provides a basis on which to investigate landscape-scale ecological processes. Additionally, changes in land use over time can lead to changes in species composition which subsequently contributes to changes in ecosystem processes at the landscape and global scales (Houghton 1994, Ahearn et al. 2005).

Along with environmental controls, land use history provides the underpinning to understanding broad-scale ecological processes. Before such processes may be studied and incorporated into long-term management plans, however, baseline data such as forest structure must be documented and mapped. Coastal Georgia plant communities and their associated structure have not been well documented using the National Vegetation Classification System (Grossman et al, 1998). Describing and mapping vegetation on a plot level will enable researchers to define and classify plant communities and understand how vegetation structure affects ecological processes on a broader scale.

Research Setting

Wormsloe Plantation, on the Isle of Hope in Georgia, provides the ideal site on which to study how past land use affects modern day vegetation patterns. The site provides excellent environmental controls in that there is very little terrain variation and the soils across the site are similar in composition. The land use history of the site, therefore, may be isolated as a strong influence on vegetation community structure. The history of Wormsloe is well documented with maps and photographs dating back to the late 1800s/early 1900s, and through written manuscripts, most of which are preserved in the Hargrett Rare Manuscripts Library at the University of Georgia. In addition, current conditions are captured in remote sensing data including aerial photographs, satellite images, and newly acquired lidar data. These documents, maps, and images provide the knowledge and evidence (e.g. the location of specific areas of pasture, cropland, and woodland) necessary to analyze how land use legacies affect modern day landscapes.

Beyond the environmental controls present at the site, Wormsloe Plantation offers a unique opportunity in which to conduct land use legacy research. From its Colonial beginnings to today, the estate has been overseen by the same family. In the 1700's and into the 1800's, the plantation was a site for agricultural experimentation. Noble and Sarah Jones, the founders of Wormsloe in 1734, planted fruit and nut trees such as pomegranate, orange and black walnut, as well as white mulberry trees to feed the silkworms the Colonial trustees hoped would translate into the valuable commodity of silk production (Swanson, 2009). Other crops, including indigo, were likely tested for viability on Wormsloe. Sea Island cotton was the primary crop planted during the antebellum years. The brackish water around the plantation was found to be unsuitable for rice production, but the family ran a rice mill as a place for area planters to process their crops. In the first part of the 20th century, the family ran a dairy operation complete with pastures, milking and bottling facilities. The various generations have had differing degrees of interest in agricultural activities on the estate; however, one value has remained consistent.

Throughout its lineage, the family has recognized the importance of land stewardship and the documentation of Georgia state history as indicated by their extensive collection of family papers, documents and books now held in the Hargrett Rare Manuscripts Collection at the University of Georgia. Family members have worked to protect the site from extensive development beyond what has been built for a private residence and agriculturally oriented buildings. This sense of responsibility has translated into the preservation of historical records, including photographs and maps that document much of the plantation's history.

Finally, through a cooperative partnership between the Barrow family and the Georgia Department of Natural Resources (GDNR), the majority of the Wormsloe property was turned over to the state in the 1970s and in 1978 the Wormsloe State Historic Site was created. The Wormsloe Foundation and the Wormsloe Institute of Environmental History (WIEH) were established in 1954 and 2008, respectively, to further conservation, ensure access for research and support education through a common passion for preserving this unique landscape.

The Center for Remote Sensing and Mapping Science in the University of Georgia Department of Geography has compiled a central geodatabase for the WIEH that contains digital copies of historical maps, ground photos and remotely sensed imagery for integrative research in ecology, history, and anthropology (www.crms.uga.edu, 2011). Cooperative partnership between the WIEH and GDNR provides an atmosphere which is conducive to field data collection over the entire original land holdings of Wormsloe. Typically, vegetation and land use studies incorporate *in situ* field measurements which include canopy height, diameter at breast height (DBH), and species composition and abundance. These data allow researchers to ascertain present vegetation patterns and to analyze stand structure. By collecting *in situ* data and using lidar at the stand level, current vegetation structure can be mapped, documented and analyzed at Wormsloe.

Objectives

The primary goal of this research is to use discrete return lidar remote sensing data to assess forest structure in the Wormsloe Historic Site in order to characterize current vegetation patterns related to historical land use legacies. This knowledge will provide valuable information on which future studies integrating archaeology, ecology and environmental history may be based. Specific objectives of this research include the following.

1. Characterize vegetation structure within Wormsloe long term vegetation plots using remotely sensed discrete return airborne lidar data. Derive descriptive statistics.

2. Analyze and compare the vegetation structure of the long term plots using metrics derived from discrete return, airborne lidar data, and statistically analyze similarities and differences between forest structure and Wormsloe land use legacy.

3. Create and incorporate displays and outreach materials using lidar visualizations that will assist visitors to the Wormsloe State Historic Site and Wormsloe Institute for Environmental History (WIEH) researchers in understanding how past land use activities on a coastal Georgia island influence the modern-day landscape. In doing so, the WIEH web site will be redesigned.

CHAPTER 2

LITERATURE REVIEW

Land Use History

Many studies have been conducted in North America and around the world linking land use history, particularly previous agricultural practices, to modern vegetation patterns and the consequences of these land practices on ecological communities. (Odum, 1971; Forman and Godron, 1986; Foster, 1992; Foster et al., 1992; Dupouey et al., 2002; Foster et al., 2003; Maloney et al., 2008; Brown & Boutin, 2009; Schulp and Verburg, 2009). A literature review shows that researchers have used several characteristics of vegetation patterns, including soil biochemical properties (Odum, 1971; Dick, 1992; von Oheimb et al., 2007; Compton and Boone, 2007; Maloney et al., 2008), invasive species presence (Standish et al., 2008), and species composition (Gerhardt and Foster, 2002, Brown and Boutin, 2009), as characteristics in which land use legacy manifests itself in the modern landscape.

The geographic extent of these studies varies far and wide across the world. In North America, land use legacies have been studied extensively in the northeast primarily due to early recognition of the importance of their influence on the landscape and the establishment of the Harvard Forest in 1907 and the Hubbard Brook Ecosystem Study in the 1950s as resources in which to study environmental history and conservation (Harvard Forest website, 2010; Hubbard Brook Ecosystem Study website, 2010). By studying biodiversity, the effects of invasive organisms, timber harvesting, soil nutrient dynamics, site history, among other long term ecological variables, researchers at Harvard Forest are working to understand forest responses to natural and human disturbance and environmental change. In the early 1950s the Hubbard Brook Ecosystem Study in New Hampshire was established to learn how ecosystems within watersheds respond to natural and anthropogenic disturbances. Using the nested watersheds in the study site, researchers monitor how devegetation and nutrient inputs affect water yield, stream chemistry, and nutrient flux and cycling affect ecosystem processes.

Research inspired from these two ecological sites provided a foundation on which numerous projects, primarily during the second half of the twentieth century until today, have been carried out throughout North America. Gordon G. Whitney describes many of the land use change concepts in his book, “From Coastal Wilderness to Fruited Plains” (1994). He provides a history of environmental change from pre-European settlement to the present in temperate North America by discussing the landforms, forest structure, climate, and native American impacts. Whitney discusses how settlement patterns, timber and wood consumption, and farming practices fundamentally changed the landscape as evidenced by modern-day vegetation patterns. Using earlier research and data as foundations on which to base their research, scientists have published a myriad of studies that relate land use legacies to modern day vegetation patterns (Maloney, et al. 2008; Fraterrigo et al., 2009; Cumming & George, 2009).

Coastal Georgia Historic Land Use

“Vegetation development in coastal regions is difficult to predict because of the numerous perturbations, disruptions, or environmental stresses affecting community change” (Statler and Odum, 1993, p. 133). This statement is especially true when attempting to reconstruct past land use on the Georgia coast, particularly on the Sea Islands, in order to evaluate current vegetation patterns. Like other coastal areas along the eastern seaboard, precolonial coastal Georgia experienced numerous hurricanes, nor’easters, fires, and periodic disease and insect outbreaks, among other natural and anthropological disturbances.   After European settlement, particularly between 1800 and 1865, the coastal landscape was transformed as planters concentrated their resources and efforts in clearing maritime forests for cotton , rice, indigo, and other crops. After the Civil War, large scale plantations made way for smaller farm operations. During the 20th century, farms were abandoned and fields made way for early successional forest species. Because of the coast's long history of disturbances, researchers must rely on historical documents in all forms to reconstruct a specific site's land use history. For example, Bratton (1985) used written descriptions by colonial observers, historic maps, coastal charts, diaries, and newspaper articles to investigate major vegetation disturbances and re-growth at Fort Frederica, Georgia.   Using a variety of resources, she determined that there were nine major human interactions (i.e,. interactions that had some influence on the vegetation patterns) with vegetation since European settlement.   Fort Frederica is one of few exceptions along the coast of Georgia where the researcher had a large amount of documentation with which to work. Perhaps this wealth of information is due to the fact that the fort was a key military location during the colonial era and that Oglethorpe, who based his operations there, required detailed information of the area.

Numerous studies have been conducted that have recorded how current land use directly and indirectly affects estuarine environments and their related flora and fauna species, (Bejerano et al., 2004; Vo et al., 2004; Walters et al., 2010; Gray et al., 2009) but there is a dearth of research on other biophysically similar islands in North Carolina, South Carolina, and Florida in which historic agricultural land use of areas is linked with terrestrial vegetation communities and patterns, possibly due to the reasons discussed in the previous section. Noted exceptions include two research projects conducted on the Georgia Sea Islands, one in which human disturbance was linked to the distribution of alien plant species, and the other linking the understory structure and composition of maritime oak and oak pine forests on Cumberland Island Seashore to past agriculture activities (Rodgers and Parker, 2003; Bratton and Miller, 1994).

Rodgers and Parker compared native and alien species distribution on two classes of islands, one class being developed primarily for tourism, and the other class being protected from development by national refuges. They stratified the two classes into habitats with differing degrees of environmental stress: primary dunes with high salt spray and saline soils and the more sheltered and inland maritime forests. They further stratified the habitats into differing levels of human disturbance. They found that "many alien species were present on all islands and the absolute cover of alien species was not significantly different among islands even though they varied substantially in their degree of accessibility and overall land use." Furthermore, alien plant cover was greater in more disturbed areas than in less disturbed areas on all islands. They concluded that human disturbance appeared to increase alien cover in general, "but in environments where the stress levels are not mitigated, human disturbance does little to foster alien invasions." While this research does not specifically link agriculture land use legacies to modern vegetation patterns, it does demonstrate how human disturbance in the landscape can alter species composition on the Georgia Sea Islands.

Bratton and Miller (1994) investigated whether understory composition in the maritime forests on Cumberland Island was primarily shaped by past agriculture activity rather than anthropogenic burning and soil moisture gradients. They used historic maps to select areas of forest that: 1) had no history of agriculture, 2) were formerly cotton fields during the plantation era of the late 18th century to the first half of the 19th century, 3) were used for grazing during the private estates from 1881 to 1916, and 4) a combination of 2 and 3. In forests with no known past agricultural activities, the understory was dense with saw palmetto, *Serenoa repens,* had high dominance indices for red bay, *Persea borbonia,* and had few vines and almost no grass and forb cover. Fields that were grazed in the late 19th century had very open understories with greater dominance of grasses and forbs and widely scattered rings of saw palmetto. Sparkleberry, *Vaccinium arboreum,* and pines, particularly loblolly, *Pinus taeda,* were also characteristic. Fields used for cotton cultivation during the plantation era, but were not shown as fields on the late 19th century map, displayed intermediate densities of palmetto and high covers of grasses, forbs, and vines. The researchers also measured greater depths of soil litter and duff in the non-agricultural sites than in the agricultural field types. Their results imply that the maritime oak forests on Cumberland Island "have not been historically maintained by either anthropogenic or natural fire, but are artifacts of cultivation and human land management extending back to aboriginal settlement of the island."

A Comparison of Two Coastal Georgia Islands

Additional research documents the historic forces behind land use patterns of some of the Georgia Sea Islands through the mid-20th century. Most notably, Buddy Sullivan has written several publications recording the cultural heritage and land use history of Sapelo Island, a Georgia island whose history parallels Wormsloe's settlement and development patterns (Sullivan, 2001). As with Sapelo, prehistoric evidence has been found on the Isle of Hope, including potsherds and shell middens. Although it is unknown to what extent prehistoric inhabitants altered the coastal Georgia landscape, it is reasonable to assume that their cultivation activities affected the environment on some level. One may also assume fires caused either by lightning strikes or advertent burns by the original occupants periodically occurred on the Georgia islands, thus further altering the landscape. While the first Europeans to set foot on

Sapelo were Spanish and French settlers, both islands were permanently settled by British and originally owned by the English Crown; Both islands also were either granted by the King, or bought from the Crown by influential early Georgians. As such, it was necessary that both islands be placed into cultivation in order to support the new colony and later, the new state, with food resources and to insert themselves as important economic forces in the fledgling United States. The resulting settlement patterns and agricultural activities changed the landscapes from pre-settlement conditions. During the Antebellum era the sites were placed under intense cotton cultivation and other crops using slave labor. After the Civil War, former slaves and out of state speculators cultivated the sites for either subsistence or investments.

On the Isle of Hope Wormsloe Plantation, former slaves farmed their own plots for a brief period of time before ownership was returned to the De Renne family. The family then leased out parcels to former slaves. On Sapelo, large portions of the island were sold to northern investors who sought net gains on their investments. However, without an organized and forced labor at their disposal, they were unable to meet pre-Civil War cotton production rates. During the first half of the 20th century agricultural activities continued at Sapelo and Wormsloe. The De Renne/Barrow family continued a variety of agricultural endeavors including cattle grazing, food crops, and a dairy operation on Wormsloe. During this same period, the majority of Sapelo was purchased by the wealthy industrialist, Howard Coffin. He set about cultivating cotton and food crops, grazed cattle, and diversified activities by building oyster and shrimp canning facilities. In 1933, Richard J. Reynolds purchased Sapelo and continued his predecessor's farming and livestock activities. In 1969, Reynold's widow, Annemarie Schmidt Reynolds, sold the northern half of Sapelo to the state of Georgia and designated it as the Reynolds Wildlife Management Area administered by the Department of Natural Resources. The state purchased

5,000 acres on the southern half in 1976 and this portion later became the Sapelo Island National Estuarine Research Reserve. The Reserve is currently managed through a partnership between GDNR and the National Oceanic and Atmospheric Administration. Like Sapelo Island, a large portion of Wormsloe was purchased by the state of Georgia in the 1970s and continues to be administered by the Department of Natural Resources as a historical site. Today, the major portion of Sapelo and Wormsloe are protected by governmental and research entities for the sake of preserving their natural and cultural heritage. Most portions of both sites have reverted back to forested environments.

The Importance of Ecological Processes in Generating Vegetation Patterns

Historical land use directly influences ecological processes that shape vegetation patterns in terms of vertical and horizontal structure. Geoffrey Parker (1995) defines vegetation structure as "…the organization of space and time, including the position, extent, quantity, type, and connectivity of the aboveground components of vegetation." Spies (1998) defines vegetation structure as applied to forests. He argues that forest structure is both a product and a driver of ecosystem processes by partitioning forests into their essential attributes including structural type, size, shape, and spatial distribution (vertical or horizontal) and discusses them in the context of their roles in the functioning of ecosystems (Table 2.1). For example, forest canopies vary both horizontally and vertically. The varying architecture of the canopy influences radiation interception, microclimate control, and habitat for a wide variety of animal species. Whether making observations from above, below, or within the canopy, measurements can be taken on reflectance, gas fluxes, epiphytic habitat, light transmission, crown position, tree size, biomass, among a myriad of other characteristics that are fundamental to the functioning of ecosystems.

Table 2.1. Components of forest structure (after Spies,1998).

Foliage	**Standing Dead Trees**
Leaf area	Diameter
Vertical distribution	Height
Leaf shape, density	Decay State
Canopy gaps, horizontal pattern	Volume, mass
Tree Crowns	Cavities
Shape	**Pit and Mound Topography**
Length	Area
Life form	Height/depth
Diameter, area, density	**Roots**
Position in stand	Size
Branch characteristics	Density, decay state
Cavities, breakage, decay	Biomass
Tree Bark	Spatial pattern
Texture	**Soil Structure**
Thickness	Aggregations
Tree Boles	Organic matter distribution
Diamter	**Landscape Structure**
Height	Stand/patch type distribution
Cavities, breakage, decay	Patch size
Gaps and spatial pattern	Patch shape
Age distribution	Habitat connectivity
Wood Tissues	Edge density
Volume	
Biomass	
Type (sapwood, heartwood)	

Forest ecologists have traditionally placed emphasis on the description and classification of species composition and other easily measured forest characteristics and applied these traits to characterize the entire canopy. Until recently, they rarely attempted to study the upper reaches of canopies in detail (Lowman & Rinker, 2004). This lack of research may be due to the difficulty of describing a forest's complex three-dimensional architecture, access limitations, and the high cost of traditional field measurements when collected over many forest stands (Kane et al., 2010; Miura & Jones, 2010). However, the architectural arrangement and intricacies of canopies are considered just as important as species composition when studying processes such as gas exchange, productivity, biodiversity, and hydrological processes (Falkowski et al., 2009). Understanding canopy structure can provide insights into processes in tree growth and can reveal important information on a forest's response to disturbance. For example, the overall vertical and horizontal arrangement of forest canopy has been shown to strongly control the photosynthetic active radiation and subsequently net primary productivity (Coops et al., 2007; Chasan et al., 1991; Brokaw and Lent, 1991). Canopy structure influences light transmission and thus, indirectly, the temperatures within the canopy. Subsequently, the varying temperatures influence leaf-level photosynthetic processes (Funk & Lerdau, 2004). Other structural characteristics that affect microclimate include water availability. Dense canopies may influence photosynthetic activity by controlling humidity levels. If humidity at the surface of a leaf decreases, this results in stomatal closure which ultimately decreases the rate of photosynthesis (Funk and Lerdau, 2004). Additionally, as a stand ages, the vertical structure of canopies become increasingly complex and provides for more diverse habitats for birds, mammals, and other fauna (Ishii et al., 2004; Franklin et al., 2002; Van Pelt and Nadkarni, 2004).

From a broader perspective, forest structure may be thought of as a product of forest dynamics in which succession and historical land use are drivers. Deterministic and stochastic processes including timing of establishment after a disturbance, height-growth rate, maximum attainable height of species, interactions among individual tree crowns, and the effects of fine-scale disturbances such as individual tree mortality or crown damage, drive ecological functions (Ishii et al., 2004). For example, trees with past damage to the crown may display forks at the main stem thus impacting branch and leaf arrangement. A disturbance such as a microburst or timber thinning operation will influence canopy structure by allowing more light to penetrate and disperse within the canopy which will influence photosynthesis processes. Past land use, including agricultural activities, timber harvesting, and human habitation have all been found to influence present species composition. These dynamics influence the age structure, growth rates, and species composition (Foster et al., 1992; Motzkin et al., 1996).

Forest Succession and Canopy Stratification

Successive changes in species dominance have been extensively studied for many years (Clements, 1916; Gleason, 1926). Oliver and Larson, 1996, describe current understanding of processes and patterns of forest stand development by synthesizing early and modern studies of succession. Early studies indicated that following a major stand replacement event (i.e., widespread windthrow, harvesting, disease and insect outbreaks) one or a few species would invade the disturbed area and dominate for a period of time. Following the initial invasion and consequent altering of the environment, a different group of species would invade and achieve dominance. The concept of one group of species replacing another group is referred to as “relay floristics” (Fig. 2.1a). This pattern would continue until a group of species would replace itself and reach a “steady state” or what early ecologists called a climax state (Cowles, 1911; Oosting, 1956; Odum, 1959). Each species group was presumed to be even-aged. More recently, most ecologists agree that the “initial floristics” (Fig. 2.1b) pattern is more prominent in stand development. After a major disturbance, most plant species existing in a stand invade shortly after the event and remain throughout the life of the stand. Species with the fastest initial growth rates will initially dominate the stand. Other slower growing species are present in the stand but not as prominent. After several years some individuals that previously dominated the stand die and are replaced by individuals that were formerly being outcompeted for resources. “Elements of both initial and relay floristics are characteristic of forest development; however, the invasion pattern after a disturbance predominantly follows the initial floristics pattern." (Oliver and Larson, 1996)

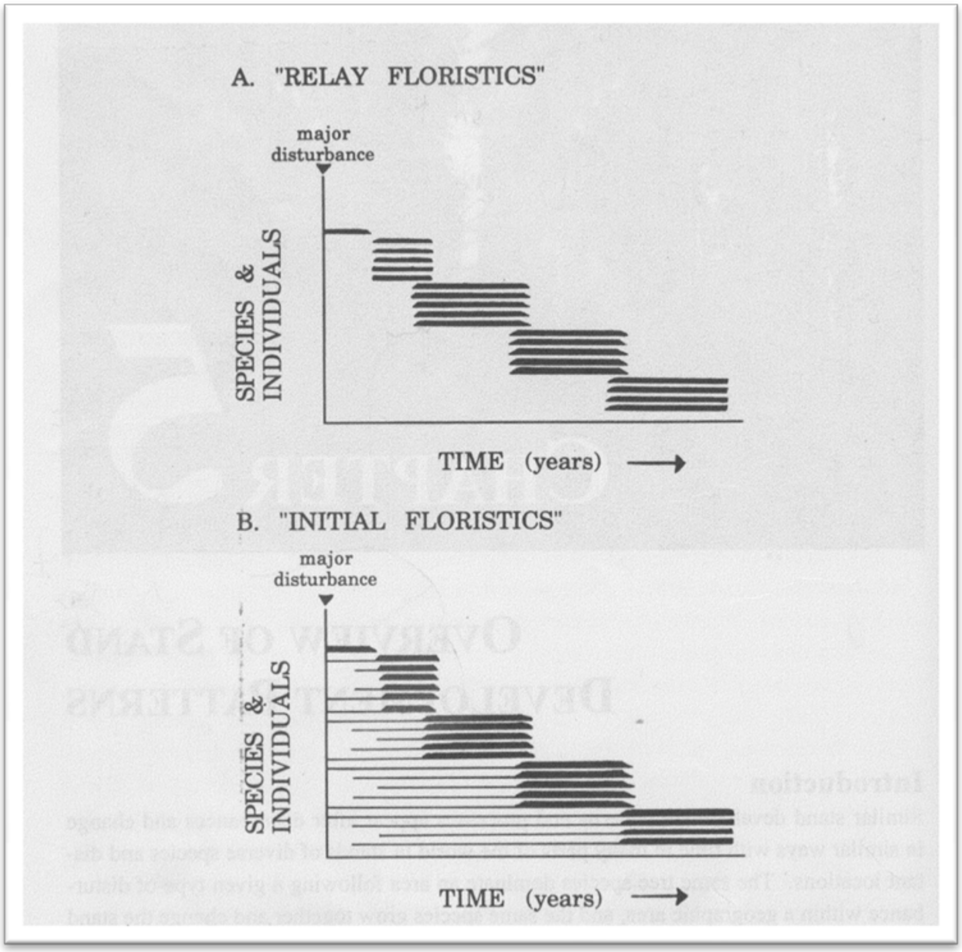

Figure 2.1 Two patterns of stand development as described by Oliver & Larson, 1996. Relay Floristics (A) is the traditional pattern where one species or group of species invades followed with replacement by a successive species or group of species. Initial Floristics (B) is the more prevalent pattern where all species are in place soon after disturbance and some species or groups of species assert dominance at different times. From Oliver & Larson, 1996, p. 146.

Underlying the broader succession process is forest canopy development. The arrangement of canopy structure is fundamental to many of the ecological processes discussed in the previous section. Ecologists must find ways to organize tree canopy in order to study and quantify a forest's architecture. Stratification has long been used in the field as a strategy by which scientists can define and separate canopy components "…such as forest leaves, and other structures, species, or individual organisms into distinct horizons, layers, or gradients," (Shaw, 2004) in order to investigate, describe, and predict a canopy's ecological processes. Moffet (2000) defines stratification as any non-uniform vertical distribution within vegetation. Smith (1973) concluded stratification is beneficial to forests because it optimizes light use, CO_2 concentrations, pollination, and dispersal, and increases structural integrity of the forest.

Shaw (2004) argues that the vertical gradient is a defining feature in forests. As tree heights increase, the structure and microclimate become more vertically organized. Smaller-stature vegetation types such as shrubs also exhibit vertical patterns (Moffet, 2001). Although a spatially heterogeneous forest (canopy gaps, uneven tree spacing, varying branch and leaf arrangements, and canopy openness) will display varying environmental characteristics, in general, the microclimate (light, humidity, temperature, and wind) of the upper canopy displays more variation in daily environmental characteristics compared to the lower canopy (Shaw, 2004). Imposing vertical planes within canopies provides a simplified way to visualize and organize concepts.

Oliver and Larson (1996) define and describe tree canopy strata in the context of stand development and succession. After a disturbance, during *the stand initiation stage*, new individuals and species continue to appear for several years. After several years new individuals do not appear and some existing individuals die. The surviving ones continue to grow larger. First, one species may grow larger and appear to dominate the stand and then another may appear to predominate. This stage is referred to as *the stem exclusion stage*. It may take several decades for a given stand to move from the stand initiation stage into the stem exclusion stage. After the stem exclusion stage, herbs shrubs, and advance regeneration again appear in the understory, growing very little, in what is called the *understory reinitiation* stage. Decades and even centuries later, the *old growth stage* occurs. Overstory trees die in an irregular fashion, and some of the understory trees begin to grow into the overstory (Fig. 2.2)

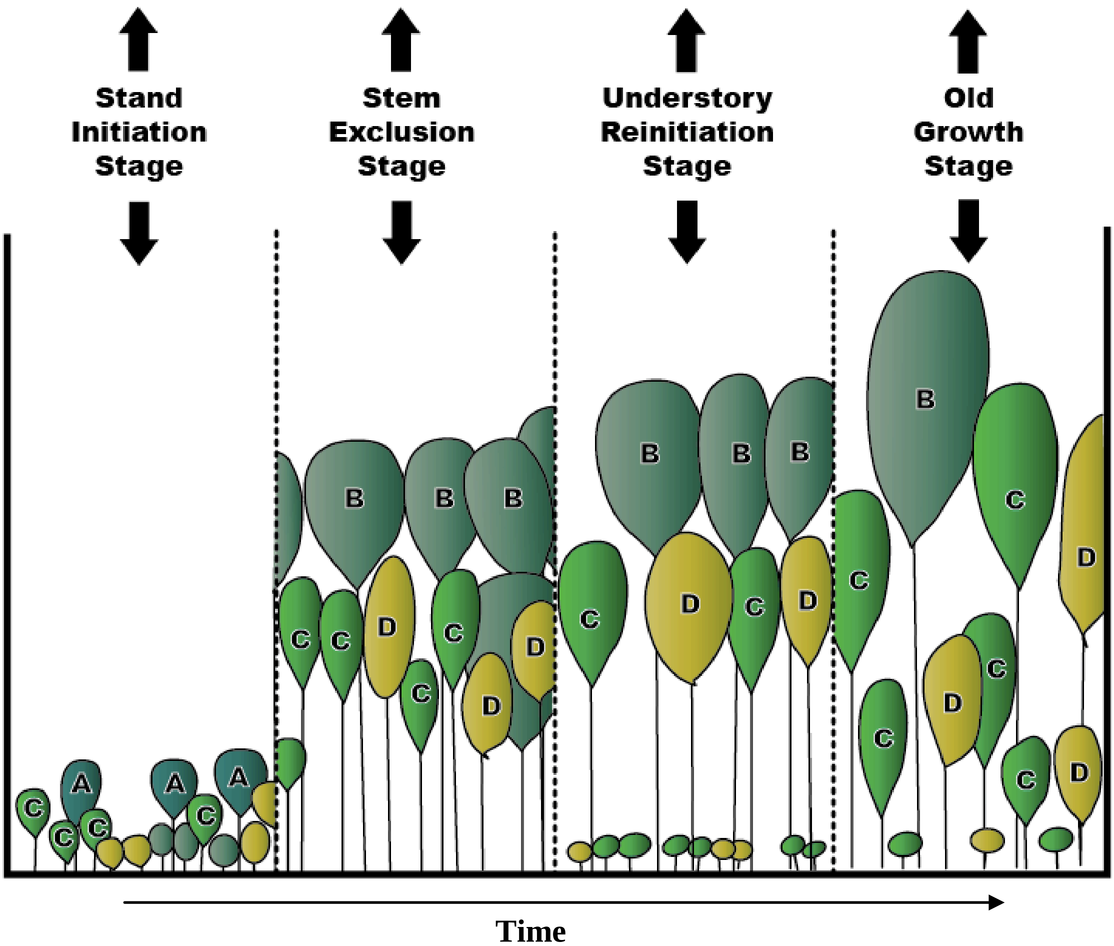

Figure 2.2. Canopy strata development through time.

It is during the Stem Exclusion Stage that stratification arises in stand structure. Environmental conditions and physiological predispositions of interacting species make it possible to anticipate future stand structure to a degree (Oliver and Larson, 1996). Characteristics including individual species growth rate, differences in ages, microsites, and spacing, enable one to predict future growth patterns within a stand. Oliver and Larson identify four primary strata within a mixed species stand (Fig. 2.3). A stand may have an *A-stratum* which contains emergents, or trees that grow taller than any other in the stand. The *B-stratum*, also called the upper continuous stratum, contains "an individual which acts as an emergent when intermixed with slower-growing species when grown with more trees of the same species." (Oliver and Turner, 1995) A *C-stratum* appears when two or more species have similar enough growth patterns but one asserts dominance and kills the other based on subtle differences in microsites, growth rates, and so forth. The dominant species is able to live beneath the shade of the B-stratum but continues to grow slowly because of reduced resources. "Eventually the continued growth of the upper stratum trees and the curtailed growth of the lower make the dominating trees much larger." (Oliver and Turner, 1995) The *forest floor stratum* contains trees and shrubs very close to the soil surface, which are usually no more than 2 m tall.

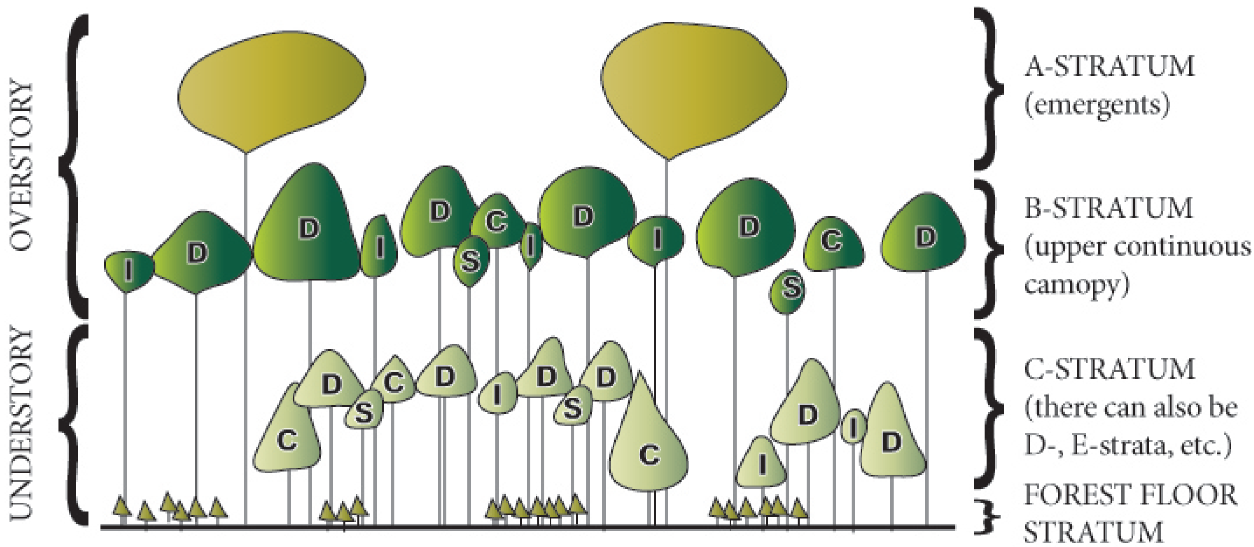

Figure 2.3. The relative positions of canopy strata and crown classes. From Oliver & Larson, 1996, p. 154.

Measuring Vegetation Structure Using Remote Sensing Techniques

By using “scaling-up” methods, researchers have had differing degrees of success mapping land cover by correlating field-collected data to the coarser spatial resolutions of conventional satellite imagery with the goal of describing broad scale ecological processes (Cullinan et al, 1997; Milne et al, 1999; Yamaji et al, 2009; Clark et al, 2010). Aerial photography has been used to map vegetation patterns since the 1960s (Kershaw, 1964; Johnson, 1969). Publically and commercially available airborne and satellite high spatial resolution imagery have increased ecologists’ research to rely less on field collected data to determine broad scale processes, thus saving time and money. However, using such data limits researchers’ abilities to measure key ecological characteristics including forest structure because traditional remote sensing approaches depend heavily on the optical sensors recording spectral reflectance in addition to the surface reflectance properties. (Harding et al, 2000). For example, passive optical sensors that detect visible to mid-infrared wavelengths rely on solar illumination of the ground and canopy surfaces. The strength of the reflected signals are dependent upon many factors including energy interactions in the atmosphere (scattering, transmission, and absorption due to water vapor, particulates, carbon dioxide, haze) and interactions with earth surface features that will return diffuse signals (Lillesand et al., 2007). Another limitation of traditional digital and softcopy aerial photography is the limited amount of forest structural detail that such data are able to record. While most airborne photographs and digital images are now flown in stereo and provide three-dimensional data, structural detail about a forest stand is limited by the height at which the area is flown, the angle at which the area is photographed, and adverse atmospheric conditions. Multiple images flown of the same area at differing angles are needed to acquire structural detail beyond canopy height. Finally, such imagery is unable to capture data beneath the tops of forest canopies, thus omitting structural data that describe a large portion of the forest.

Lidar Metrics

In recent years, ecologists have discovered lidar to be a valuable tool with which they can obtain data about tree and stand structure on a detailed level (Lefsky et al., 2002). Lidar sensors use an active pulse of electromagnetic energy to measure the distance between the sensor and a target surface by determining the elapsed time between “the emission of a short-duration laser pulse and the arrival of the reflection of that pulse” (Lefsky et al., 2002). When the sensor measures repeated pulses along a transect on the ground, the result is an outline of the ground surface and all objects, including vegetation, that reside on the ground surface (Fig. 2.4). Each pulse forms a circular area referred to as an “instantaneous laser footprint” on the ground (Jensen, 2006). A single pulse can generate one return or multiple returns depending on whether it encounters any material with local relief. By analyzing multiple return lidar, researchers may gain a more thorough understanding of stand architecture (Fig. 2.5). Typical point density is between 0.3 m and 2 m and laser footprints range from 0.25 to 2 m (Maune, 2007). While traditional passive optical sensors are able to measure generalized ground characteristics along a horizontal plane with relative success, lidar’s ability to record horizontal X and Y positions, and vertical Z positions at high spatial resolutions enables researchers to obtain more detailed and accurate characteristics of forest structure.

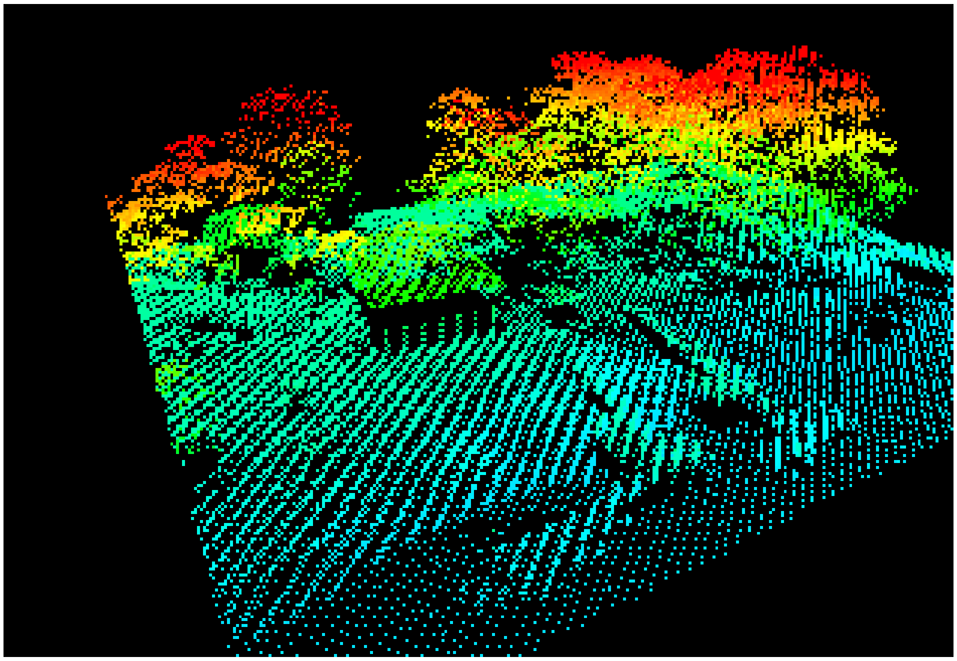

Figure 2.4. Perspective view of lidar point cloud data showing rooftops and trees for an area on the Isle of Hope, Georgia.

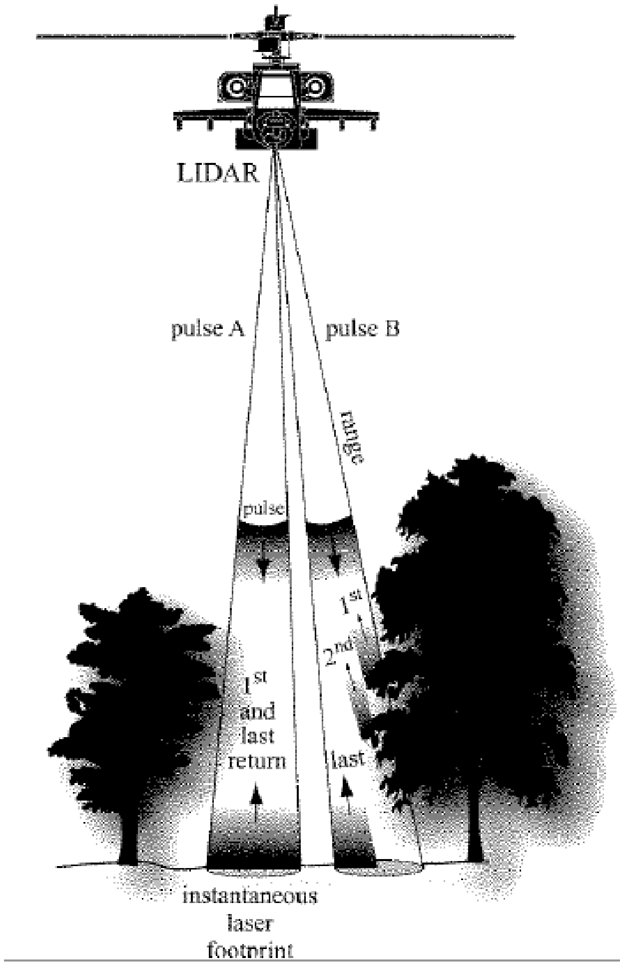

Figure 2.5. Multiple returns may be generated from a single lidar pulse (From Jensen, 2006).

Using lidar metrics and field data, researchers have successfully characterized forest succession, predicted neotropical migrant bird breeding habitat, estimated timber volume, and differentiated tree species, in a addition to a myriad of other applications (Kane et al., 2010; Naesset, 1997; Kim et al., 2009). Most research projects have used stand attributes including mean tree height, basal area, crown dimensions, species composition, cover, LAI, and biomass, correlated with lidar-derived metrics such as mean canopy height and canopy density, to address the above mentioned research questions (Coops et al., 2007; Goodwin et al., 2007). Additionally, scientists have used the first return lidar pulse type to derive individual tree height and average canopy height, changes in foliage distribution, as well as canopy surface terrain (Kane et al.,2010 a and b; Parker et al., 2004). Very little research, however, has incorporated the full suite of return type pulses into forest structure analyses with the exception of one project conducted by Miura & Jones (2010). The researchers used all return types available (1 through 4) to characterize the components of forest ecological structure, by generating statistics that indicate the openness, presence of vegetation, and density of vegetation at differing layers in the forest canopy profile. The researchers found the lidar metrics were good predictors for the presence of understorey and mid-storey vegetation, LAI, canopy cover, canopy depth in medium and high vegetation, openings above medium vegetation, and vertically dense canopies in the high vegetation.

As discussed above, there are many publications that find strong correlations between field based measurements and lidar metrics. This research project capitalizes on other research findings by using conclusive evidence of lidar's strength as a tool with which to measure forest stand structural attributes. Since past land use contributes to modern day vegetation composition and structure, this research aims to find relationships between forest structure and land use legacies using lidar data.

CHAPTER 3

BACKGROUND AND STUDY AREA

The study area is on the Isle of Hope, an inner barrier island approximately 16 km southeast of Savannah, Georgia (Fig. 3.1). The Isle of Hope is a component of the Princess Anne Shoreline complex, one of a series of Pleistocene sand shelves. The complex is characterized by marsh and lagoonal facies (USGS, 2010). The Georgia coast experiences moderate climate conditions. Precipitation averages roughly 125 cm per year along the coast (NOAA, 2010). Average summer temperatures are around 32°C and winter daily temperatures average around 10°C. The dry season occurs in the winter months and the wet season arrives during the summer months when chances of hurricanes increase. Snowfall is very rare on the Georgia coast (Georgia State Climatology Office, 1998) and experiences approximately 315 frost free days (NOAA, 2010).

The area may be classified as a Coastal Fringe Evergreen Forest, a subclass of the more broadly defined Southeastern Maritime Forest (Bellis, 1995). This forest class is defined by the following forest characteristics: The forest canopy is dominated by *Quercus hemisphaerica, Q. virginiana*, and *Pinus taeda*. Other canopy trees include *Q. falcata, Q. nigra, Carya glabra*, and *Pinus palustris*. Species including *Osmanthus americanus*, *Persea borbonia, Magnolia virginiana, Illex opaca, and Juniperus virginiana*, form the understory. *Illex vomitoria* is the most typical shrub. Other shrubs including *Myrica cerifera, and Sabal minor*, contribute a large component to the understory. Vines commonly found include *Vitis rotundifolia*, *Smilax spp.*, *Gelsemium sempervirens*, and *Campsis radicans*. The herb layer is very sparse and low in diversity.

The Wormsloe Plantation, which encompasses over half of the Isle of Hope and is roughly 350 ha in size, bounds the study site. Most soils on Wormsloe are classified as a local series of sand, loam, or a variation between the two classes. The topography is flat with elevations ranging from approximately 1.5 m near the marsh edge to 4.5 m towards the south central portion of the property (Fig 3.2). Extensive ditches of varying depth that were dug in the 1700s and 1800s to keep fields drained are still visible across the property today. The plantation is surrounded by salt marsh and tidal creeks including Jones Narrows, an offshoot of the Skidaway River, on the east side, and the Moon River on the south and west sides. The Isle of Hope community abuts the property boundary on the northern border. Beyond the marshes and creeks to the east are Long Island and Skidaway Island. The mainland lies across the marsh to the west.

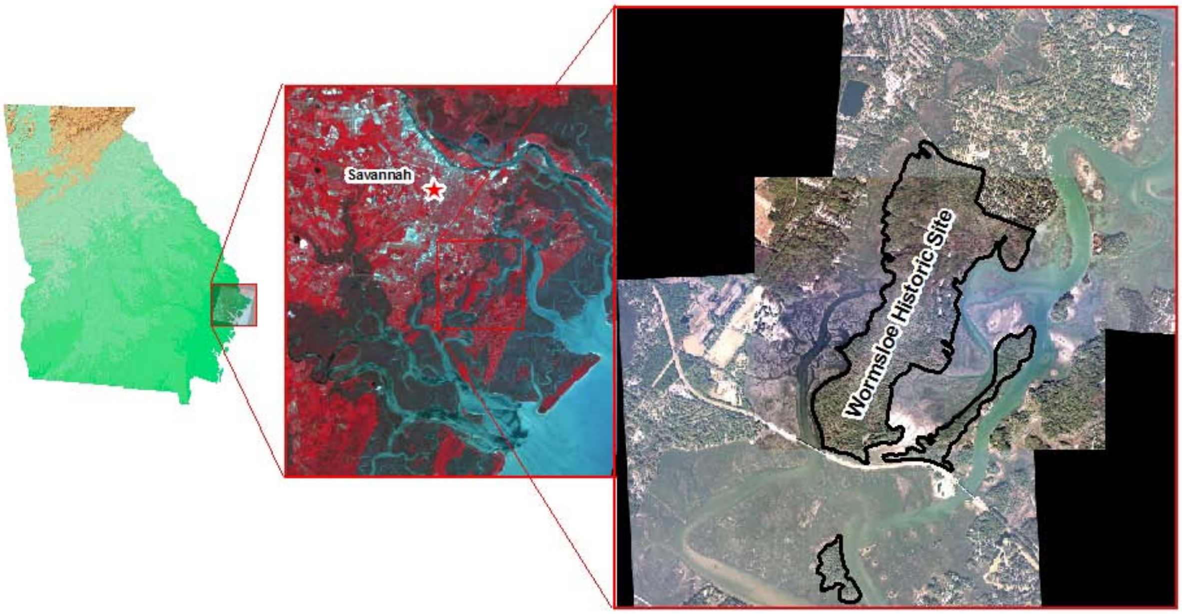

Figure 3.1. Wormsloe Plantation is located on the Isle of Hope, which is approximately 16 km southeast of Savannah, Georgia.

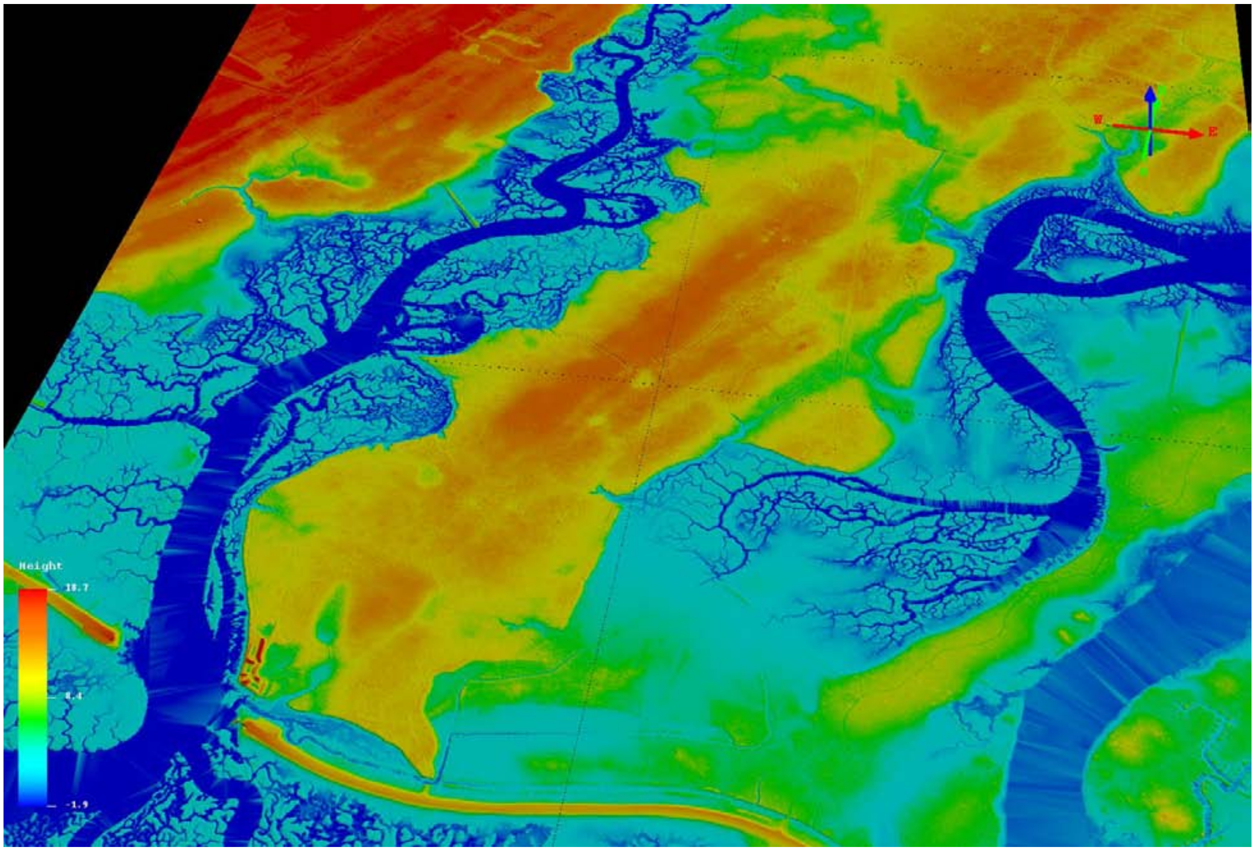

Figure 3.2. Lidar derived DEM of Wormsloe. Relief varies little across the study site with the minimum elevation being 1.5 m (shown in green) and the maximum elevation being 4.5 m (shown in red).

Prior to European settlement in the 1730s, coastal Georgia was occupied by Native Americans for over 4,000 years as evidenced by the presence of shell middens and other ancient artifacts. The earliest recorded human presence on coastal Georgia was during the Archaic Period, which lasted about 10,000 to 3,000 years ago (The New Georgia Encyclopedia website, 2010). Beginning around 1450, the narrow strip of barrier islands was occupied by the predecessors of the Guale Indians. Little archeological evidence indicates cropland activities whereas, natives further inland relied more on vegetable cultivation for sustenance. The presence of discrete shell and bone middens, indicate a predominantly hunting, fishing, and gathering society rather than one based on agriculture. Furthermore, sites located on barrier islands were more nucleated and larger than those located inland where they were smaller and more spread out (Saunders, 2000). Based on the above evidence one may speculate that impacts on the landscape were localized as opposed to widespread prior to European colonization. Nonetheless, the natives' activities would have impacted vegetation patterns on some level by influencing deer browsing activity through hunting, burning areas for communities, and adjusting soil chemistry with the formation of shell middens.

Prior to European colonization, mainland coastal Georgia was likely dominated by longleaf pine (*Pinus palustris*) forests due to naturally occurring fires inhibiting the growth of non-fire species, such as live oak (*Q. virginiana*), and encouraging fire adapted species including longleaf pine. John Abbot, who explored the Georgia Lowcountry in the late 1700s just as colonists were fully establishing their presence, describes many of the areas in this region as being in extensive pine woods, or flats (Stewart, 2002). Unlike the mainland forests however, the barrier islands may have consisted mostly of oak forests. Bratton (1985) states that after colonization but prior to the Antebellum period, live oak forests were predominant rather than the contemporary pine seen on St. Simons Island today. The Isle of Hope and other Georgia barrier islands likely had the same forest characteristics to St. Simons due to similar cultural activities and biophysical characteristics.

The founders of Wormsloe Plantation, Noble and Sarah Jones, immigrated from England in early 1733 with James Oglethorpe to help found a colony in the New World with philanthropic ideals as its basis (Coulter, 1955). From the plantation's beginning, agricultural experimentation was prioritized as a way to help make the new colony economically successful and sustainable. White mulberry trees (*Morus alba*) for silkworm cultivation (Coleman, 1976), vegetable crops, and livestock were of initial importance as the colony established its roots.

Exotic trees were also introduced during this time. A letter from Benjamin Franklin to Noble Jones included Chinese tallow (*Triadica sebifera*) seeds; the seeds were sent for the purposes of Jones testing their viability in the coastal Georgia climate. The tree became naturalized and today it occurs from the South Carolina coastal plain, south to Texas. Although this initial flurry of agricultural activity may indicate extensive croplands and forest clearing for pasturage, Swanson (2009) states, "Even after more than half a century of human settlement, Wormsloe and the surrounding coast retained vestiges of pre-colonial wildness at the conclusion of the Revolutionary War."

After Noble Jones's death in 1775, his children, Mary and Noble Wimberley Jones owned the property, respectively, until 1804. Based on historical maps, Wormsloe does not appear to have been a substantial working plantation during this time period and neither child lived or spent much time on the property. In 1804, Noble Wimberley Jones deeded the property to his son, George Jones. In 1819, George Jones contracted with an overseer to raise cotton and rented the house to a widower. The terms included cultivating 20 acres, from which it may be interpreted to mean that there was only 20 acres of cleared land on the property. In 1825, George Jones contracted to have a house built on Wormsloe to use as his country retreat (Kelso, 1979).

According to Swanson (2009), the dawn of the cotton culture brought extensive changes to the Wormsloe landscape in the 1800s, as Sea Island cotton became the plantation's staple crop and primary income producer. Former colonial fields where vegetables once grew were now being cultivated for Sea Island cotton. The first confirmed report of the crop being grown on Wormsloe is in 1806 on the 20 acres of cleared land. By the 1850s, most fields were planted in cotton and slaves were clearing forests for its cultivation. Oyster shells, livestock manure, imported South American guano, and mud from the marsh were used to revitalize the fields that were depleted from repeated cultivation.

By the 1860s, the property had expansive hay and corn fields; sugarcane and peanuts were also being grown. Clearing of woodlands continued as pastures for sheep and cattle were needed. Numerous structures were constructed to support the agricultural activities including barns, sheds, and stables that were built using wood from surrounding forests. A cotton gin and rice mill were built in the 1850s near the house that replaced Noble Jones's original tabby fort. An increase in the slave population also required more demand on the plantation's natural resources. In addition to harvesting timber from the surrounding woodland, wood was collected for heating and cooking purposes, undoubtedly further impacting the landscape. Agriculture on Wormsloe was halted during the Civil War for 3 to 5 years when the family retreated to the Blue Ridge Mountains.

Following the war, the Reconstruction era brought extensive changes to Wormsloe as it did all across the southeastern United States. Wormsloe's presence as a traditional Southern plantation came to an end with the advent of abolition. "Without slave labor, Wormsloe moved from a southern staple plantation to a rural pleasure ground and the site of smaller-scale but more diversified agriculture over the last third of the nineteenth century, a transition that mirrored changes taking places across the Lowcountry." (Swanson, 2009)

George W. Jones (who later added the surname De Renne), the master of Wormsloe during Reconstruction, rented the plantation to northern investors, made sharecropper arrangements and leased to newly freedmen after the Civil War. Unfortunately, none of these arrangements were economically successful for the Jones family. During the four decades after the war, areas of unimproved and arable land mostly remained the same; however, the types of agricultural activities shifted from cotton cultivation to vegetables and fruits, fodder for livestock, and pasture grass cultivation.

In 1885, a new law banned open range livestock in Chatham County, thus excluding roaming livestock from ranging on the forests at Wormsloe. Using historical photographs, Swanson (2009) observed the differences in the forests before and after the passage of the law:

> "During the 1870s and 1880s, wire fences surrounded the plantation house and outbuildings to exclude passing animals, and the forest was relatively open, with little understory as high as a cow could reach. Few seedlings grew between the larger trees, and longleaf pines in their fragile “grass” stage were noticeably absent. Pictures from the early twentieth century revealed a much different landscape. With the plantation herds and neighboring livestock safely in pastures and pens, the fences surrounding Wormsloe’s buildings were gone, and portions of the woods were much thicker. In one detailed photograph of the piney woodlands, young longleaf seedlings crowd the foreground of the frame. Not all of Wormsloe faced this transition. Portions of the estate remained in dairy pasture, and workers kept the landscaped grounds surrounding the house open and orderly, but other portions of the plantation underwent ecological succession once absent the pressure of continual grazing."

Swanson goes on to describe the young pines and oaks re-colonizing the hammock land and shrubs returning to previously grazed forest floors in the photographs.

In the mid 1890s, a commercial dairy farm was established on Wormsloe. George De Renne purchased dairy cows and chickens. In order to meet the demanding dietary needs of his dairy cattle, De Renne increased the quantity of hay, peas, beans, rye, and oats grown on former cotton fields. Fences were built around pastures to keep the livestock contained and to reduce time spent rounding up the cattle for the required daily milking. Truck farming also contributed to the plantation's income. Ultimately, however, dairy operations on Wormsloe ceased to exist by the 1930s with because the advent of pasteurization eliminated the need for locally produced milk. Where crops grew and pasture land was once maintained, early successional shrubby vegetation and pines soon re-colonized the open fields.

During the early part of the 20th century, the Savannah population and development expanded southward. The northern portion of the Isle of Hope was subdivided into numerous lots and schools and churches were constructed. The old fields and former woodlands were replaced with impervious surfaces including roof tops, asphalt for roadways, and concrete for sidewalks. Skidaway Road divided the northern urbanized environment from Wormsloe's former agricultural fields and successional woods. Subsequent generations of the family preserved the natural integrity of their land with wise planning that included a conservation easement and donating a large portion of the estate to the state of Georgia in 1974. That same year the southern pine beetle infested the pines on Wormsloe and the state of Georgia carried out a salvage timber operation by removing most of the pine trees.

The site’s long history of agricultural cultivation and grazing undoubtedly shaped its modern day environment. Today, most of the site is mixed hardwood and pine forests with the exception of the private residential area which consists of widely spaced live oaks and other ornamental vegetation. The Georgia Department of Natural Resources owns 333 hectares, which is known as the Wormsloe State Historic Site. A visitor's center, nature trails, and interpretive historic features are open to the public. The Barrow family, direct descendents of the original settlers of the property, Nobel and Sarah Jones, own 25 hectares where a private residence and outbuildings are located and the Wormsloe Foundation owns 6 hectares where a historic cabin remains (Wormsloe Institute for Environmental History website, 2010).

CHAPTER 4

METHODOLOGY

As part of an effort to characterize existing plant communities and document changes through time, the WIEH funded UGA CRMS to follow the model of Harvard Forest (www.harvardforest.fas.harvard.edu) to establish 33 permanent vegetation plots across Wormsloe Plantation (Fig 4.1). The placement of each plot was partly chosen based on its environmental history as documented in the 1897 map titled "An Index Map of Wormsloe, Showing the improvements being made spring, 1897." Land use legacies considered for representation in vegetation plots included human habitation, and forest clearing, crop cultivation, and disease and pest outbreaks. In addition, plot locations considered areas of pine removal following the southern pine bark beetle in the mid 1970s. Plots were distributed throughout the Wormsloe State Historic Site, Long Island, and Pigeon Island land holdings and selection finally attempted to characterize the different vegetation communities and land use histories.

The GPS coordinates of the center of each plot were located and documented using a Garmin eTrex unit. Plant species presence and abundance are currently being measured in the 33 nested plots. Species, DBH, and abundance of trees, which are defined as single stem woody plants greater than or equal to 5 cm DBH and generally over 5-m in height, are being surveyed in 20 m x 20 m (or 400 m^2) plots. Shrubs, defined as single or multi-stem woody plants less than 5 cm DBH and generally under 5-m in height, and saplings, defined as single-stem, woody plants less than 10 cm DBH and generally under 5-m in height, are being surveyed for species and abundance within 10 m x 10 m (or 100 m^2) plots nested within the 20 m x 20 m plots. Finally, herbaceous woody and non-woody plant species that are generally less than 1 m in height are being surveyed in 1 m x 1 m (or 1 m^2) plots.

Figure 4.1 Vegetation plots have been established across Wormsloe Plantation to characterize current plant communities and to monitor long term plant dynamics.

Creating a 200 year Spatio-Temporal Land Use Database

The land cover (field, evergreen forest, and mixed forest) of each plot was determined by interpreting maps and aerial photographs collected from various years and sources and compiled into a central WEIH geodatabase by UGA-CRMS. The earliest map dating from 1810, this digital collection contains scanned and georectified historical maps from the UGA Hargrett Rare Books and Manuscripts Library and federal agencies, USGS topographic maps and aerial photographs in black-and-white, color infrared (CIR), and true color format spanning 1971 to present (Table 4.1). This temporally-rich geospatial database provided information for designating the land use/land cover of each plot for each decade between 1810 and 2010. Although spatially comprehensive, some of the maps and aerial photographs did not cover the entirety of the study site and thus, some plots were not represented on these documents. Since the time between the date of each map/aerial photograph was highly variable (11 years, 4 years, 21 years, and so forth) the land cover timeline was interpolated for equal 10-year intervals.

To assign land covers for the unrepresented plots, land cover was determined by examining earlier maps and aerial photos in order to extrapolate land cover. For example, a plot that was in evergreen forest 50 years previous to the most recent map being examined was marked as mixed forest for the time interval in question. Presumably, this fifty year time interval was a sufficient amount of time for a pine dominated forest to have succeeded into a mixed forest. Such estimates were based on information related to maritime forest succession. Other factors, including documented agricultural activities on the property and the general accuracy of each map was taken into consideration when documenting historic land cover. Therefore, the same land cover as the previous ten years was assigned to the current time interval. This process was repeated over the entire 200 year timeline in order to fill in “time gaps” for each plot. Table 4.2 shows land use/land cover plot assignments for the three time periods.

Table 4.1 Maps and aerial photographs of varying sources and accuracies were used to determine each plot’s land cover over a 200 year span.

Year	**Type**	**Source**	**Percent Coverage**
1810	Sketch	Documentation from De Renne Family Collection, Hargrett	95%
1897	Sketch/painting	Hargrett Rare Book & Manuscript Library	60%
1908	Sketch	Hargrett Rare Book & Manuscript Library	95%
1912	Topographic	Army Corps of Eng/ USGS	100%
1933	Sketch	US Coast & Geodetic Survey: Air photo compilation	100%
1937	Sketch	Farm Map Tracing: USDA & A.A.A.	50%
1945	Topographic	USGS	100%
1957	Topographic	USGS	100%
1971	b&w aerial photograph	Unknown origin from Skidaway Institute for Oceanography	95%
1976	b&w aerial photograph	Unknown origin from UGA Maps Library	100%
1988	b&w aerial photograph	NHAP, USGS	90%
1999	CIR aerial photograph	NAPP, USGS	100%
2009	True color aerial photograph	NAIP, USDA	100%

Table 4.2 LULC changes in plots spanning three time periods: Antebellum, Postbellum, and Pine Beetle Infestation periods

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Antebellum Period

Plot No.	1820	1830	1840	1850	1860	Disturbance Score	Disturbance Class
1	Field	Field	Evergreen forest	Evergreen forest	Evergreen forest	12	High
2	Field	Field	Field	Field	Field	15	High
3	Mixed forest	Mixed forest	Mixed forest	Field	Field	9	Medium
4	Mixed forest	Mixed forest	Mixed forest	Field	Field	9	Medium
5	Field	Field	Field	Field	Field	15	High
6	Mixed forest	Mixed forest	Mixed forest	Mixed forest	Mixed forest	5	Low
7	Mixed forest	Mixed forest	Mixed forest	Mixed forest	Mixed forest	5	Low
8	Mixed forest	Mixed forest	Mixed forest	Mixed forest	Mixed forest	5	Low
9	Mixed forest	Mixed forest	Mixed forest	Field	Field	9	Medium
10	Mixed forest	Mixed forest	Mixed forest	Field	Field	9	Medium
11	Mixed forest	Mixed forest	Mixed forest	Field	Field	9	Medium
12	Mixed forest	Mixed forest	Mixed forest	Mixed forest	Mixed forest	5	Low
13	Mixed forest	Mixed forest	Mixed forest	Mixed forest	Mixed forest	5	Low
14	Mixed forest	Mixed forest	Mixed forest	Field	Field	9	Medium
15	Mixed forest	Mixed forest	Mixed forest	Field	Field	9	Medium
16	Mixed forest	Mixed forest	Mixed forest	Mixed forest	Mixed forest	5	Low
17	Mixed forest	Mixed forest	Mixed forest	Mixed forest	Mixed forest	5	Low
18	Mixed forest	Mixed forest	Mixed forest	Mixed forest	Mixed forest	5	Low
19	Mixed forest	Mixed forest	Mixed forest	Field	Field	9	Medium
20	Mixed forest	Mixed forest	Mixed forest	Mixed forest	Mixed forest	5	Low
21	Mixed forest	Mixed forest	Mixed forest	Field	Field	9	Medium
22	Mixed forest	Mixed forest	Mixed forest	Field	Field	9	Medium
23	Mixed forest	Mixed forest	Mixed forest	Mixed forest	Mixed forest	5	Low
24	Mixed forest	Mixed forest	Mixed forest	Mixed forest	Mixed forest	5	Low
25	Mixed forest	Mixed forest	Mixed forest	Mixed forest	Mixed forest	5	Low
26	Mixed forest	Mixed forest	Mixed forest	Mixed forest	Mixed forest	5	Low
27	Mixed forest	Mixed forest	Mixed forest	Mixed forest	Mixed forest	5	Low
28	Mixed forest	Mixed forest	Mixed forest	Mixed forest	Mixed forest	5	Low
29	Mixed forest	Mixed forest	Mixed forest	Field	Field	9	Medium
30	Mixed forest	Mixed forest	Mixed forest	Mixed forest	Mixed forest	5	Low
31	Mixed forest	Mixed forest	Mixed forest	Field	Field	9	Medium
32	Mixed forest	Mixed forest	Mixed forest	Mixed forest	Mixed forest	5	Low
33	Mixed forest	Mixed forest	Mixed forest	Mixed forest	Mixed forest	5	Low

Postbellum Period

Plot No.	1870	1880	1890	1900	1910	Disturbance Score	Disturbance Class
1	Evergreen forest	Mixed forest	Mixed forest	Mixed forest	Mixed forest	6	Low
2	Evergreen forest	Evergreen forest	Evergreen forest	Evergreen forest	Evergreen forest	10	Medium
3	Field	Field	Field	Field	Evergreen forest	14	High
4	Field	Field	Field	Field	Field	15	High
5	Field	Field	Field	Field	Field	15	High
6	Mixed forest	Mixed forest	Mixed forest	Mixed forest	Mixed forest	5	Low
7	Mixed forest	Mixed forest	Mixed forest	Mixed forest	Mixed forest	5	Low
8	Mixed forest	Mixed forest	Mixed forest	Mixed forest	Mixed forest	5	Low
9	Field	Field	Field	Field	Evergreen forest	14	High
10	Field	Field	Field	Field	Evergreen forest	14	High
11	Field	Field	Field	Field	Evergreen forest	14	High
12	Mixed forest	Mixed forest	Mixed forest	Mixed forest	Mixed forest	5	Low
13	Mixed forest	Mixed forest	Mixed forest	Mixed forest	Field	7	Low
14	Evergreen forest	Evergreen forest	Evergreen forest	Mixed forest	Mixed forest	8	Medium
15	Evergreen forest	Evergreen forest	Evergreen forest	Mixed forest	Mixed forest	8	Medium
16	Field	Field	Field	Field	Evergreen forest	14	High
17	Evergreen forest	Evergreen forest	Evergreen forest	Evergreen forest	Evergreen forest	10	Medium
18	Mixed forest	Mixed forest	Mixed forest	Mixed forest	Mixed forest	5	Low
19	Field	Field	Field	Field	Field	15	High
20	Mixed forest	Mixed forest	Mixed forest	Mixed forest	Mixed forest	5	Low
21	Field	Field	Field	Field	Field	15	High
22	Field	Field	Field	Field	Field	15	High
23	Mixed forest	Mixed forest	Mixed forest	Evergreen forest	Evergreen forest	7	Low
24	Field	Field	Field	Field	Evergreen forest	14	High
25	Field	Field	Field	Field	Evergreen forest	14	High
26	Field	Field	Field	Field	Evergreen forest	14	High
27	Field	Field	Field	Field	Evergreen forest	14	High
28	Mixed forest	Mixed forest	Mixed forest	Evergreen forest	Evergreen forest	7	Low
29	Field	Field	Field	Field	Field	15	High
30	Mixed forest	Mixed forest	Mixed forest	Mixed forest	Mixed forest	5	Low
31	Field	Field	Field	Field	Evergreen forest	14	High
32	Mixed forest	Mixed forest	Mixed forest	Mixed forest	Mixed forest	5	Low
33	Mixed forest	Mixed forest	Mixed forest	Mixed forest	Mixed forest	5	Low

Pine Beetle Infestation Period

Plot No.	1970	1980	1990	2000	2010	Disturbance Score	Disturbance Class
1	Mixed forest	Mixed forest	Mixed forest	Mixed forest	Mixed forest	5	Low
2	Mixed forest	Mixed forest	Mixed forest	Mixed forest	Mixed forest	5	Low
3	Mixed forest	Mixed forest	Mixed forest	Mixed forest	Mixed forest	5	Low
4	Mixed forest	Mixed forest	Mixed forest	Mixed forest	Mixed forest	5	Low
5	Field	Evergreen forest	Evergreen forest	Evergreen forest	Evergreen forest	11	Medium
6	Mixed forest	Mixed forest	Mixed forest	Mixed forest	Mixed forest	5	Low
7	Mixed forest	Mixed forest	Mixed forest	Mixed forest	Mixed forest	5	Low
8	Field	Evergreen forest	Evergreen forest	Evergreen forest	Evergreen forest	11	Medium
9	Mixed forest	Mixed forest	Mixed forest	Mixed forest	Mixed forest	5	Low
10	Mixed forest	Mixed forest	Mixed forest	Mixed forest	Mixed forest	5	Low
11	Mixed forest	Mixed forest	Mixed forest	Mixed forest	Mixed forest	5	Low
12	Mixed forest	Mixed forest	Mixed forest	Mixed forest	Mixed forest	5	Low
13	Field	Mixed forest	Mixed forest	Mixed forest	Mixed forest	7	Low
14	Mixed forest	Mixed forest	Mixed forest	Mixed forest	Mixed forest	5	Low
15	Mixed forest	Mixed forest	Mixed forest	Mixed forest	Mixed forest	5	Low
16	Field	Field	Mixed forest	Mixed forest	Mixed forest	9	Medium
17	Evergreen forest	Evergreen forest	Evergreen forest	Evergreen forest	Evergreen forest	10	Medium
18	Mixed forest	Mixed forest	Mixed forest	Mixed forest	Mixed forest	5	Low
19	Mixed forest	Mixed forest	Mixed forest	Mixed forest	Mixed forest	5	Low
20	Mixed forest	Mixed forest	Mixed forest	Mixed forest	Mixed forest	5	Low
21	Field	Evergreen forest	Evergreen forest	Evergreen forest	Evergreen forest	11	Medium
22	Evergreen forest	Evergreen forest	Evergreen forest	Evergreen forest	Evergreen forest	10	Medium
23	Mixed forest	Mixed forest	Mixed forest	Mixed forest	Mixed forest	5	Low
24	Field	Evergreen forest	Evergreen forest	Evergreen forest	Evergreen forest	11	Medium
25	Field	Evergreen forest	Evergreen forest	Evergreen forest	Evergreen forest	11	Medium
26	Field	Evergreen forest	Mixed forest	Mixed forest	Mixed forest	8	Medium
27	Mixed forest	Mixed forest	Mixed forest	Mixed forest	Mixed forest	5	Low
28	Mixed forest	Mixed forest	Mixed forest	Mixed forest	Mixed forest	5	Low
29	Mixed forest	Mixed forest	Mixed forest	Mixed forest	Mixed forest	5	Low
30	Mixed forest	Mixed forest	Mixed forest	Mixed forest	Mixed forest	5	Low
31	Mixed forest	Mixed forest	Mixed forest	Mixed forest	Mixed forest	5	Low
32	Evergreen forest	Evergreen forest	Evergreen forest	Evergreen forest	Evergreen forest	10	Medium
33	Mixed forest	Mixed forest	Mixed forest	Mixed forest	Mixed forest	5	Low

In order to examine significant historical periods in which land use was potentially a major influence on modern day forest structure, the timeline was subdivided into three 50 year time intervals that represented significant environmental disturbances and/or land use shifts. The Antebellum period spanned from 1810 to 1860; the Postbellum period spanned between 1870 and 1910; and the Pine Bark Beetle period spanned from 1970 to present day. During the Antebellum period, Wormsloe management promoted sea island cotton cultivation because it commanded the highest price of those crops suitable for agriculture on the Georgia coast. Because of this intense cultivation, Wormsloe went from a mostly forested property in the late 1700's and the first part of the 1800's to a profitable plantation where cotton fields dominated the landscape. After the Civil War, during the Postbellum era, a variety of crops continued to be cultivated at Wormsloe; however, the extent of cultivation declined with the lack of slave labor necessary for broad scale agricultural activities. The third significant period at Wormsloe began in the 1970's. In 1974, the southern pine bark beetle weakened and/or killed the majority of slash and longleaf pines that dominated the landscape on the island throughout the 20th century. The Georgia Department of Natural Resources began salvage timber operations immediately following the beetle outbreak. The timber harvesting left large areas of cleared field and shrubby areas, thus, once again, shifting the land cover on Wormsloe.

After determining land cover for each plot, the three subsets, representing the major land use eras at Wormsloe were examined. Within each era, the individual plots were assigned a disturbance score based on how many times that plot was in a particular land cover or land use (LULC). These classes, which included Mixed Forest, Evergreen Forest, and Field, were weighted based on the assumption that some LULC have greater impact on vegetation structure than others, mainly due to the extent and frequency of soil disturbance. In order to capture the level of disturbance over the 200-year record of historical land uses, a point system was developed. Fields are assumed to undergo the greatest disturbance, evergreen forests are more recently abandoned fields and mixed forests have the least disturbance with longer recovery time and/or lack of former use as an agricultural field. For example, if a plot is in Field land use for a 10 year interval then it receives 3 points. If it is in Evergreen Forest for a 10-year interval, it receives 2 points, and if it is in Mixed Forest then it receives 1 point. Following point assignments, the total points were calculated for each plot within the three major land use eras. The scores were then classified using natural breaks into three categories: low, medium, and high levels of disturbance. See Table 4.2 for land cover classes, disturbance scores, and disturbance levels for each plot during the three time periods.

In addition to levels of disturbance, vegetation structure may be influenced by the frequency of LULC change. A point system of transitions was therefore developed. After assigning disturbance levels to the plots, each plot's three disturbance levels were summarized by examining how many times the disturbance levels changed over the course of the three time periods. For example, Plot 6 had three "low" disturbance levels over the three time periods. It received a 0, or "low" transition level because its disturbance level remained the same over the course of the three time periods. The disturbance levels for Plot 1 changed once; therefore, it received a 1, or "moderate" transition level. Plot 31 received a 2, or "high" transition level because its disturbance levels changed twice. Table 4.3 shows Transition Level scores and classes for each plot.

Table 4.3. Disturbance levels and resulting transition scores and classification for each plot.

Plot No.	Antebellum	Posttbellum	Pine Beetle	Transition Score	Transition Class
1	high	low	low	1	moderate
2	high	medium	low	2	high
3	medium	high	low	2	high
4	medium	high	low	2	high
5	high	high	medium	1	moderate
6	low	low	low	0	low
7	low	low	low	0	low
8	low	low	medium	1	moderate
9	medium	high	low	2	high
10	medium	high	low	2	high
11	medium	high	low	2	high
12	low	low	low	0	low
13	low	low	low	0	low
14	medium	medium	low	1	moderate
15	medium	medium	low	1	moderate
16	low	high	medium	2	high
17	low	medium	medium	1	moderate
18	low	low	low	0	low
19	medium	high	low	2	high
20	low	low	low	0	low
21	medium	high	medium	2	high
22	medium	high	medium	2	high
23	low	low	low	0	low
24	low	high	medium	2	high
25	low	high	medium	2	high
26	low	high	medium	2	high
27	low	high	low	2	high
28	low	low	low	0	low
29	medium	high	low	2	high
30	low	low	low	0	low
31	medium	high	low	2	high
32	low	low	medium	1	moderate
33	low	low	low	0	low

Lidar Data & Processing

The Savannah Area Geographic Information System (SAGIS), in partnership with the United State Geological Survey (USGS) and two other state organizations, worked to produce The Coastal Georgia Elevation Project. The purpose of the Elevation Project was to acquire lidar-derived high resolution elevation data from which to produce contours for the full extent of coastal Georgia and approximately 80 km inland; an area of approximately 12,180 km^2 (Chalmers and Simmons, 2010). Lidar data were collected over the Wormsloe area during leaf-off conditions (December, January, and February) between 2009 and 2010. At this time, the sensor, flight altitude, and wavelength used are unknown. Data were collected with a maximum field of view of 40 degrees (20 degrees off nadir). Lidar point cloud data were processed with 1.0 m maximum post spacing, a horizontal (bare earth) accuracy of +/-18.5 centimeters RMS minimum and a vertical accuracy in vegetation of +/-37 centimeters RMS minimum were required (ArcNews, Winter 2010/2011). A subset of seven tiles, each covering a 2.25 km^2 area, which encompassed Wormsloe proper, Long Island to the west, and Pigeon Island to the south, was obtained from SAGIS for the purposes of this research project (Fig. 4.2).

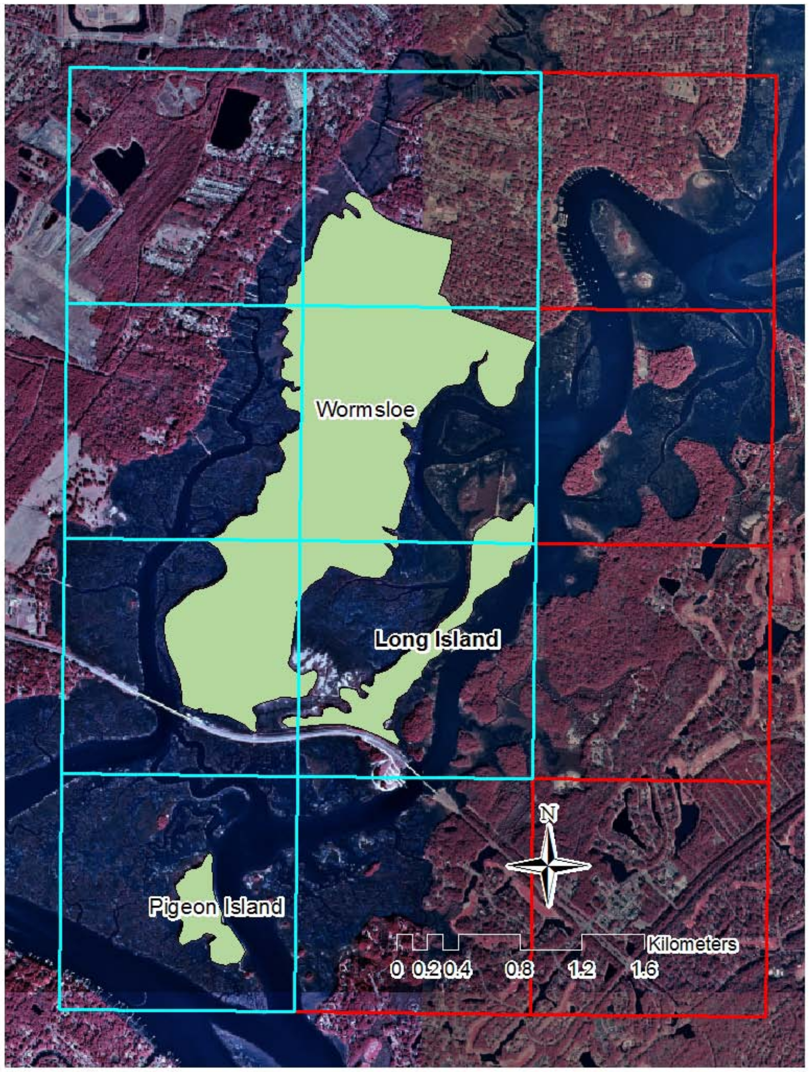

Figure 4.2 Lidar data tiles highlighted in blue were used for data analysis.

The center of each vegetation plot was recorded using a GPS unit in the field. Using the GPS coordinates as reference, the Crop Tool in Lidar Analyst was used to extract 33 LAS subsets representing each 20 x 20 m^2 vegetation plot. Each LAS point cloud file was opened in Quick Terrain Modeler and saved as an ASCII data file. The files included the X, Y, and Z coordinates, along with intensity values, the return number and number of returns for each lidar pulse, and the classification (1=nonground points and 2=ground points) for each pulse. In Quick

Terrain Modeler, a 1 foot x 1 foot grid digital elevational model (DEM) representing the study site was generated using the ground (Class 2) lidar points (See Figure 3.2).

In ArcGIS 10.0, each ASCII file was exported as a three-dimensional ESRI ArcGIS point shapefile. Using the Extract Values to Points tool within the Spatial Analyst tool set, raster values from the DEM were assigned to the corresponding points within the shapefile. The Z value (elevation above sea level) of each point was subtracted from the corresponding raster value to obtain a height above ground for each point.

Proposed Forest Characterization Scheme

This project uses a forest characterization scheme based on one proposed by Miura and Jones (2010). They classified their point cloud data into 4 classes: Ground (0 m), Low veg (>0-1 m), Medium veg (>1-5 m), and High veg (>5 m). In order to use a forest structure characterization scheme that would effectively describe the vegetation structure for all vegetation plots in this study, the point shapefiles were classified into eight vertical layers as opposed to 4 used in the Miura and Jones study. The increased numbers of strata with smaller elevational intervals are used for the following reasons. Jennings et al. (2009) divides canopy strata based on growth forms of individual plants in a theoretical forest plot. The field stratum ranges from 0 to 0.5 m; the shrub stratum is >0.5 to 3.5 m; and the tree stratum is >3.5 to 12 m. This research is part of a broader long term study on the vegetation plots, of which the vegetation plot locations were established based in part on the Jennings growth forms. In this regard, the author seeks to use a similar scheme that will dovetail into the larger WIEH Longterm vegetation monitoring project in order to help inform future research projects. Secondly, because of the high population of white-tailed deer in the study area, deer browsing may have a strong influence in the recruitment of herbs, shrubs, and saplings. In this context, this project is concerned with depicting the vegetation structure within the deer browse zone (0 to 1.5 m) in order to enable comparisons between non-browsed and browsed areas in future studies. A minimum threshold of 0.5 m above ground level was established to accommodate for leaf litter, downed branches, logs, and all other non-photosynthetic matter. This stratum is referred to as "forest floor". Finally, the author sought to characterize variations and patterns (i.e. point clumping, low point density, high point density, etc.) that were visually observed throughout the vertical profile of each plot's canopy; therefore, the strata discussed above were further divided into smaller elevational ranges. Table 4.4 shows the final canopy strata divisions and their associated elevation ranges.

Table 4.4 Proposed forest structure scheme for describing canopy strata.

Strata #	Classified Layers	Elevation Range (meters)
0	ground	≤ 0
1	forest floor	>0.001 to ≤ 0.5
2	low	>0.5 to ≤ 1.5
3	low	>1.5 to ≤ 5
4	medium	>5 to ≤ 10
5	medium	>10 to ≤ 20
6	high	>20 to ≤ 30
7	high	>30

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Following Miura and Jones (2010) methodology, the lidar returns from each stratum were sorted into "Types" using queries in ArcGIS. Their methodology allows for quantification of gaps, canopy cover, and vertical density, variables which effectively quantify and describe forest stand structure. Four types of lidar returns were defined: "Type 1 are singular returns, returns in which there is only one return per pulse. Type 2 are first of many returns, that is, part of the pulse of energy has interacted with a canopy facet (a branch, leaf, etc.) and has been reflected back to the sensor but much of the energy has continued to travel through the canopy. Type 3 are intermediate returns, which are subsequent interactions of the pulse described in Type 2. Type 4 are the last of many returns, which are the last returned pulses back to the sensor" (Miura & Jones, 2010, p. 1072). Figure 4.3 shows an example vegetation plot lidar point cloud (Plot # X) with the height scheme (a.) and pulse types (b.).

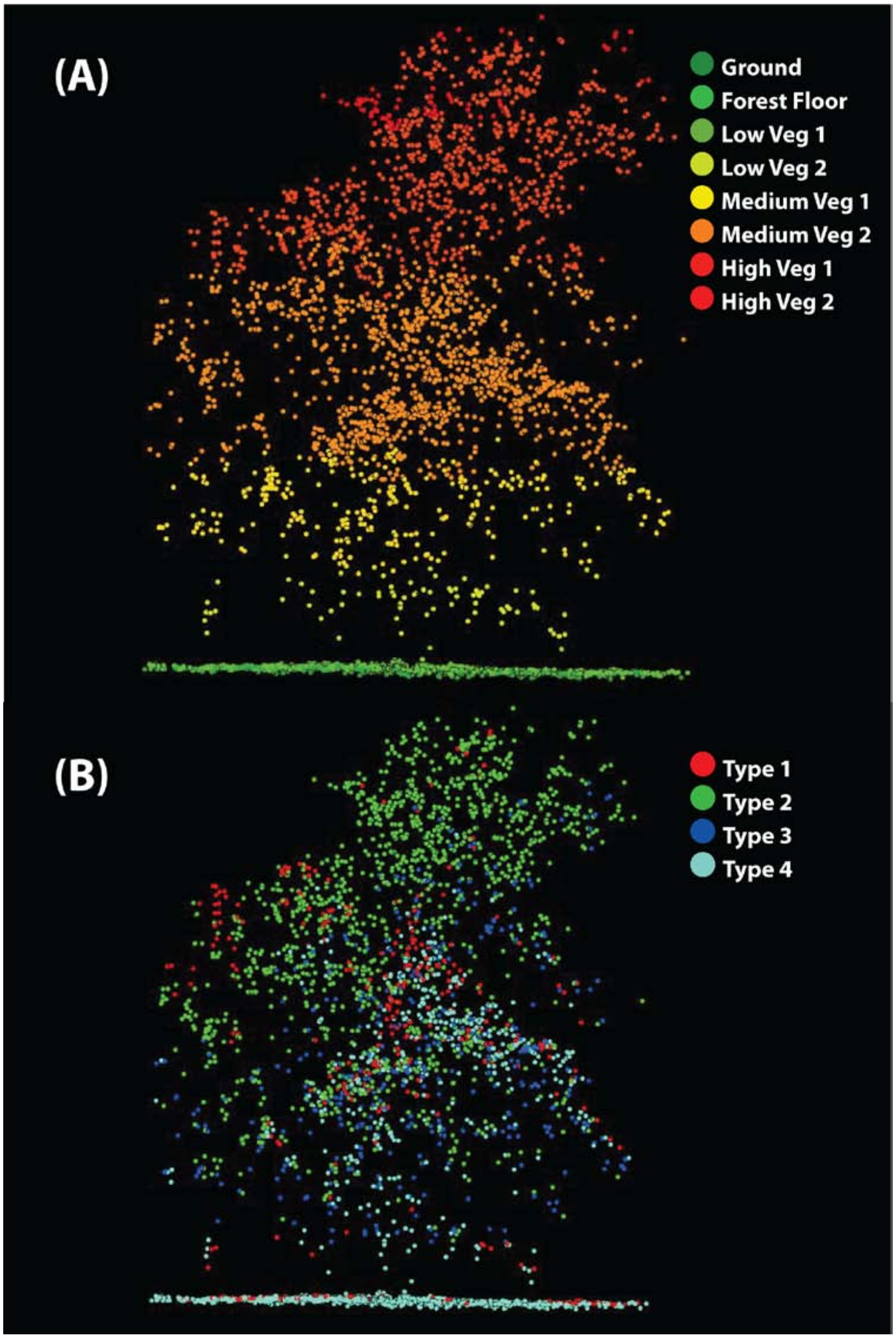

Figure 4.3 Lidar point cloud classification. (a) Lidar point cloud data was first classified into 8 layers: Ground (≤0 m), Forest Floor (0.001-≤0.5 m), Low Veg1 (>0.5-1.5 m), Low Veg2 (>1.5 - ≤ 5 m), Medium Veg1 (>5 - ≤ 10 m), Medium Veg2 (>10 - ≤20 m), High Veg1 (>20 - ≤ 30 m), and High Veg2 (>30 m). (b) Four types of lidar returns: Type 1 (singular returns), Type 2 (first of many returns), Type 3 (intermediate returns) and Type 4 (last of many returns).

Miura and Jones (2010) use the following expression to calculate the total number of returns, *T*:

$$T = \sum_{i=0}^{i=8} \sum_{j=1}^{4} R_{ij}$$

where *R* denotes the lidar returns, *i* denotes the classified stratum (0 and 1 = ground, 2 and 3 = low vegetation, 4 and 5 = medium vegetation, 6 and 7 = high vegetation) and *j* denotes the return type (1 = Type 1, 2 = Type 2, 3 = Type 3, and 4 = Type 4). The number of returns for each Type was calculated for each of the eight strata . Subsequently, each number was divided by the total number of returns in each plot, resulting in a ratio. Type 1 and Type 2 are the result of first interactions with objects (branches or leafs) in the canopy. This suggests that there is an opening above this pulse interaction (that is, no interaction above these points). The number of returns in the low, medium and high strata suggests the presence of vegetation in each of these layers." Using the calculated ratios and adapting this project's forest scheme to the scheme proposed by Miura and Jones (2010), formulas are shown in Table 4.5.

*Table 4.5 Miura & Jones (2010) lidar metrics for examining gaps, openness, and density at various levels in forest canopy strata.*Revised for additional strata.*

Description	**Lidar Return Ratio**	**Miura & Jones (2010) Correlated Field Variables**	**Miura & Jones (2010) Formula**	***Revised Formula**
O_G Opening above the ground	*Ground* Type 1	Total volume coarse woody debris	$\frac{R_{41}}{T}$	$\frac{R_{01}+R_{11}}{T}$
O_L Opening above low vegetation	*Low veg* Types 1 & 2	Field mean canopy cover	$\frac{R_{31}+R_{32}}{T}$	$\frac{R_{21}+R_{31}+R_{22}+R_{32}}{T}$
V_L Presence of understorey vegetation	*Low veg total* Types (1,2,3, & 4)	LAI for vegetation < 1 meter	$\frac{R_{31}+R_{32}+R_{33}+R_{34}}{T}$	$\frac{R_{21}+R_{31}+R_{22}+R_{32}+R_{23}+R_{33}+R_{24}+R_{34}}{T}$
CC Canopy cover	*Medium veg* Types 1 & 2 and *High veg* Types 1 & 2	Field derived canopy cover	$\frac{(R_{21}+R_{22})+(R_{11}+R_{12})}{R_{41}+(R_{31}+R_{32})+(R_{21}+R_{22})+(R_{11}+R_{12})}$	
O_M Opening above medium vegetation	*Medium veg* Types 1 & 2	Opening above medium vegetation	$\frac{R_{21}+R_{22}}{T}$	$\frac{R_{41}+R_{51}+R_{42}+R_{52}}{T}$
V_M Presence of mid-storey vegetation	*Medium veg* total (Types 1,2,3, & 4)	DBH weighted canopy depth in medium veg.	$\frac{R_{21}+R_{22}+R_{23}+R_{24}}{T}$	$\frac{R_{41}+R_{51}+R_{42}+R_{52}+R_{43}+R_{53}+R_{44}+R_{54}}{T}$
V_H Presence of high trees	*High veg* total (Types 1,2,3, and 4)	DBH weighted canopy depth in high veg.	$\frac{R_{11}+R_{12}+R_{13}+R_{14}}{T}$	$\frac{R_{61}+R_{71}+R_{62}+R_{72}+R_{63}+R_{73}+R_{64}+R_{74}}{T}$
D_H Vertically dense canopy of high trees	*High veg* Types 3 and 4	DBH weighted canopy depth in high veg.	$\frac{R_{13}+R_{14}}{T}$	$\frac{R_{63}+R_{73}+R_{64}+R_{74}}{T}$

Statistical Analysis

To graphically characterize potential relationships of the lidar-derived variables among the plots, a detrended correspondence analysis (DCA) ordination was performed with the software, PC-ORD 4.0 (McCune & Mefford, 1999). Ordination is a group of methods which attempts to reveal relationships between ecological communities. Community ecologists employ ordinations where analysis of the effects of multiple environmental factors on many species simultaneously is necessary. Absent of ordination methods, such multi-dimensional data would be impossible for researchers to analyze and interpret and performing separate univariate analysis for each species would be unrealistic when multiple species are present (The Ordination Web Page, 2011). Ordinarily, variables derived from field data such as species importance values are employed in ordination methods. For the purposes of this study, the lidar-derived variables indicative of forest structure replaced such field variables. Correlations of individual lidar variables to the first two ordination axes were used to identify structural characteristics representative of hypothetical gradients.

After ordinating plots in forest structural space using DCA, the relationship between disturbance levels during the three time periods and structural characteristics were examined visually for patterns by plotting the different categories on the ordination diagram. Transition levels were then examined for impacts on forest structure.

Redesigning the Wormsloe Institute for Environmental History Web Site

In order to provide access to results (such as this lidar study of vegetation structure) for Wormsloe researchers and the general public, and to increase and enhance multidisciplinary collaboration and synergy, visualizations and additional information were incorporated into the WIEH web site. In addition, WIEH and GDNR want to promote visitation and appreciation of the Wormsloe State Historic Site. Although a WIEH website was created and maintained by CRMS, a redesign was desired to allow display and access of research results. This lidar study of vegetation structure within the 33 longterm vegetation plots was used as a case study for showing 3D visualizations, background information, maps, aerial photographs, and ground photographs. The redesign of the WIEH web site was achieved using Adobe Dreamweaver 4.0 and using an open source CSS website layout (Viklund, 2010). Specific changes in format and redesign are described in Chapter V, Results and Discussion, of this document.

CHAPTER 5

RESULTS AND DISCUSSION

Correlations Among Lidar Derived Variables

Lidar return ratio variables for each plot are presented in Table 5.1. Descriptive statistics were obtained from SAS statistical software (Table 5.2). Correlations between several of the lidar derived variables used in this study reinforce Miura and Jones's (2010) technique of using lidar multiple return ratios to characterize forest canopy strata. Table 5.2 shows the basic statistics of the eight lidar return ratio variables characterizing the lidar point data within the 33 longterm vegetation plots used in the ordination.

Table 5.1. Lidar return ratio variable values for each of the 33 longterm vegetation plots.

Plot No.	**O_G**	**O_L**	**V_L**	**CC**	**O_M**	**V_M**	**V_H**	**D_H**
1	0.036	0.048	0.158	0.831	0.215	0.390	0.202	0.005
2	0.017	0.003	0.017	0.965	0.244	0.441	0.324	0.000
3	0.210	0.038	0.074	0.615	0.342	0.408	0.053	0.000
4	0.025	0.003	0.018	0.950	0.304	0.488	0.244	0.001
5	0.062	0.010	0.032	0.891	0.053	0.106	0.562	0.024
6	0.144	0.082	0.144	0.649	0.408	0.484	0.012	0.000
7	0.184	0.050	0.094	0.628	0.395	0.433	0.000	0.000
8	0.036	0.005	0.023	0.931	0.209	0.339	0.353	0.013
9	0.051	0.020	0.062	0.882	0.314	0.405	0.216	0.000
10	0.064	0.026	0.084	0.826	0.396	0.534	0.032	0.000
11	0.035	0.017	0.072	0.892	0.259	0.458	0.184	0.008
12	0.076	0.043	0.092	0.801	0.448	0.527	0.032	0.000
13	0.077	0.218	0.425	0.541	0.347	0.376	0.000	0.000
14	0.075	0.025	0.061	0.825	0.216	0.332	0.280	0.025
15	0.057	0.006	0.023	0.878	0.215	0.423	0.258	0.024
16	0.101	0.024	0.059	0.771	0.419	0.481	0.000	0.000
17	0.032	0.034	0.118	0.877	0.238	0.425	0.238	0.000
18	0.042	0.057	0.201	0.823	0.096	0.201	0.396	0.032
19	0.051	0.012	0.047	0.872	0.321	0.461	0.109	0.000
20	0.093	0.071	0.170	0.734	0.409	0.510	0.045	0.000
21	0.179	0.013	0.029	0.734	0.070	0.116	0.471	0.011
22	0.103	0.012	0.039	0.741	0.153	0.254	0.244	0.006
23	0.110	0.040	0.069	0.738	0.337	0.456	0.086	0.000
24	0.030	0.004	0.029	0.936	0.148	0.315	0.343	0.003
25	0.037	0.004	0.020	0.925	0.197	0.345	0.315	0.003
26	0.145	0.150	0.192	0.558	0.372	0.419	0.000	0.000
27	0.010	0.012	0.075	0.958	0.403	0.581	0.088	0.000
28	0.075	0.023	0.064	0.838	0.417	0.487	0.091	0.000
29	0.070	0.022	0.058	0.824	0.373	0.515	0.058	0.000
30	0.047	0.011	0.042	0.890	0.457	0.523	0.008	0.000
31	0.040	0.003	0.031	0.918	0.367	0.521	0.124	0.005
32	0.260	0.113	0.158	0.486	0.027	0.032	0.387	0.062
33	0.020	0.000	0.008	0.960	0.143	0.356	0.400	0.050

Table 5.2. Simple statistics describing lidar return ratio variables. See Table 4.5 for variable descriptions. n=33.

Lidar return ratio variables	Mean	Std Dev	Sum	Minimum	Maximum
O_G	0.08	0.06	2.60	0.01	0.26
O_L	0.04	0.05	1.20	0.00	0.22
V_L	0.08	0.08	2.79	0.01	0.43
CC	0.81	0.13	26.69	0.49	0.96
O_M	0.28	0.12	9.31	0.03	0.46
V_M	0.40	0.13	13.14	0.03	0.58
V_H	0.19	0.16	6.16	0.00	0.56
D_H	0.01	0.02	0.27	0.00	0.06

The analysis of the lidar data indicates that the lidar derived variables may have correlations with field collected variables that are currently being measured at Wormsloe. For example, lidar derived opening above low vegetation (O_L) showed strong correlation with the presence of understory vegetation (V_L), as shown in Table 5.3. Miura and Jones (2010) demonstrated that O_L and V_L were strong predictors of field derived mean canopy cover (i.e. the percentage of canopy projected area) and Leaf Area Index (LAI) for vegetation less than one meter in height, respectively. While the mere presence of understory vegetation does not automatically mean there are canopy openings above the low vegetation, collecting LAI data and canopy cover data at Wormsloe, and correlating these data with the appropriate lidar derived variables may show a strong relationship in the low vegetation stratum. Conversely, CC and V_L showed a moderate *inverse* relationship at Wormsloe. Miura and Jones found that CC and V_L were correlated with field derived mean canopy cover and LAI for vegetation less than one meter in height, respectively. One would expect a direct correlation with these two variables (i.e. the LAI index increases as the percent canopy cover increases). However, the lidar derived variables in this project showed the opposite relationship. Based on the correlations listed in Table 5.3, field derived data collected at the Wormsloe vegetation plots are necessary to make meaningful conclusions as to the efficacy of lidar's ability to characterize vegetation structure.

Table 5.3 Pearson's R correlations between lidar derived variables. All significance levels are P<.0001. Dashes indicate insignificant correlations.

	O_G	O_L	V_L	CC	O_M	V_M	V_H	D_H
O_G	1	-	-	0.87	-	-	-	-
O_L	-	1	0.93	0.8	-	-	-	-
V_L	-	0.93	1	-0.66	-	-	-	-
CC	0.87	0.8	-0.66	1	-	-	-	-
O_M	-	-	-	-	1	0.89	0.93	0.71
V_M	-	-	-	-	0.89	1	0.78	0.66
V_H	-	-	-	-	0.93	0.78	1	0.63
D_H	-	-	-	-	0.71	0.68	0.64	1

In addition to the lidar derived variable correlations, most plots were visited and ground photographs were taken of the four cardinal directions and the canopy. Vegetation was identified and measured at eight plots as part of the ongoing CRMS-WIEH longterm vegetation monitoring project. These preliminary site visits provided an opportunity for comparing ground observations with structural characteristics that were observed in the point cloud data thus, reinforcing the lidar data's efficacy of representing ground-based data.

Using two plots that differ considerably in their canopy structure, the utility of the lidar data to characterize vegetation structure becomes apparent. Unlike the other plots that are pine dominated on Wormsloe, Plot 32, which is located on Pigeon Island, was not logged in the 1970's. The lack of harvesting activities may be due to the inefficiency, both logistical and economical, of extracting a very small amount of board feet from an isolated island. In addition, based on field observations and preliminary field measurements, the two pine trees that compose the upper canopy are relatively large in size, making it likely that they were present long before the 1970s. The raw lidar measurements show this plot has the highest tree height, at 34 meters, of the 33 plots used in this project. Additionally, there is a very low density of lidar returns in the medium vegetation stratum and a relatively high density of returns in the low vegetation strata, unlike the typical plot on Wormsloe. Figure 5.1 compares the raw lidar returns between Plot 28, a typical plot, and Plot 32, an atypical plot, at Wormsloe.

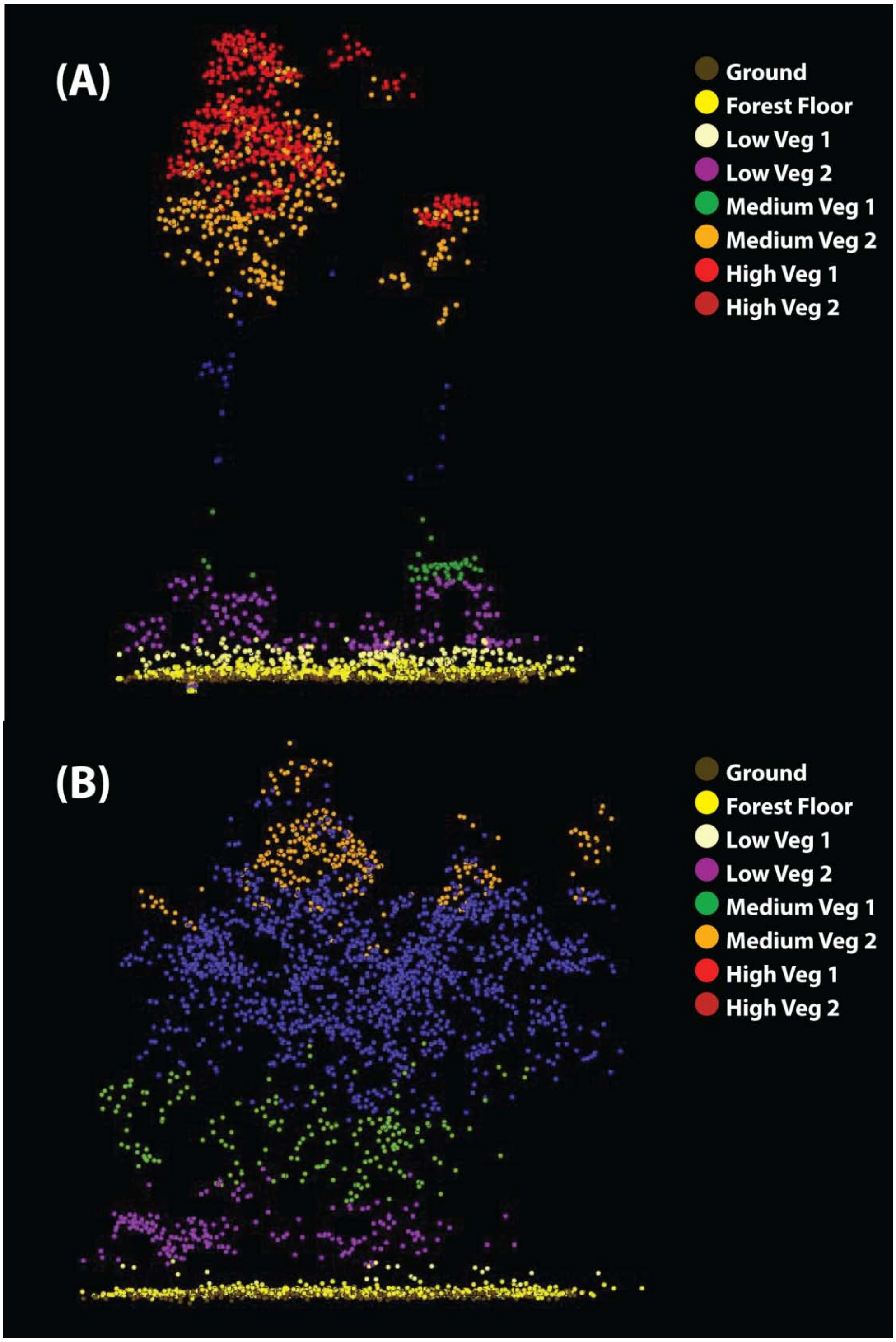

Figure 5.1 Plot 32 (A) displays atypical structural characteristics with a very tall tree height, high density low vegetation, and low density mid-canopy. Plot 28 (B) shows typical structural characteristics of a vegetation plot at Wormsloe with a higher density mid-canopy, low density low vegetation and shorter tree height.

The individual lidar variables reinforce the structural differences between the plots. For example, Plot 28 had a value of 0.07 for the ratio of opening above the ground (O_G) and Plot 32 had a value of 0.23 for the same variable. The differing values indicate very little vegetation is present (i.e. there is an opening, or gap above the ground) in the first five meters above the ground in Plot 28, and relatively more vegetation in the same stratum in Plot 32. Based on field observations, Plot 28 has a sparse shrub layer and Plot 32 has a dense shrub layer. Plot 28 had a value of 0.49 for the presence of mid-story vegetation (V_M) and Plot 32 had a value of 0.03 for the same variable. Unlike Plot 32 which has little vegetation in the medium stratum, Plot 28 has a relatively high amount of vegetation in the same stratum. Unlike the other pine dominated plots in the study, Plot 32 was not logged in the 1970s. Although it was not logged, GDNR personnel indicate that the area burns semi-regularly due to unauthorized campfires left to burn the vegetation. Disturbance factors that are not incorporated into this analysis may account for the Plot's disparate structural characteristics when compared to Wormsloe's other pine dominated plots.

Ordination Results and Discussion

Relationships between the plots were examined using a detrended correspondence analysis (DCA) based ordination. Ordination using the lidar derived variables was able to explain 13% of the variance in structural attributes on the first axis and 4% on the second axis (Fig. 5.2). Using the lidar variables as the sole data set in the ordination leaves a large portion of the variance unexplained. However, using strictly structural data has advantages to interpreting how structural patterns in the forest at Wormsloe may be influenced by past land use legacies. By limiting the inputs to canopy characteristics in the ordination, one is able to view the structural characteristics in isolation from other variables such as species composition, soil characteristics, salt spray impacts, and many other environmental gradients. This enables the identification of structural gradients that may be present.

Lidar metrics describing canopy structure were used as the variable inputs. The DCA ordination of the lidar variables suggests that plots may be distinguished by using canopy height, canopy cover, and relative openness of under- and mid-story density characteristics. The first axis is strongly correlated with presence of high trees (V_H) (r= 0.96) and strongly negatively correlated with opening above medium vegetation (O_M) (r= -0.87). These two lidar metrics are presumably surrogates for canopy depth in high vegetation and field derived opening above medium vegetation, respectively (Miura and Jones, 2010). Most plots were grouped on the middle one-third of Axis 1, which indicates they have intermediate levels of openness above the mid-story and intermediate levels of canopy height. Plots 13 and 26 were placed on the low end of Axis 1, indicating a low canopy height and open mid-story (Fig. 5.3). The second axis shows a strong negative correlation with presence of mid-storey vegetation (V_M) (r= -0.87) and thus, is presumably a surrogate for canopy depth in medium vegetation using Miura and Jones' (2010) forest characterization scheme. Most plots were placed on the low end of Axis 2, indicating that they have dense mid-stories. Plot 32 was placed on the high end of Axis 2, indicating a very sparse mid-story.

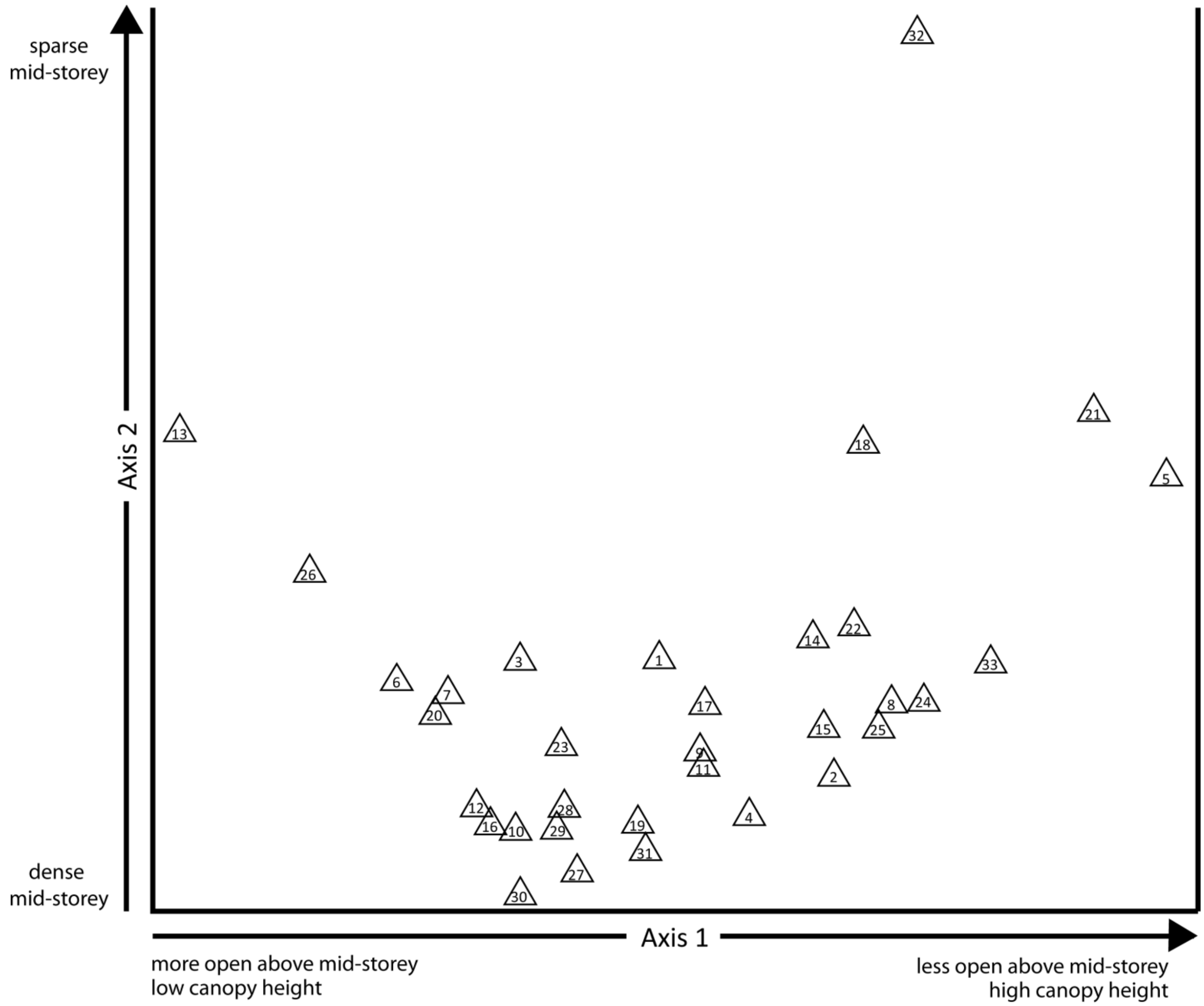

Figure 5.2 Relationships between plots were examined using a detrended correspondence analysis based ordination. Lidar metrics describing canopy structure were used as the variable inputs. Axis 1 represents gradients showing the canopy height and mid-storey openness gradient. Axis 2 represents a mid-storey density gradient.

Figure 5.3 Plots 13 (a) and 26 (b) have relatively open canopies as indicated by ground photos and their placement on the low end of axis 1.

Ordinations used in ecological studies commonly incorporate many types of variables, including field derived data, to derive a comprehensive view of patterns across a landscape. These data may be biotic or abiotic in nature, and include species composition statistics, soil moisture and chemical composition characteristics, micro- and macro-topography, distance from a habitat transition (i.e. an “edge”), elevation, among numerous other characteristics found in a given landscape. An ordination is a multivariate analysis that allows for the simultaneous measurement of site characteristics whenever there are more than two variables that may influence the particular characteristic in question. The resulting analysis produces gradients along any number of axes. Generally, the steeper the gradient, or axis, the more distinct or discontinuous are communities. The ordination in this project was performed without the benefit of field data incorporated into the analysis; instead the ordination is based exclusively on remotely sensed lidar data.

In this project, using strictly lidar-derived structural characteristics of forest vegetation, certain plots are outliers in the ordination space. As discussed above, Plot 32 is categorized as having little to no disturbance and it is located near the maximum extent of Axis 2, whereas, other plots that are categorized as having the same disturbance level are located on the lower first half of Axis 2. In this regard, other environmental characteristics are needed to conduct a thorough analysis of past land use influences on vegetation structure. For example, an analysis that includes Plot 32 would ideally incorporate a "distance to edge" variable. Since Plot 32 is located on a small island, its relative closeness to tidal rivers may, to a certain degree, override the fact that it escaped the 1974 pine removal. Its island location may have a strong influence on biophysical characteristics.

Comparing Patterns in Canopy Structure Between Three Significant Eras at Wormsloe

In order to assess the possible influence of disturbances in the three eras, the disturbance levels for each plot per era were overlaid on the ordination results. Upon initial visual inspection of the Antebellum overlay, plots with low and moderate levels of disturbance appear to form loose groups in the ordination space (Fig. 5.4). During the Postbellum period, three groups of plots representing the three levels of disturbance emerge, although the relationships between the disturbance level groups appear more distinct than those in the Antebellum period (Fig. 5.5). Although one might expect more influence from disturbance during the Antebellum era due to high rates of agricultural activities, based on historical documentation, these cultivation activities did not begin until the 1830s, well into the Antebellum time period. Agricultural activities carried out by newly freed slaves and northern investors continued throughout the entire Postbellum period, which is reflected in the higher frequency of disturbance on the ordination graph.

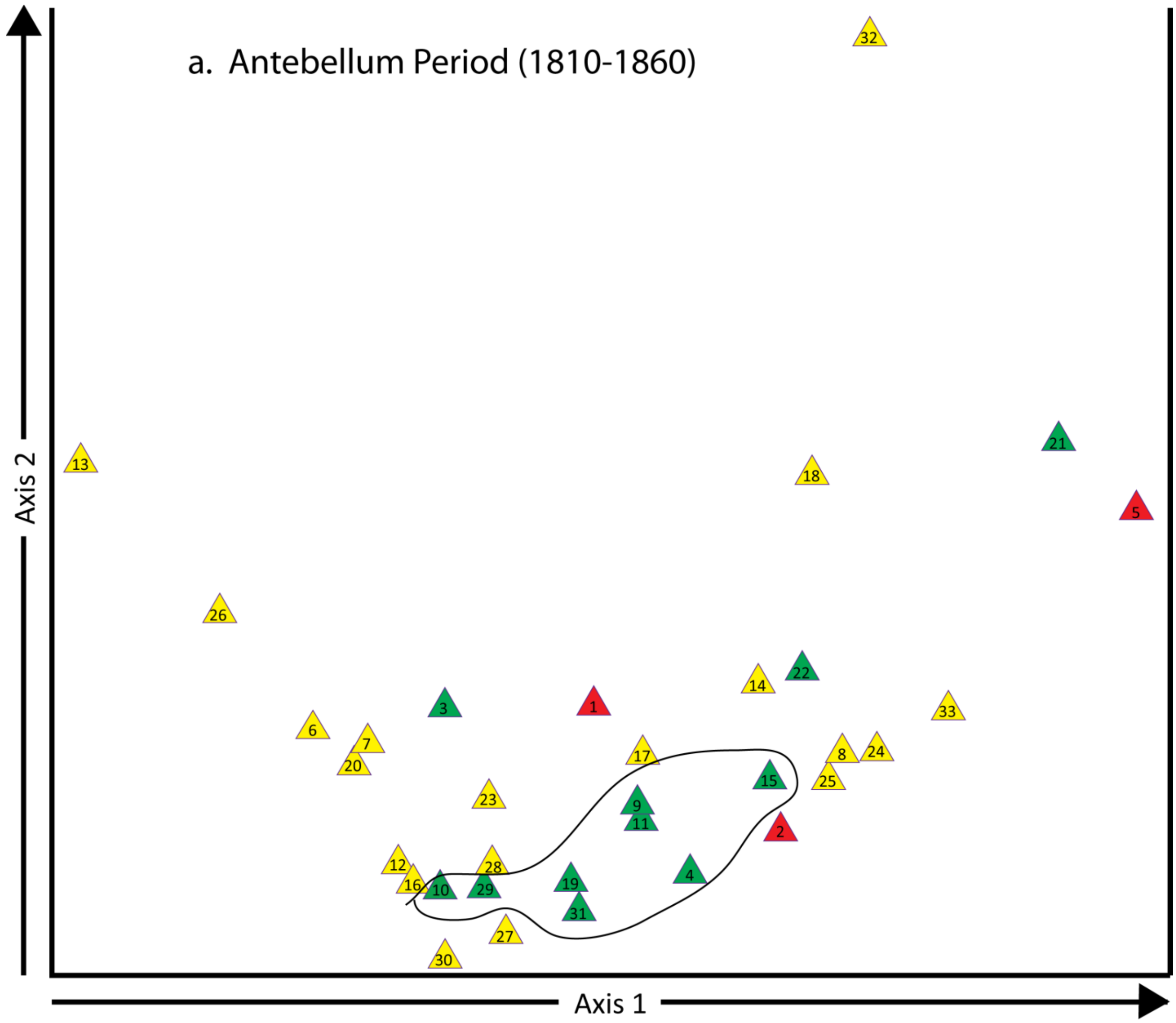

Figure 5.4 Antebellum disturbance levels overlaid onto ordination.

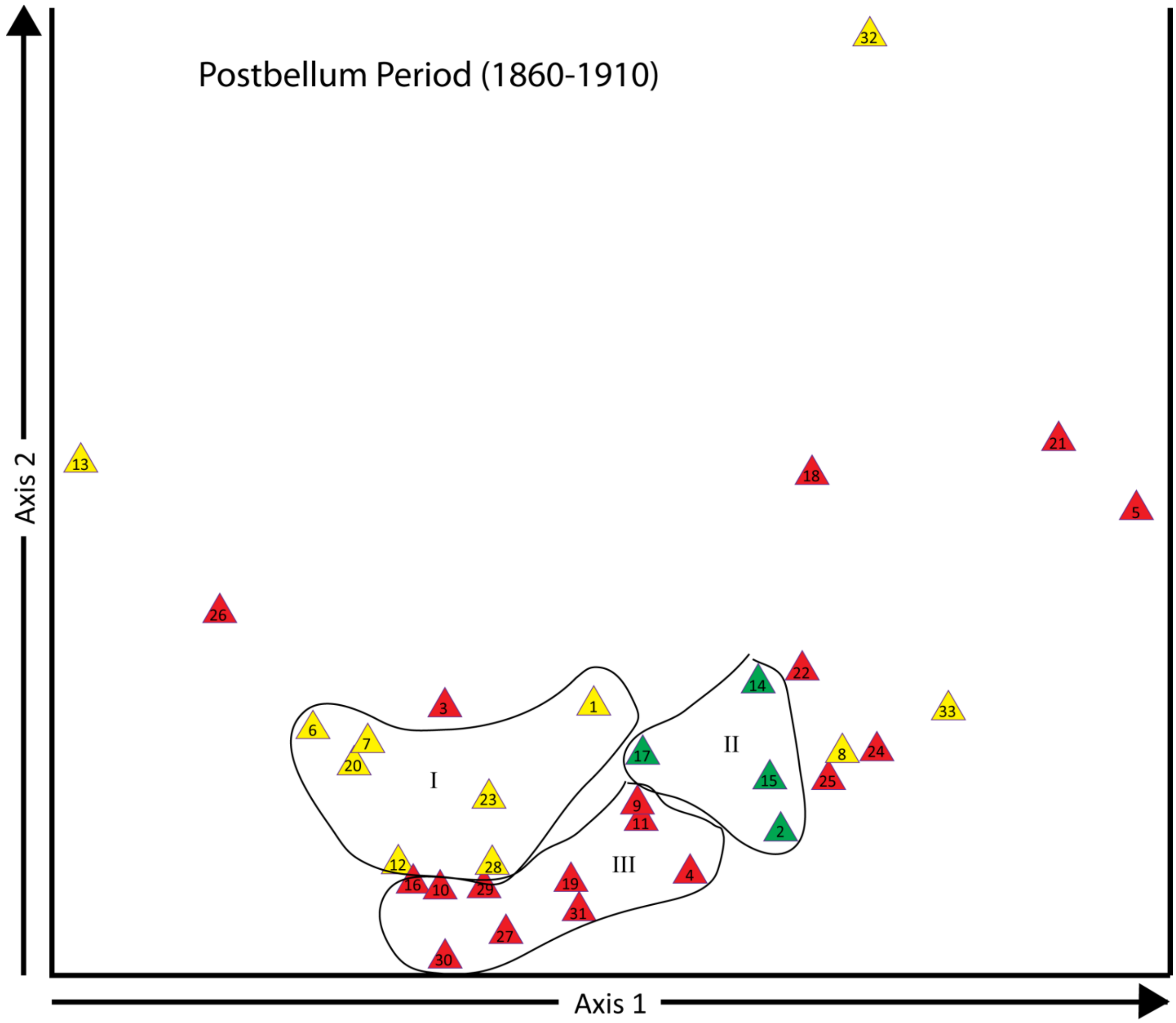

Figure 5.5 Postbellum disturbance levels overlaid onto ordination.

Within the Pine Beetle Infestation overlay, plots with moderate levels of disturbance display an upward trend on Axis 2 (Fig. 5.6). Eight of the thirty-three plots were in Field land cover post pine beetle infestation logging activities during this time period. These eight plots are unevenly distributed across Axis 1 from the lower to the higher gradient with Plots 16 and 26 on the lower end and the other moderate disturbance plots towards the higher end.

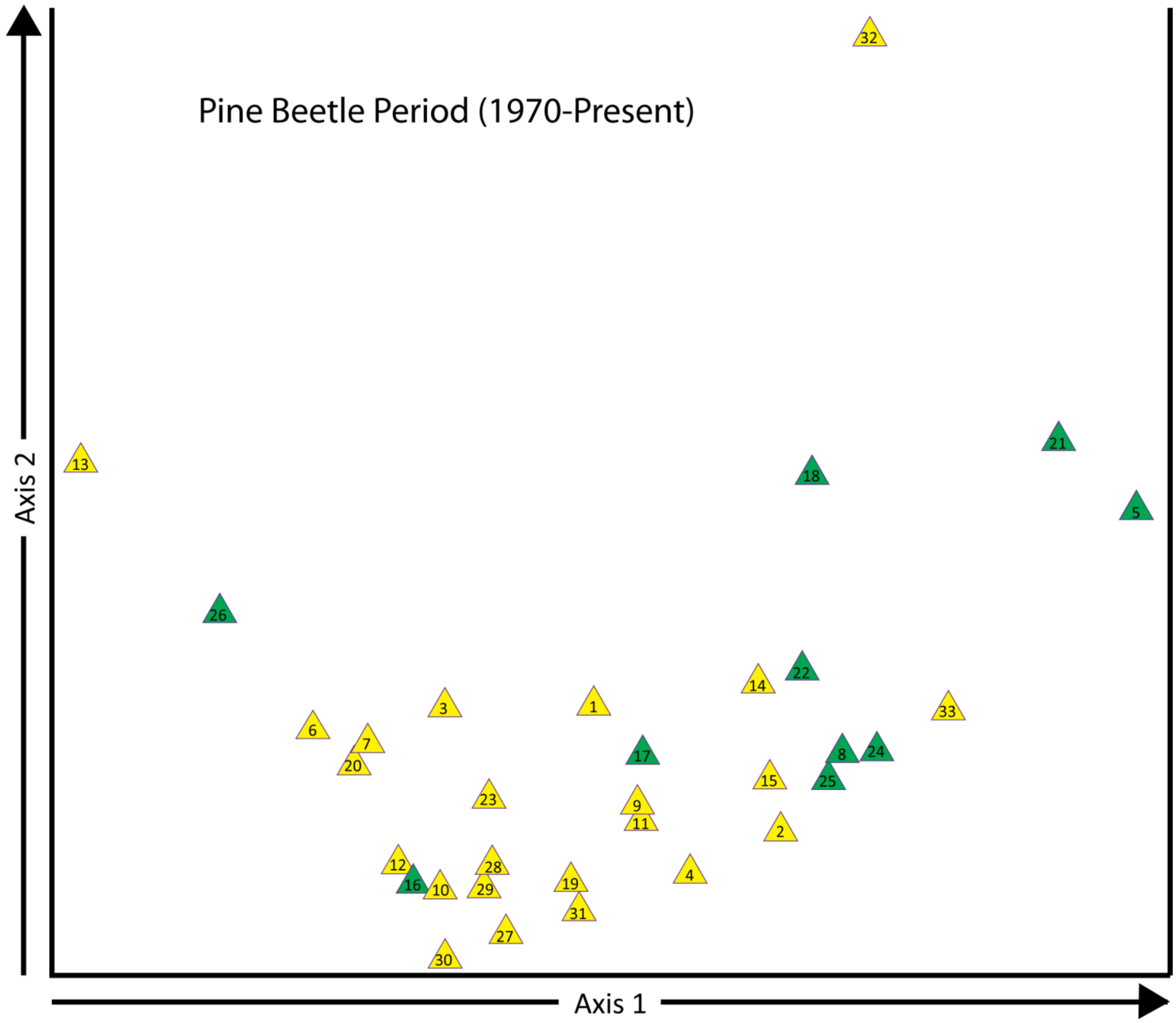

Figure 5.6 Pine Beetle Infestation disturbance levels overlaid onto ordination.

Closer examination reveals that Plots 16 (Fig. 5.7 a and b) and 26 (Fig.5.7 c and d) differ considerably in structure among one another and between those plots in the group. The disparate locations on the graph are likely due to differing physical locations on the study site. Although Plot 16 was logged soon after the pine beetle infestation, it consists primarily of small water oaks instead of the expected secondary successional pines. Plot 26, also logged after the infestation, is located on the edge of Long Island, the location where the island is at its narrowest (Figure 5.7 c and d). Underlying biophysical properties of these plots, including salt spray, tidal creek influences, soil moisture and chemical composition may differ greatly with those plots located in the interior of the property. The “logged” plots are located on the upper end of Axis 1. Although two of these plots, 24 and 25, occur on Long Island (Fig. 5.7 a and b), they are located toward the island’s interior, perhaps limiting those environmental influences that control the structure in Plot 26. These two plots along with 5, 21, 8, and 22, located on Wormsloe proper, are pine dominated and fall on the second half of Axis 1. Logging activities appear to have encouraged a higher canopy height and a denser mid-story in forest structure within this latter group of plots.

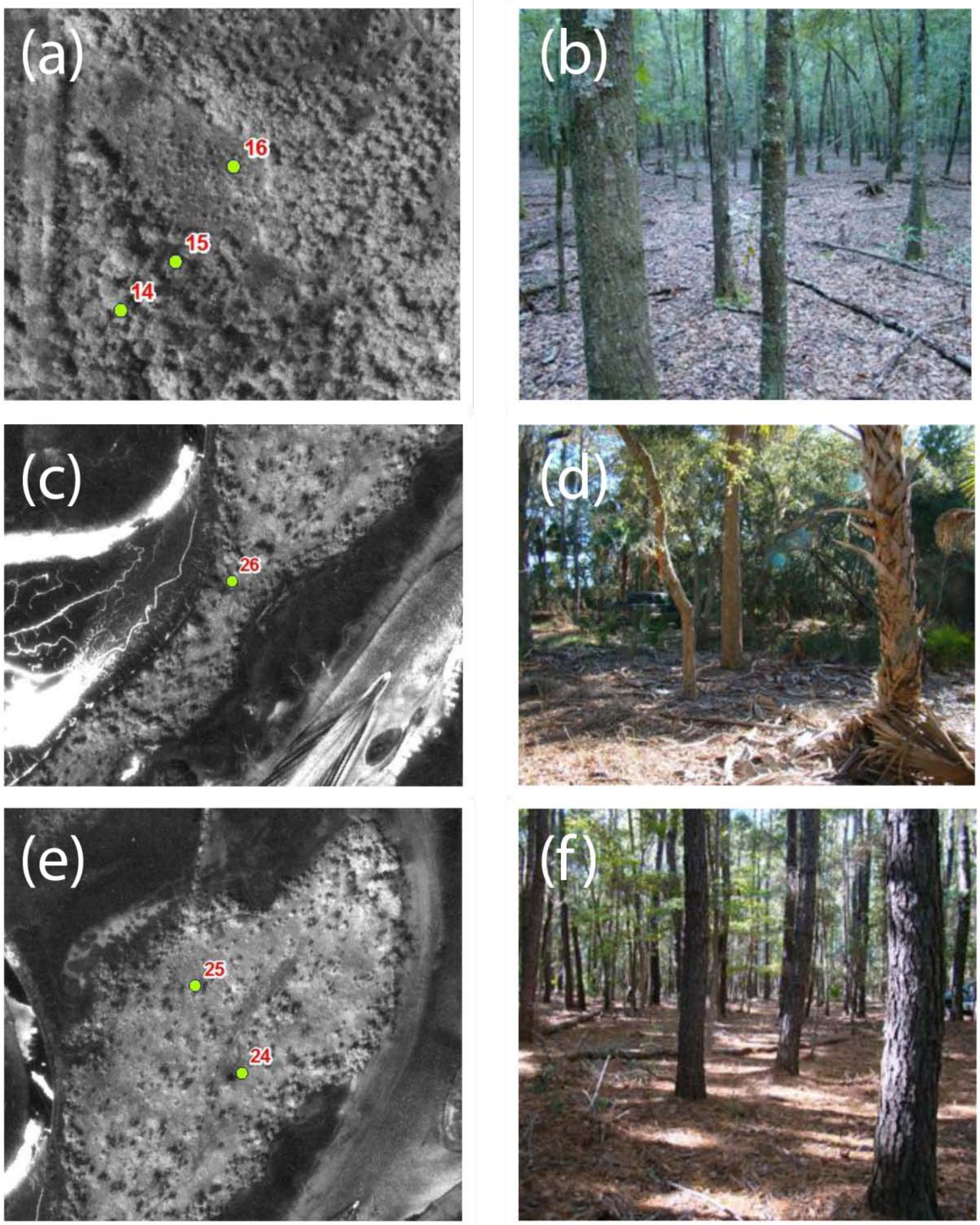

Figure 5.7   Although Plots 16, 26, 24, and 25 were logged in 1974-1975, they currently display differing forest structure. Plots 16 (a) and 26 (c) are primarily young hardwoods (b) and sabal palm (d), respectively whereas Plots 24 and 25 (e) are pine dominated (f). Their incongruent locations on the ordination graph may be explained by different physical and biological environments. The above aerial photograph was taken in 1975 following beetle infestation and after logging activities.

As discussed above, plots appeared to from loose to somewhat distinct groups based on their varying disturbance levels within the three time periods. However, it was necessary to exclude some plots that lay isolated in the ordination space in order to form the groups. One-way analysis of variances (ANOVAs) were used to test whether axes scores between the low, moderate, and high disturbance level plots were indeed different based on their structural characteristics. Table 5.4 presents Axis score descriptive statistic for each time period per disturbance level. Although the plot groups appear to occupy different areas of the ordination space, they don't in a statistically meaningful way. The tests indicate that the groups are not significantly different (Table 5.5).

Table 5.4 Axis score statistics for time periods and respective disturbance levels.

	Axis 1		Axis 2	
Time Period (classification)	***Mean***	***Std. Dev***	***Mean***	***Std. Dev***
Antebellum (low disturbance)	60	33	31	28
Antebellum (moderate disturbance)	59	22	23	17
Antebellum (high disturbance)	64	36	35	21
Postbellum (low disturbance)	59	33	35	31
Postbellum (moderate disturbance)	85	8	25	7
Postbellum (high disturbance)	73	34	28	19
Pine Beetle (low disturbance)	64	28	25	25
Pine Beetle (moderate disturbance)	84	38	43	31

Table 5.5 ANOVA analyses of Axes 1 and 2 scores between groups of low, moderate, and high disturbance levels during the three time periods revealed no significant differences in their influences on vegetation structure (P=0.05).

	Axis 1				Axis 2			
Time Period	***df***	***F***	***F-critical***	***P-value***	***df***	***F***	***F-critical***	***P-value***
Antebellum	2	2.3	3.3	0.11	2	0.5	3.3	0.59
Postbellum	2	1.3	3.3	0.28	2	0.8	3.3	0.42
Pine Beetle	1	2.4	4.1	0.12	1	3.1	4.1	0.08

Land Cover Transition and Dynamics

In addition to comparing the three time periods and their relative disturbance levels, a fourth overlay was explored by summarizing the disturbance levels for each plot over the three time periods. The resulting summation produced a Transition overlay in which the plots were examined for patterns that may arise from the various transient states that the plots have undergone through the years (Fig 5.8).

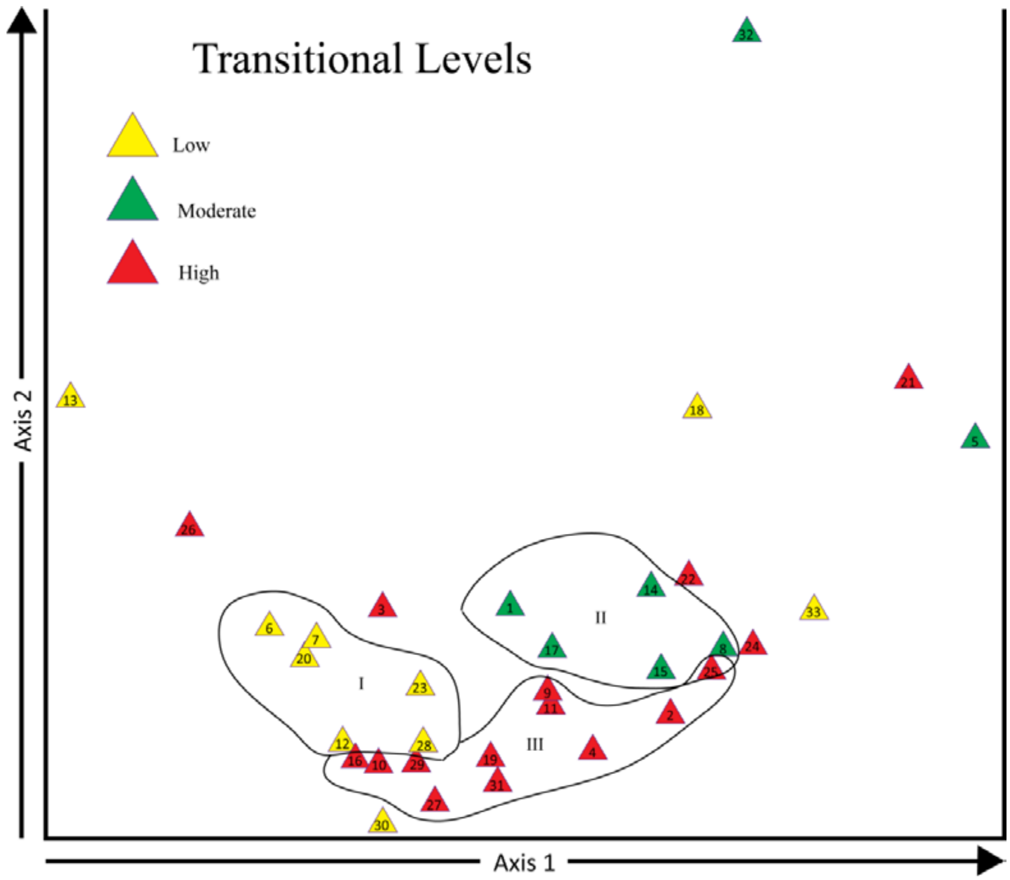

Figure 5.8. Transition levels among plots reflect 200 years of forest dynamics at Wormsloe.

Group I, those plots with the lowest transition levels are located on the first half of Axis 1 and Group II, those plots with a moderate level of transition, are located on the second half of Axis 1. Group III , those plots with a high level of transition, are placed below the first two groups on Axis 2. Group I and Group II plots stratify across Axis 1. Group I plots have lower canopy heights and are more open above the mid-story whereas, Group II plots have higher canopy heights and are less open above the mid-story. Group III plots display a range of canopy heights and mid-story characteristics but have denser mid-stories than those in Groups I and II. Plots within Group II and III may have higher canopies than those in Group I resulting from undocumented fine-scale disturbances, including individual tree mortality. Such fine-scale disturbances would reduce competition among the trees resulting in higher rates of growth in height and crown dimensions.

A one-way ANOVA was performed using the first and second axis scores of each group. Table 5.6 presents descriptive statistics for the three transition levels based on Axis 1 and Axis 2 scores. The analysis on Axis 1 indicated that the three transition groups were different based on their structural characteristics in the mid-story and the canopy height ($F=4.9$, $df=2$, $P < 0.05$). The mid-story density characteristics varied between the transition groups and the differences between the groups on Axis 2 approached significance ($F=2.8$, $df=2$, $P=0.08$); however, they did not differ enough to provide insight into whether the disturbance levels impacted mid-storey structure. Table 5.7 presents ANOVA results.

Table 5.6 Descriptive statistics for Transition class scores on Axes 1 and 2.

	Axis 1		**Axis 2**	
Transition (classification)	**mean**	**std. dev**	**mean**	**std. dev**
Transition (low)	50	32	28	20
Transition (moderate)	93	23	45	34
Transition (high)	70	25	22	18

Table 5.7 ANOVA analysis of Axes 1 and 2 scores reveal differences between the transition groups on Axis 1 (P=0.05).

	df	**F**	**F-critical**	**P-value**
Axis 1	2	4.9	3.3	0.04
Axis 2	2	2.7	3.3	0.07

Overall, the DCA ordination results suggest that the transition levels (or cumulative past levels of disturbance) are influencing specific locations and certain characteristics in the forest canopy at Wormsloe, primarily within the mid- to upper canopy, and canopy height. The following discussion uses the shrub layer (e.g. low vegetation) to compare and contrast the groups because field photographs depict this stratum better than the medium to high vegetation strata, where the plots are differentiated in the ordination. Although the comparisons are not directly related to the gradient revealed in the ordination, the low vegetation is most certainly influenced by middle- to upper-canopy characteristics, which regulate light and moisture within the canopy profile.

Since the low transition plots have experienced the least disturbance, one may assume that they are characterized by tall trees, a well-developed shrub layer, and canopy gaps. Based on Oliver and Larson's (1996) forest stand development scheme, these plots should be in either the understory reinitiation stage or the old growth stage. Based on field observations and the lidar data, the plots do not have the characteristic tall trees of the old growth stage. However, some of the plots do contain a shrub layer that is present in the stages mentioned. Most notably, saw palmetto (*Serenoa repens)* occurs at varying degrees in the shrub layer in these plots. Saw palmetto grows vegetatively from horizontal stems and rhizomes. Previous studies have found that the absence of saw palmetto in maritime forest understories is an artifact of past agricultural activities where plowing broke up and prevented the formation of rhizomes (Bratton & Miller, 1994). Additionally, other shrub species, including wax myrtle (*Myrica cerifera)*, red bay (*Persea borbonia)*, fetterbush (*Lyonia lucida)*,and horse sugar (*Symplocos tinctoria*), form a shrub layer that is sparse or absent in the plots with a moderate level of transition.

The understory within plots with moderate transition levels varies somewhat among one another and with those with low transition levels. Plot 1, for example, has an open sparse shrub layer which consists of scattered sabal palm (*Sabal palmetto*) saplings. Unlike saw palmettos, sabal palms rely on pollination for reproduction and are therefore influenced less by a land use history of active farming. Plot 14 is located in a swamp which consists of one bald cypress (*Taxodium distichum*), red maples (*Acer rubrum*), sweetgum (*Liquidambar styriciflua*), wax myrtle, and sabal palms. Plot 15 contains several large hickory and magnolia (*Magnolia virginiana*) trees, along with other small hardwoods and Plot 8 consists of slash pines, magnolias, water oak, and a tall subcanopy layer. Its shrub layer is sparse.

Plots with high transition scores reflect a range of structural characteristics over Axis 1 that are reflected in both the low and moderate transition plots. They have variable canopy heights and a range of relative openness above the mid-canopy scores. These plots stratify out from the other two groups based on mid-story canopy characteristics. The high transition plots have higher density mid-stories than those in the low and moderate transition groups. This characteristic may be a function of forest succession in the group. During the most recent time period, the Pine Beetle Era, most of these plots were classified as low level disturbance plots. The plots' forest successional stage may be at a point where most tree crowns are classified as codominant, a class in which trees are more or less crowded by other trees from the sides (Oliver and Larson, 1996).

Interpreting transition scores over a time period that extends back 200 years poses difficulties because many generalizations about land use and land cover must be made. When these generalizations are compared with more specific or detailed data (e.g. structural characteristics) the direct relationship between the two data sets is difficult. Additionally, transition scores impose definitive classes on forests that are otherwise undergoing the continuous process of stand development and succession. Adding to the complexity of such analysis, succession in most forest stands does not progress in a linear fashion. Numerous perturbations, including individual tree mortality, windthrow, minor fire events, and commercial timber thinning, further complicate an analysis that attempts to generalize processes. Despite these complexities, the cumulative impacts of disturbance on forest structure over time may be key to understanding how such impacts influence modern vegetation structure. In this study varying levels of disturbance influenced canopy height, mid-story density, and openness above the mid-story.

Deer Browsing on Wormsloe

Based on field observations, Wormsloe appears to have a high white-tail deer population and deer browsing likely has a substantial influence on vegetation structure and composition. Depending on the deers' preferences, certain species in the forest may be suppressed by browsing causing decreased recruitment and preventing these trees from becoming dominant components in the plot or the canopy. Other species that are not palatable to deer may replace such species. The result is forest structure modification to the extent that some wildlife species, particularly those dependent on dense understory, may be adversely affected. On a broader level, high deer densities can cause shifts towards forests with fewer species.

Although deer population data for Wormsloe are not available, deer can be observed at any given time during the day and night throughout the site. Browsing, particularly on early succession tree species such as sweetgum, is evident in and around many of the vegetation plots. Lidar data can be used to visualize and quantify deer browse effects on structure. In turn, these data can be used to model projected structure and composition into the future. The lidar data point clouds used in this project indicate low density vegetation patterns below the browse line, estimated to be approximately 1.5 m, in many of the plots. For example, Plot 1 shows very few lidar returns below the 1.5 m browse line (Fig. 5.9a). With the exception of a few plots, most vegetation plots on Wormsloe proper and Long Island display similar density patterns in the same stratum. In contrast, Plot 32, which is located on the smaller Pigeon Island, has a relatively high density of lidar returns below the browse line. Given its small size and distance from the mainland, it is unlikely that Pigeon Island can support a deer population with its limited resources. The relative low lidar return densities in the deer browse zone in most plots on Wormsloe proper and Long Island, and the relative high lidar return densities in Plot 32 on Pigeon Island, may be indicative of heavy and light deer herbivory, respectively. The influence of deer browse on species composition, structure and overall biodiversity deserves further exploration at Wormsloe.

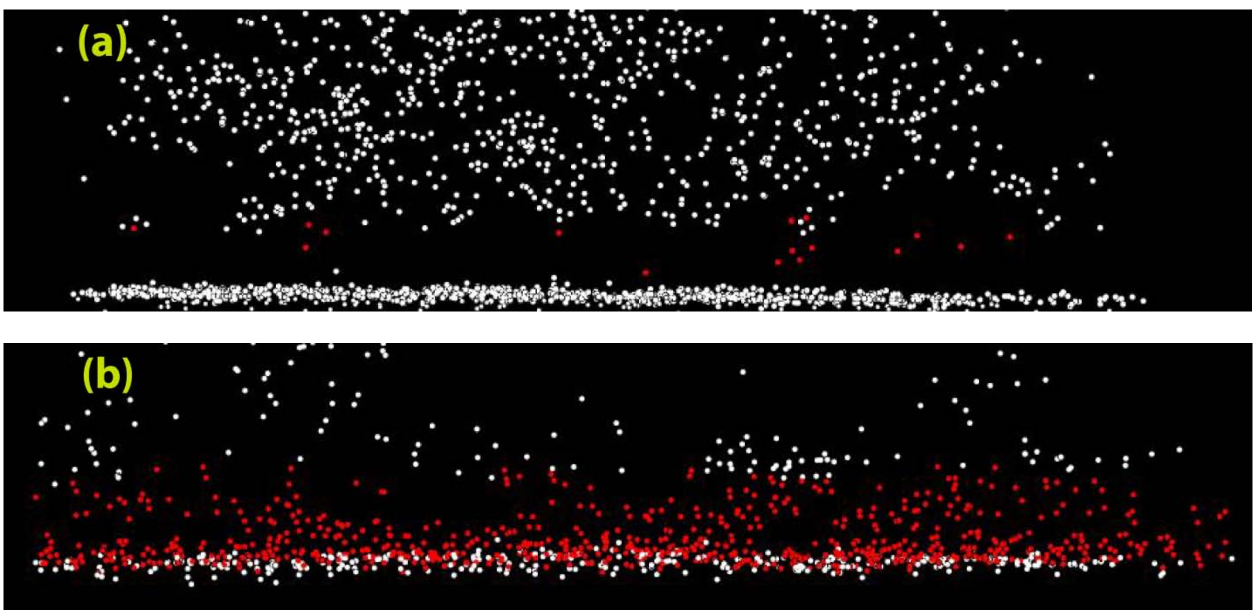

Figure 5.9. Lower portions (0-5m) of canopy lidar point clouds in two plots. Red points represent lidar returns in the deer browse zone. Plot 1 (a) displays low density points in the deer browse zone on a mainland plot whereas, Plot 32 (b) on Pigeon Island, displays relatively high density points in the deer browse zone.

Redesigning the Wormsloe Institute for Environmental History Web Site

Using a free CSS template downloaded from the internet (Viklund, 2010) as a guide, the WIEH web site was redesigned with Adobe Dreamweaver CS4 as the editing platform. The fundamental organization and content of the original WEIH website was used as the framework for the new site. Primary pages include a Home page, an About page providing the viewer with background and history of Wormsloe, a Research and Education page, a People page with links to researchers and Wormsloe Fellows and biographies, a Media and Links page with downloadable presentations and music, and finally, a Contacts page (Fig. 5.9). From these primary pages, the user may choose to view more information about projects, people involved with Wormsloe, and additional history and background. Additionally, there is a link to the Science Advisory Committee which includes members' professional affiliations. The user's experience is enriched with the use of links of interest throughout the website.

Figure 5.10 Upper half of WIEH home page with newly designed format and menu.

A new banner that incorporates the WIEH acorn logo was designed and placed at the top of each page in order to provide consistency and branding throughout the website. An early Colonial era map of coastal Georgia. provides the backdrop for the logo.

Research projects described in the web site include the Long Term Vegetation Plots (LTVP) and Dendrochonology activities being conducted at Wormsloe. The Dendrochronology page includes descriptive text and photographs of students and researchers conducting dendrochronological work on Wormsloe (Fig. 5.8). The LTVP include a description of the project and an interactive map that enables website visitors to view the plots at 3 scales. Each plot is represented by red circles overlaid on a landscape scale aerial photograph of Wormsloe that shows surrounding tidal creek and marsh habitat. The visitor may click on each circle to view photographs at ground level of the plots (Fig. 5.11). Additionally, each plot has a lidar point cloud profile image that further describes vegetation structure using large-scale remotely sensed data. By viewing ground photographs of vegetation in each plot next to the respective lidar point cloud that represents that plot, viewers may gain a more thorough understanding and appreciation of the variations in forest structure across Wormsloe.

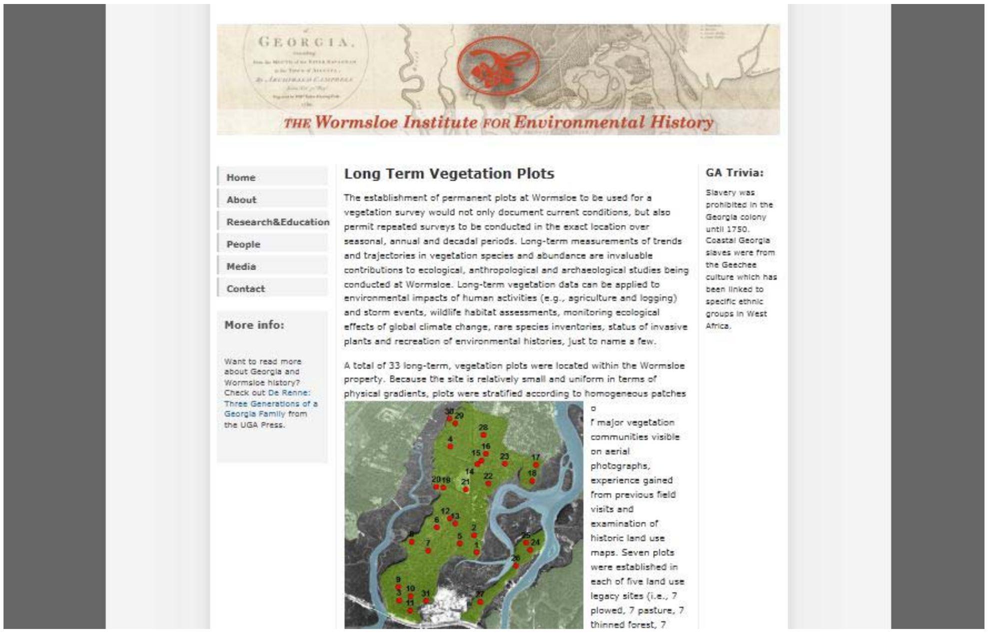

Figure 5.11 Longterm Vegetation Plot research page with descriptive text and interactive map.

Figure 5.12   Longterm vegetation plot 21 example. Vegetation plot pages consist of ground photographs of the cardinal directions, a canopy photograph, and a lidar point cloud visualization.

The new website was designed with the intentions of increasing the public's awareness of Wormsloe State Historic Site and WIEH as an important entity through which Georgia state history may be promoted and preserved. Future additions to the website will promote collaboration among researchers in ecology, archeology and history. With the addition of projects conducted by the UGA College of Environment and Design, ongoing projects including herpetological surveys, and potential future ornithological surveys, and interactivity through geovisualization tools, the new WIEH website is a dynamic tool that can help increase communication and perhaps inspire new research based on Wormsloe's multi-faceted history.

CHAPTER 6

CONCLUSIONS

The use of airborne discrete return lidar can be successfully used to characterize maritime forest structure on a coastal Georgia barrier island. Lidar point cloud data may be quantified and analyzed in multiple ways to study forest structure, as shown by this research. The lidar data were stratified into eight layers within 33 forest plots and, using multiple returns from the lidar data, ratios were computed to characterize canopy cover and gaps, as well as vertical density and presence of various canopy strata. The resulting ratios were used to derive an ordination, followed by graphing the results of the ordination analysis. Three eras that reflected major land use shifts at Wormsloe were used to classify each plot within the Antebellum era (1810-1860), the Postbellum era (1870-1910) and the Pine Beetle Infestation era (1970-2010). Using past Land Use Land Cover (LULC) for each plot within these eras, the plots were classified as having low, moderate, or high disturbance levels. Each plot was also classified as low, moderate, or high transition based on how the number of times their disturbance levels changed over the three time periods. The resulting disturbance and transition classifications were overlaid onto the ordination graph and inspected for patterns, or relationships, among and between the plots. Disturbance level classifications during the three significant time periods did not reveal patterns in the ordination. However, transition levels among the plots did indicate that varying levels of transition, or change, at Wormsloe, may have significantly differing impacts on modern day vegetation structure.

In regards to the objectives of this study, all were met but some deserve further study in order to relate historic land use legacies with modern day forest structure characteristics. The first objective was measure vegetation structure in 33 forest plots using lidar point cloud data to derive statistics indicative of each plot's vertical structure. This was achieved by stratifying point cloud data by elevation within each plot, and calculating canopy statistics that have been correlated to structural characteristics including canopy cover, gaps, and density in previous biodiversity assessment studies. This study stratified each canopy into 8 layers in order to accommodate for commonly accepted growth form concepts in forest canopies (Jennings et al., 2009) and personally observed patterns within the point cloud data (gaps and clumping of points). This stratification also provides quantitative data for potential future studies of white-tailed deer impacts on the vegetation at Wormsloe. A product of Objective 1 includes an extensive spatio-termporal data set that documents the plots' lulc over a 200-year span. These data will be valuable in future research projects where land use history, forest dynamics, and forest transitions are important in understanding habitat on Wormsloe.

The second objective of this research was to ordinate the plots using the lidar derived vegetation structure statistics. This task was performed by inputting the canopy statistics into a DCA ordination using PC-ORD v. 4.0 software. The disturbance and transition levels for each plot were then overlaid onto the resulting ordination graph to explain the ordination distribution. The graphs were examined for possible relationships between the lidar derived statistics, disturbance levels, and transition levels that may influence forest structural characteristics. While no clear relationships emerged between disturbance levels and the three time periods examined, the transitional levels affected structure in differing ways. Plots classified as having low transition levels were more open above the mid-story and had lower canopy heights. Plots classified as having moderate transition levels were more closed above the mid-story and had higher canopy heights. Plots classified as having high transition levels generally displayed denser mid-stories than those in the low and moderate transition groups.

The third objective, which was to redesign the Wormsloe Institute for Environmental History web site and create and incorporate lidar visualizations to help visitors to the web site gain an understanding of how land use legacy has helped shape the modern day landscape. This objective was met by using a CSS template and Adobe Dreamweaver CS4 to create a new layout and add new content. Information including research projects, people involved with WIEH activities, and photographs were incorporated into the various pages on the website. A new banner that includes the WIEH acorn logo appears on the top of all pages to provide consistency and cohesiveness throughout the website. Lidar point cloud data representing the 33 plots were included as part of the Long Term Vegetation Plot research page, and accessible via clickable red dots on a stylized landscape scale aerial photograph of the property. The new WIEH website will not only promote the preservation of Georgia state history, it will also increase communication and collaboration between researchers and inspire new ideas for those who are interested in the intersections of ecology, history, and archeology.

Future Work

This research project lays the groundwork for future vegetation studies at Wormsloe. It provides a spatio-temporal data set that documents 200 years of LULC change for the longterm vegetation plots. It also contributes another spatial layer, consisting of high resolution lidar point cloud data, from which accurate digital elevation models may be generated. In addition, lidar point clouds representing each plot have been extracted and isolated from larger data sets and are ready for use in future vegetation structure and geovisualization research. Finally, lidar metrics that characterize density, openness, and gaps have been calculated for each plot. These characteristics provide valuable insight into habitat suitability for many animal species. This research stratified the plot canopies into 8 layers. Collapsing the strata into 4 four layers may change the ratios; thus gaps and relative openness may become more apparent in the resulting metrics. Additionally, Oliver and Larson, 1996, state that forests typically do not begin to stratify until the stem exclusion stage. Environmental conditions and physiological predispositions dictate when a stand will reach this stage. Driving these factors is stand age. The trees within the plots used in this research vary in age to a certain degree, and some plots may not have had enough time to develop strata. It may be useful in future work to examine each plot canopy as a whole and incorporate cluster analyses into efforts to further characterize vegetation structure.

As discussed in Chapter 5, the deer population at Wormsloe is likely impacting forest structure. Future research incorporating species composition surveys and permanent deer exclosures to examine differences between browsed and non-browsed areas is recommended. In doing so, researchers and managers gain a better understanding of how maritime forests may appear with healthy deer populations and compare them with forests that have high deer densities.

As alluded to in previous sections, when examining the entire group of vegetation plots across Wormsloe, the incorporation of field derived environmental characteristics into vegetation structure analyses may reveal more distinct patterns in a land use legacy ordination. Future work should include how well the lidar data capture structural characteristics in the field. In doing so, vegetation surveys are necessary to measure species composition and richness, and field-derived structural characteristics including canopy height, leaf area index, and other commonly measured field based variables. Soil characteristics are commonly used in ordinations. The soil series on Wormsloe generally display similar characteristics. For example, all of the soil series (e.g. Albany, Chipley, Galestone, Leon, etc.) are classified as being slightly to extremely acidic. Some series have poor drainage characteristics while others have moderate drainage characteristics. Permeability also varies somewhat in these soils, but not significantly. Adding specific pH levels, and relative permeability and drainage characteristics specific to each plot to the ordination would enhance the analysis and perhaps produce a noticeable plot shift on the axes. While the relief at Wormsloe appears minor, slight elevation gradients probably influence soil types, and the addition of elevation values might further elucidate any patterns among the vegetation plots.

Along with soil characteristics and relative distance from ecotone boundaries, the potential for other biophysical characteristics to help link canopy structure to land use legacies is high. Wormsloe has a long and rich history spanning from the time of its formation as a barrier island, to an era where ancient inhabitants harvested shellfish from its surrounding waters, to the time of European colonization when drainage ditches were created and cotton fields cultivated, to present day, where it is a conserved historic property. Temporary human habitation structures are long gone, but perhaps they made their permanent mark by subtly changing soil chemical properties which may, in turn, give rise to a slightly different suite of species from other locations on the property. The original 1734 fortified house at Wormsloe for example, is made of shell and lime mortar. The ruins of this building material would be expected to create an area of localized basic and enriched soil favored by some tree and shrub species. There are any number of environmental variables that can be used in statistical analyses. The potential for further research on land use legacies and their effects across the Wormsloe landscape is great.

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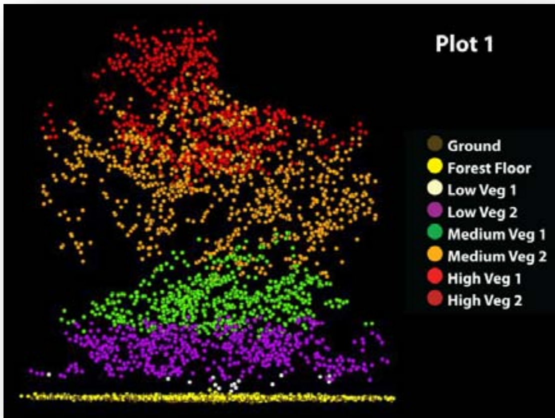
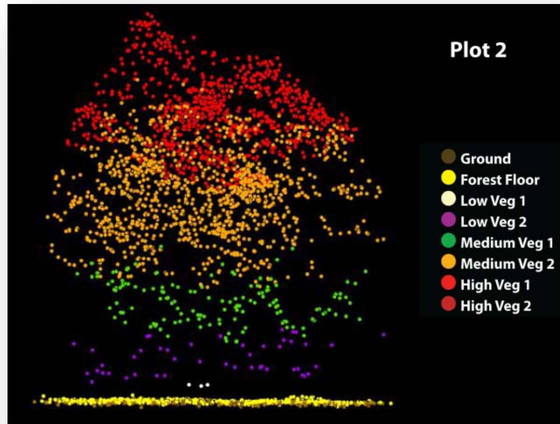
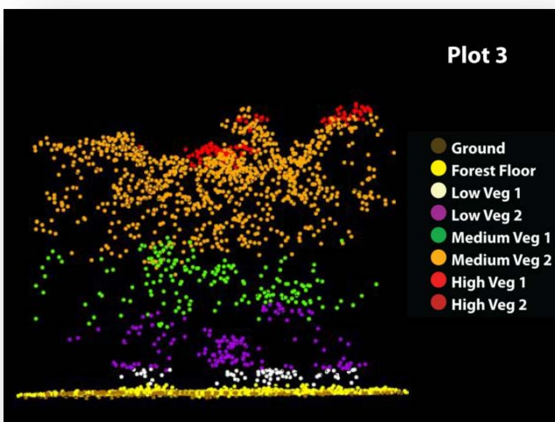
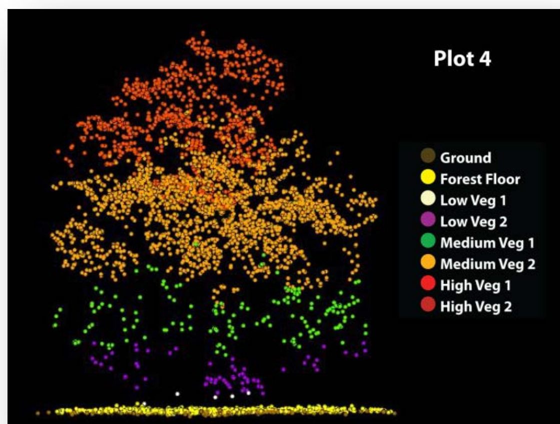
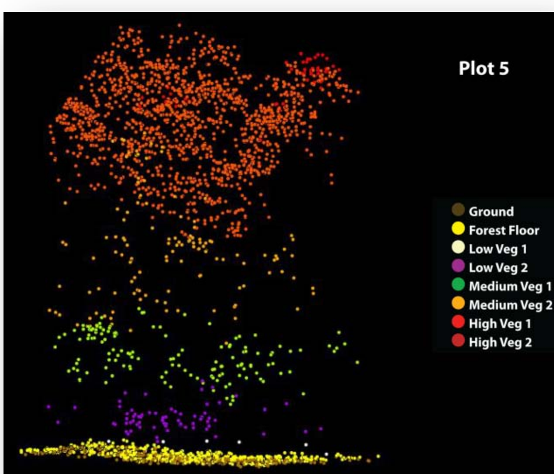
APPENDIX: LIDAR POINT CLOUD PER PLOT

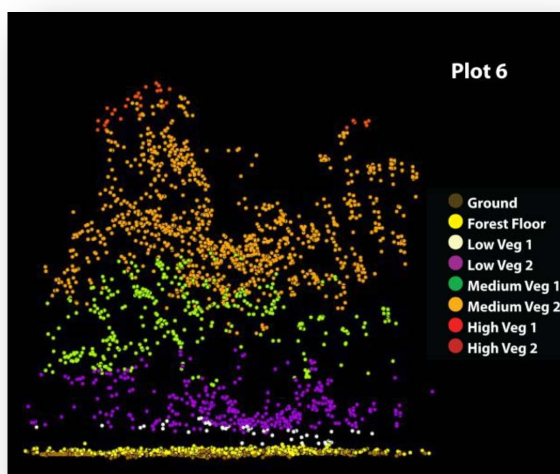


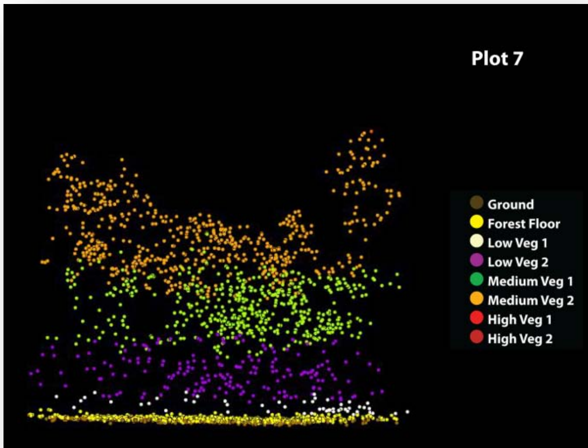








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Ground
Forest Floor
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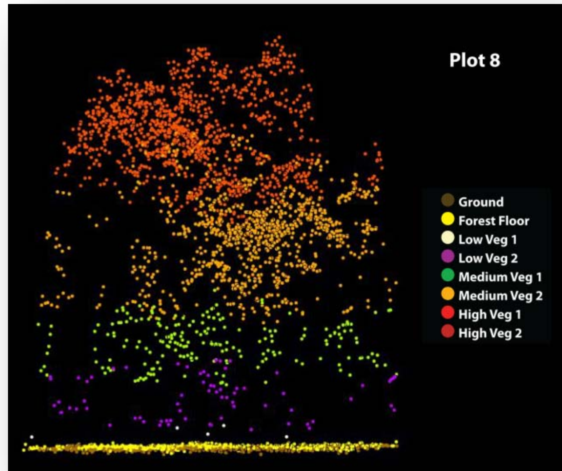
Low Veg 2
Medium Veg 1
Medium Veg 2
High Veg 1
High Veg 2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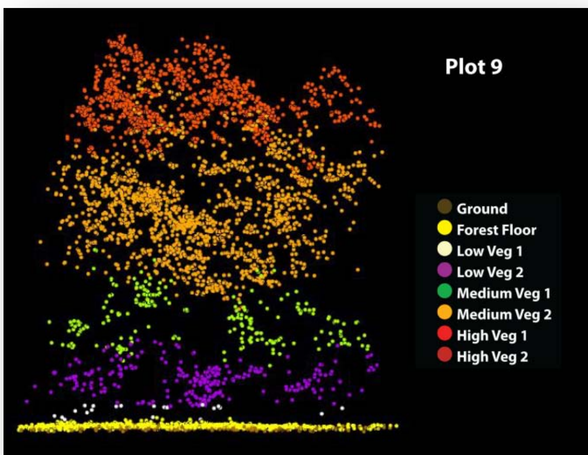
High Veg 2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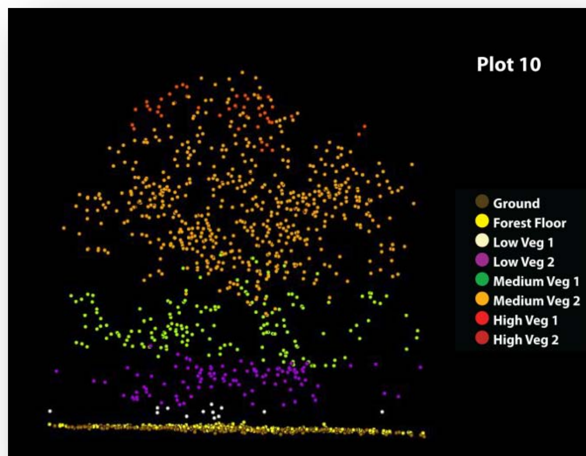
High Veg 2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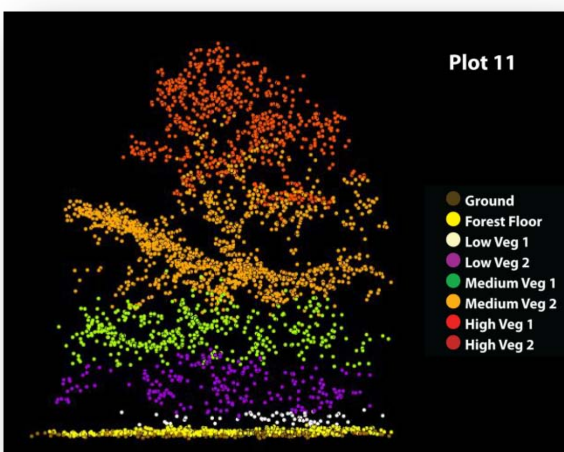
High Veg 2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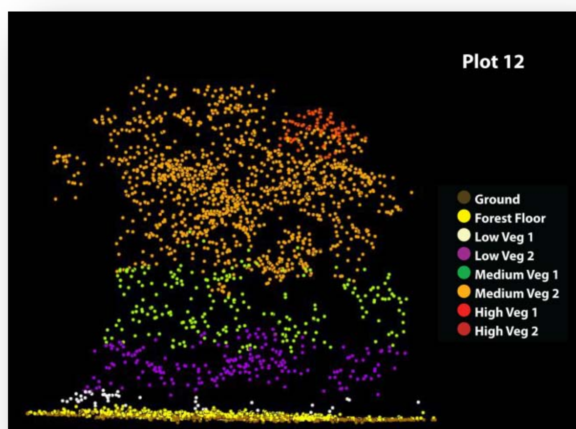
High Veg 2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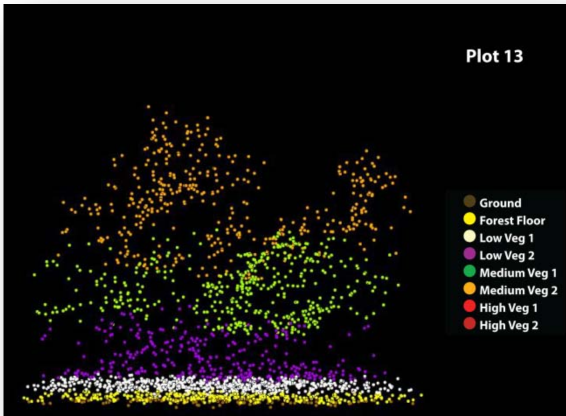
High Veg 2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Forest Floor
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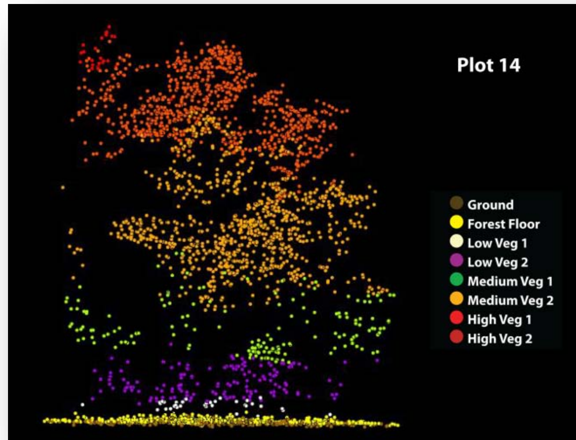
High Veg 1
High Veg 2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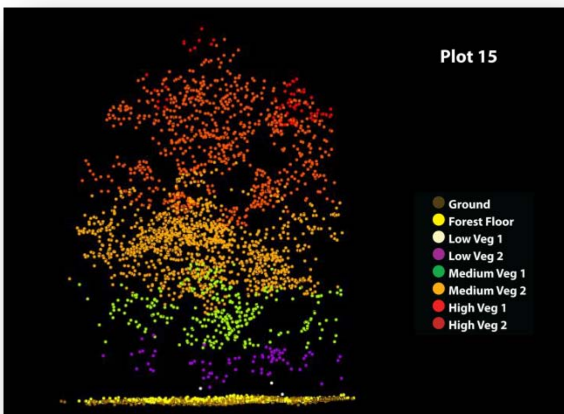
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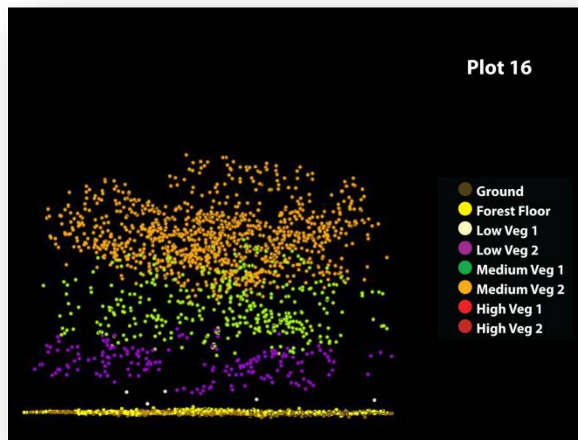
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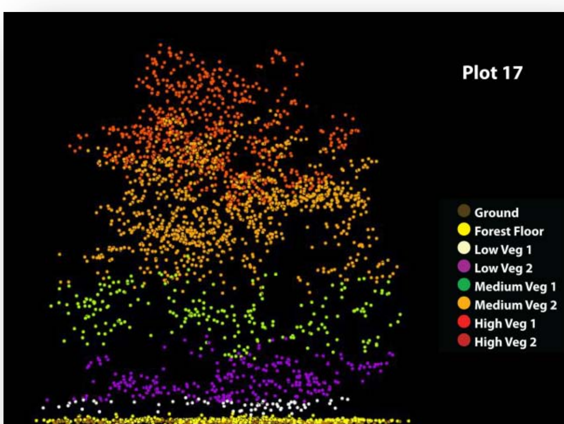
High Veg 2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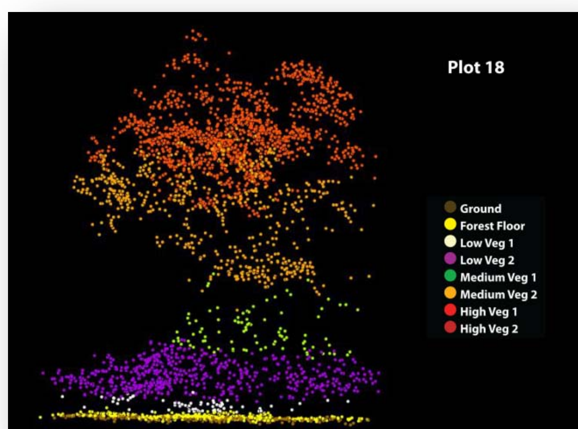
High Veg 2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Forest Floor
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Medium Veg 2
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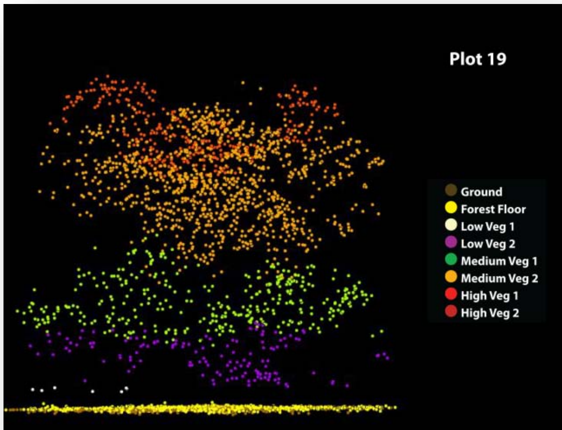
High Veg 2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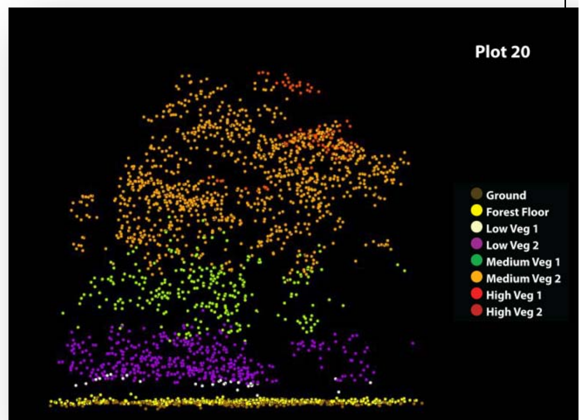
High Veg 2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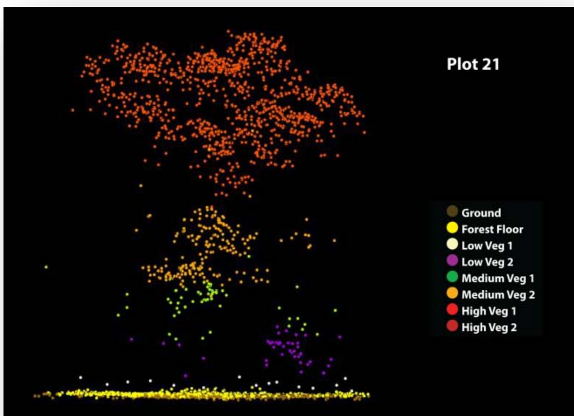
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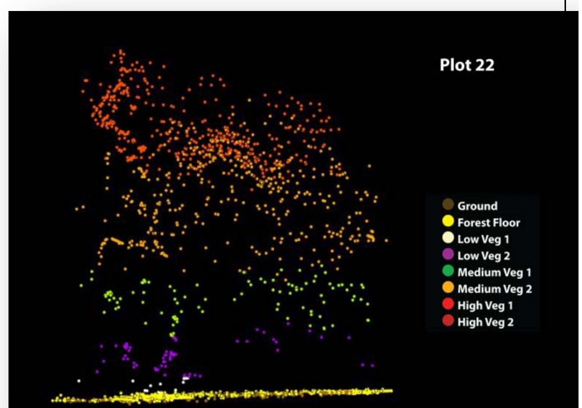
High Veg 2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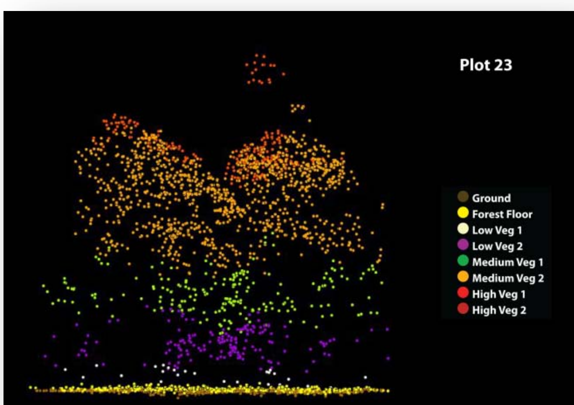
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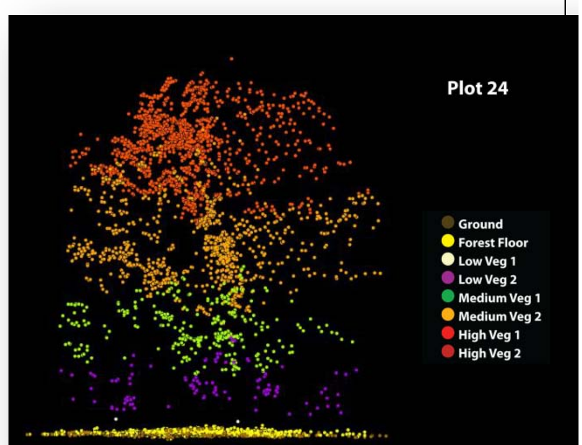
High Veg 2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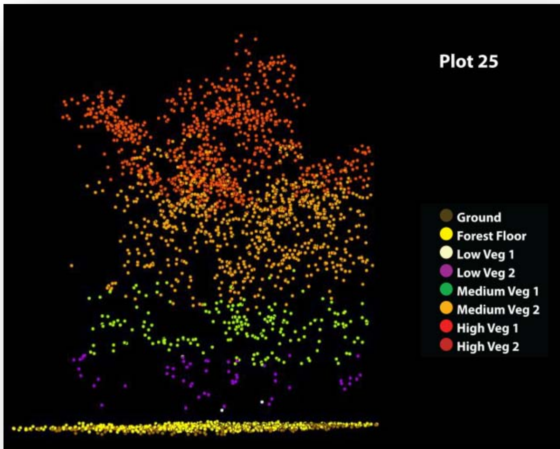
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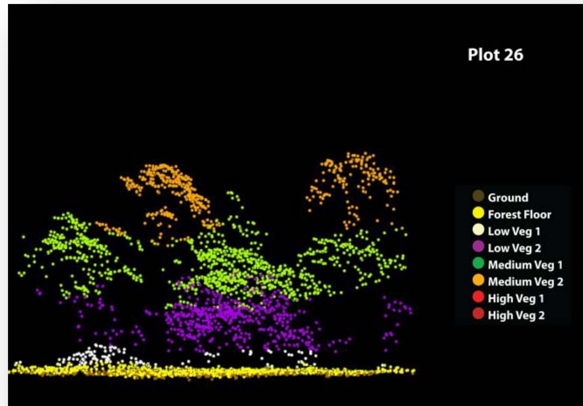
High Veg 2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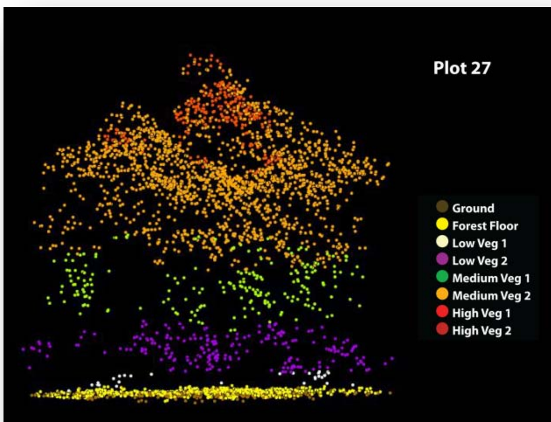
High Veg 2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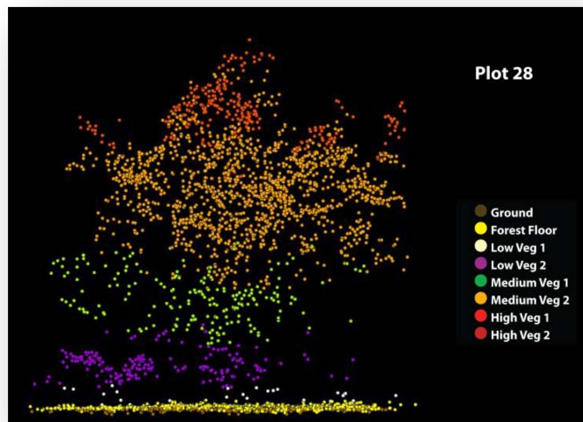
High Veg 2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Forest Floor
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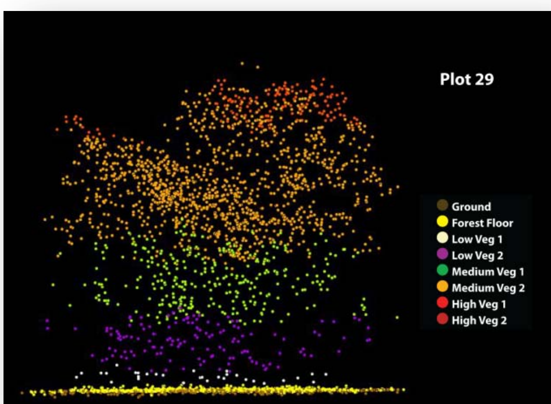
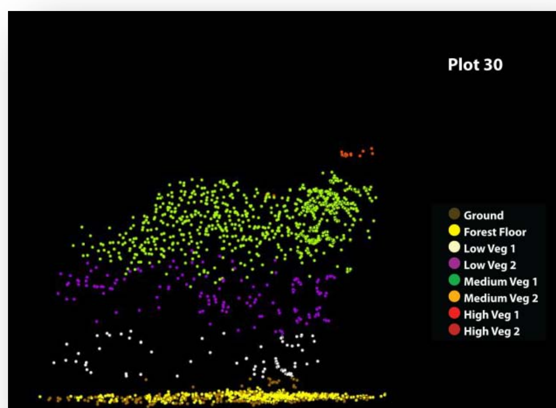
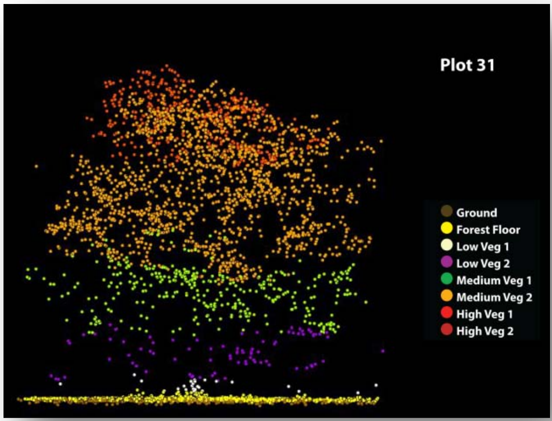
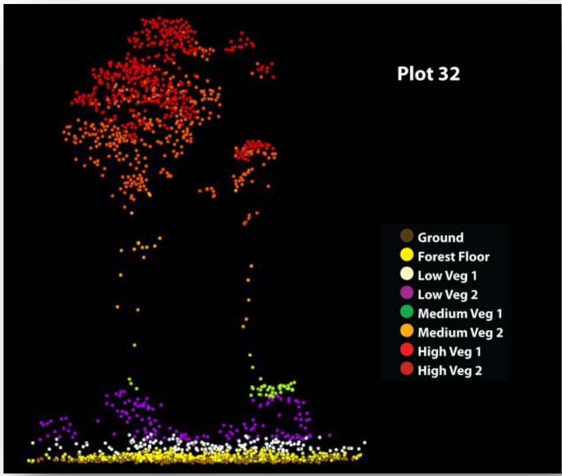
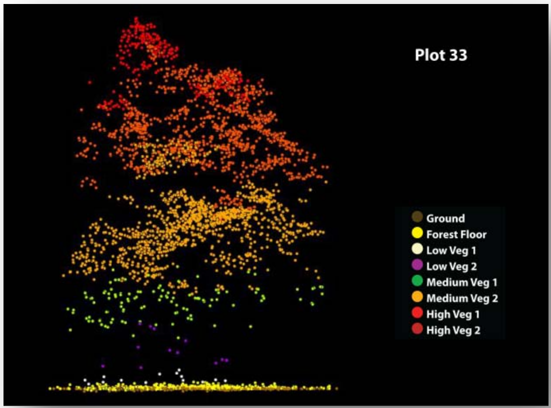
High Veg 1
High Veg 2


Plot 29
Ground
Forest Floor
Low Veg 1
Low Veg 2
Medium Veg 1
Medium Veg 2
High Veg 1
High Veg 2


Plot 30
Ground
Forest Floor
Low Veg 1
Low Veg 2
Medium Veg 1
Medium Veg 2
High Veg 1
High Veg 2


Plot 31
Ground
Forest Floor
Low Veg 1
Low Veg 2
Medium Veg 1
Medium Veg 2
High Veg 1
High Veg 2


Plot 32
Ground
Forest Floor
Low Veg 1
Low Veg 2
Medium Veg 1
Medium Veg 2
High Veg 1
High Veg 2


Plot 33
Ground
Forest Floor
Low Veg 1
Low Veg 2
Medium Veg 1
Medium Veg 2
High Veg 1
High Veg 2