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THE IMPACT OF FIRE ON SOIL CHARACTERISTICS IN THE MARITIME FORESTS ON SAPELO ISLAND, GA

by

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ABSTRACT

Human activities have drastically altered natural fire regimes in countless ecosystems by suppressing and/or effectuating fires. In the past, management strategies were formulated to eliminate the occurrence of fire altogether but as we have become more aware of the benefits of fires such as reducing the amount of fuel build-up, recycling of nutrients for healthier plant communities and the promotion of biodiversity, prescribed burns are now considered an integral part of forest management. While many studies have explored the benefits of fires on plant communities, very few studies look at the impacts of fire on soil characteristics. Sapelo Island, which is located off the coast of Georgia, USA experiences both prescribed fires and natural wildfires. The goal of this study was to investigate the impact of different fires on soil characteristics. We hypothesized that soil from areas impacted by wildfires would have significantly different soil characteristics, especially when compared with soils from the prescribed fire areas or soils from areas not affected by the same fires. Four sites were chosen for sampling, two prescribed and two natural wildfire sites. Soil samples were collected at each site from burned and nearby unburned areas. Soils were analyzed for pH, extractable minerals including P, K, Ca, Mg, Zn, Mn, Cu, B, and Na (all measured in ppm), soil texture, and organic matter (OM). Some soils from wildfire sites had lower soil nutrient concentrations, OM, and CEC, as well as, sandier soil texture than unburned samples while others had higher nutrient availability, OM, CEC, and silt fraction than unburned samples. Soils from prescribed fire sites had no significant differences in most soil characteristics between burned and unburned samples. Results suggest that prescribed fires do not cause significant changes in soil characteristics and can overall be beneficial whereas some wildfires are likely to negatively affect soil characteristics.

Table of Contents

LIST OF TABLES

LIST OF FIGURES

Chapter 1: Introduction

Fires have been occurring in ecosystems long before humans arrived, and many sites around the world contain some preservation of burnt material from as far back as 440 mya (Glasspool et al., 2004). Today, humans are responsible for 84% of all wildfires, and therefore, have drastically expanded Earth’s fire regime (Balch et al., 2017). The other 16% of fires are naturally occurring, many caused by millions of lightning strikes that occur every year (Gowlett, 2016). High-intensity fires can degrade soils while low to moderate intensity fires convert nutrients stored in plant biomass and soil into forms that organisms can readily utilize (Schoch & Binkley, 1986). Soils sustain many biological, hydrological, and atmospheric processes (Neary et al., 1999).

Soils and fires have been ecologically intertwined for millions of years. Soils provide sustenance to the vegetation that fuels forest fires and fires convert vegetation into nutrients that contribute to new plant growth (Brown & Smith, 2000). Fires have many soil-forming impacts that can either enhance or degrade soils. Forest fires result in increased nutrient availability and biodiversity but have also been found to result in the loss of soil structure and increased water repellency (Santín & Doerr, 2016). In areas that experience fires on returning intervals, there is a need for scientific investigation on the effects of fire on soils. The optimal procedures for managing forests with fires is intrinsically associated with the physical and chemical properties of soils. Fires have rejuvenating benefits because of their capacity to transform organic matter into available forms that organisms can obtain from the soil. When a fire burns through an ecosystem, it converts biomass/litter/soil into ash thus altering the soil's chemical and physical properties (Brown & Smith, 2000). Forest managers often conduct prescribed fires ranging from low to moderate intensities to reduce the build of fuel (biomass, surface litter, soil, etc.), recycle nutrients for healthier, native plant communities, and promote biodiversity (Alcañiz et al., 2018). Understanding the effects of fire on soils can ensure that managers are utilizing prescribed fires effectively to maximize benefits.

Controlled fire in the U.S. south was first introduced to European settlers by Native Americans and it was primarily used to increase visibility and to assist with foraging by free-range cattle (Johnson & Hale, 2002). In the early 1900s, U.S. policies supported practices that frequently suppressed naturally occurring fires in forests to protect lives and investments (van Wagtendonk, 2007). The U.S. Forest Service (USFS) had an established 10 a.m. rule in 1935, which instructed managers to suppress every fire that occurred in the forests before 10 a.m. the following day (Pyne, 2001). Managers continued to use fire suppression practices in forest management for years after this rule was implemented. However, in the 1970s, wildfire began to receive recognition from scientists and managers for its vital role in managing native flora and non-game species (Johnson & Hale, 2002). The current increase in severity and frequency of fires is in part due to suppression practices of the past (Arno & Brown, 1991). For instance, in 1988 a high-intensity fire occurred in Yellowstone National Park as a result of fire suppression practices, so the USFS decided to implement a “let-burn” policy that would allow some fires to burn to reduce the fuel load (Williams, 2005). Then in 1992, the Chief of the USFS changed policies to remove clearcutting as a standard practice because of the negative ecological impacts associated with it. Prior to this change, the USFS had predominantly been involved in logging so this policy change significantly reduced the use of clearcutting (Williams, 2005). Today, a large proportion of the USFS budget is used to conduct prescribed burns and monitor forest health. In

2018, the USFS Budget was $4.73 billion with $2.495 billion of that allocated to Wildland Fire Management (USDA, 2017).

Although more attention is put on the weather-related extreme fire events in the western U.S., the Southeast experiences the highest number of wildfires each year (Wang et al., 2016). In the Southeast, managers intentionally set forest fires under specific conditions to achieve management goals aimed at reducing biomass accumulation and preventing severe forest fires. These fires, known as prescribed fires, can improve soil quality and restore forests to historical states. Prescribed fires are effective management tools widely used throughout the U.S. Recently managers have recognized the value of fire within ecosystems and have implemented management strategies that encourage healthy plant communities. Current strategies are based on managing fuels and encouraging the presence of native plant species (Wagner & Fraterrigo, 2015).

Conducting prescribed burns requires an entire team of fire professionals who can predict how a fire will behave based on environmental factors and effectively contain it. Before prescribed fires can be conducted, managers must have a detailed understanding of site history, plant community type, plant growth stages, and environmental factors/weather conditions that are typical in the area (personal communication with B. Tyler May 2019). On a typical day in the field, fire professionals will oversee all operations by checking weather conditions and communicating with the community, forest managers, and other professionals in the field (Dixon et al., 2012). Biologists will commonly come to provide consultation and observe the impact of fire on the ecosystem (personal communication with B. Tyler May 2019). Before they begin the prescribed burn, they must set a small test fire and monitor it to ensure conditions are safe, and then a decision is made whether a prescribed fire can be successfully executed (Dixon et al., 2012). Forest managers have become undeniable experts in executing prescribed burns but more knowledge on how fires impact soil characteristics could increase the efficacy of prescribed burns.

Fire is not the only method used by forest management in the south to reduce fuel loads. Mechanical treatments that remove fuel or change fuel structure are also used by managers to reduce biomass. Weeds and/or invasive species commonly infiltrate a tree stand and out-compete small saplings. Managers utilize herbicides to protect tree populations from potentially harmful weeds (Willoughby, 1996) and control invasive species (Fuhlendorf et al., 2002). Forest managers commonly use herbicides to remove, select, or reduce specific species or species groups.

Mechanical methods are utilized to remove fuels from forests, condense fuels closer to the ground, or mechanically change fuel structure (Marshall et al., 2008). Popular treatments include roller-chopping, logging, mowing, and other mechanical operations (Weekley et al., 2008). The impacts of mechanical treatments vary depending on the environmental conditions of each area. In some areas logging resulted in significantly higher bare sand cover and invasive species than fire, and therefore logging was not recommended for forest restoration efforts (Weekley et al., 2008). Soil type plays a role in determining which type of mechanical treatment is appropriate, for example, applying pressure to soils that have small particle sizes can be very harmful to organisms within the soil (Marshall et al., 2008). A study evaluating the impact of fire and thinning on soil properties found that thinning had overall positive impacts on soil (Boerner et al., 2007).

Soils connect the atmosphere, lithosphere, hydrosphere, and biosphere. The chemical/physical properties of soils dictate what types of vegetation grow in an area, how water is retained in the ground, how much carbon is being released into the atmosphere, and countless other ecological processes (Santos et al., 2019). While fires are commonly used as management approaches and generally accepted as being beneficial, there is a lack of scientific knowledge on forest fire effects on ecosystems that can be utilized by managers to determine the types of procedures they should use to achieve desired outcomes (J. O'Brien, personal communication, October 17, 2019). Fires vary widely and it is necessary to understand how varying fire intensities, both prescribed and natural, impact soil characteristics. More research is therefore, needed to understand whether current fire practices are promoting healthy soils or not. The goal of this project was to evaluate soil characteristics from areas that experienced prescribed fire and natural wildfires and see how they compare with soils from areas that did not experience those fires. We hypothesized that soil from areas impacted by wildfires would have significantly different soil characteristics, especially when compared with soils from the prescribed fire areas or soils from areas not affected by the same fires.

Chapter 2 : Literature Review

Climate change is impacting fire behaviors and patterns around the world because as temperatures rise, fire intensities and occurrences are also increasing (Holden et al., 2016). Fires play a large role in the conversion of terrestrial carbon into atmospheric carbon (Dixon & Krankina, 2011). For example, in California, atmospheric carbon increased by 2 ppm after large wildfires that occurred in 2017 (Li et al., 2019). Increased forest fires could, therefore, significantly contribute to global climate change, which would reciprocally result in more fires. Studies have predicted that fires will become more frequent and extreme during the summer months in the southeastern US (Kovaleva & Ivanova, 2013). The mismanagement of forests in California has resulted in higher severity fires that impact larger areas (Bekker & Taylor, 2010)**.** The Amazon rainforest has been experiencing increased wildfires and studies predict that climate change and deforestation practices will cause this trend to rise (Bush et al., 2008). Extreme fire weather events have been rampaging throughout Australia and climate models predict more extreme fire events if high emission continues (Hasson et al., 2009). Fire occurs in every biome on the planet therefore, understanding all aspects of current fire dynamics in forests will lay the foundation for predicting how climate change will impact fire regimes over time.

Fire behavior varies based on factors such as plant community structure, weather conditions, fire type (head, flank, or backing fire), and the type of terrain within a particular area (Ryan, 2002). Head fires burn in the same direction of the wind, backing fires burn against the wind, and flanking fires burn perpendicular to the direction of the wind (Ryan, 2002). A fire regime can be understood as the recurring properties of fire in a specific location (He et al., 2019). Each component associated with fire behavior is crucial to understanding how fires can be controlled by managers. Additionally, understanding the fire regime that occurs in an area can help managers determine the best methods for conducting prescribed burns. Fire frequency, fire intensity, and fire severity together make up an area’s fire regime.

Fire frequency is the number of fires that occur within a specific time period (Ryan, 2002). Many areas have returning intervals of forest fire based on climate factors (He et al., 2019). In the U.S., suppression practices decreased the frequency of forest fires thus resulting in higher amounts of biomass and increased risk of severe wildfires. Historically, many forests were maintained by frequently occurring wildfires (Gleason, 1913). That is why today prescribed burns are commonly performed on recurring intervals. In oak savannas and woodlands located in Minnesota, it was found that high-frequency fires killed large percentages of saplings (including various species of oak, maple, and others), whereas low-frequency fires resulted in the highest tree sapling yield (Peterson & Reich, 2001).

Fire intensity is described as the energy output resulting from a fire (Keeley, 2009). The temperature range for low intensity fires is > 250 ^{o}C, moderate intensity is > 400 ^{o}C, and high intensity fires occur at > 675 ^{o}C (Araya, 2016). The higher the intensity of a fire, the more heat the soils and soil inhabitants must endure. High fire intensity typically has negative effects on ecosystems in areas that do not have fire regimes (Graham, 2003)**.** The 2003 Cedar Fire was a large, high severity wildfire that occurred in California, U.S., destroying most living biomass in the area. Many of the native species did return after the second growing season, but the impacted areas had more exotic species (Franklin et al., 2006). Low-intensity fires are preferred by managers because they reduce biomass accumulation but retain healthy native plant communities. Conducting prescribed fires at low intensity also decreases the risk of negative impacts on ecosystems and human interest. The impact of surface fires with varying intensity on the living ground vegetation was studied in the middle-taiga forests of Central Siberia. It was revealed that fires, regardless of their intensity, decreased the percentage cover and the biomass of ground vegetation. However, high fire intensity changes soil properties and the germination success of seeds, thereby impacting the types of plants that thrive in the area (Kovaleva & Ivanova, 2013).

Fire severity is characterized in terms of the amount of organic matter lost as a result of a fire (Keeley, 2009). Fire severity classes were originally described by Ryan and Noste (1985) as unburned (plants unchanged), scorched (visible burn scars with negligible impacts), light (surface litter and understory charred to incinerated), moderate (surface litter and understory fully incinerated), and deep (vegetation and surface litter fully incinerated (Ryan, 2002). Typically, fire intensity is positively correlated with fire severity. Managers can determine how negatively an environment is impacted based on the severity of the fire.

Fire contributes to healthy soil organisms in numerous ways, a critical one being nutrient cycling. Accumulated soil organic matter must be broken down into a form that can be utilized by plants and microorganisms (St. John & Rundel, 1976). When a fire burns through an ecosystem, it converts nutrients stored in plants and ground litter into forms that can be readily utilized by new plants (Brown & Smith, 2000; St. John & Rundel, 1976). Past studies have attributed increased plant growth within fire regimes to increased nutrient availability (Pearson et al., 1972; Scharenbroch et al., 2012; Wilbur & Christensen, 1983)**.** In many fire-dependent ecosystems fire plays a direct role in recycling nutrients. Although fire is responsible for the removal of biomass, it makes nutrients available to plants thus, encouraging new plant growth (Brown, 2000).

An important soil function is its role in storing and supplying nutrients such as N, P, Na, Mg, Ca, and K and a soil's ability to effectively serve this function depends on its chemical properties such as pH, cation-exchange capacity (CEC), and soil organic matter, among others. Soil nutrient pools are largely determined by biogeochemical cycling, which is how chemical nutrients crucial for sustaining life move through biotic and abiotic components of a system (Santos et al., 2019) ensuring their continued supply. Studies have shown that fire can result in increased soil nutrients immediately after a fire event (Badia & Marti, 2002; Dean et al., 2015; Kutiel & Naveh, 1987). When fire burns through an area, the organic matter close to the surface is combusted releasing chemical nutrients and subsequently impacting soil chemical properties (Debano, 1991). Soil pH plays an important role in influencing the availability of those nutrients and studies show that the most suitable pH range for healthy plant growth is between a pH of 5 and 6 (Gentili et al., 2018). High intensity (Badia & Marti, 2002) and low to moderate intensity fires (Boerner et al., 2007; Certini, 2005) have been found to increase soil pH. High temperatures can result in complete combustion of organic matter, releasing bases that increase soil pH and contribute to the development of pyrogenic carbon (Santín & Doerr, 2016).

Terrestrial life has evolved with the presence of fire and consequently resulted in fire-dependent plant morphologies. Fire suppression can have negative impacts on forest plant populations. Researchers used fire scar chronology to determine when fires occurred in *Pinus pungens* communities in Virginia U.S. that experienced fire exclusion. The study showed that areas that experienced fire exclusion had lower seedling establishment (Sutherland et al., 1995). Areas affected by fires develop plant communities adapted to fires as fire-tolerant species become more prevalent (Verma et al., 2017). For example, the Jack pine, *Pinus banksiana,* has serotinous cones that require heat to release seeds and allow germination to occur (Mullen, 2017). Lack of fires lowers the rate of successful germination and subsequently reduces the population of this species. Some plant adaptations increase organisms' odds of surviving during a fire. The Ponderosa pine has thick heat-resistant bark that can withstand high temperatures and drops its lower branches to prevent fire from spreading to its crown (Mullen, 2017).

Plant biomass provides the fuel that is ignited during a fire. Higher amounts of biomass result in longer and/or higher intensity fires. The fuels present within an ecosystem influence the duration and intensity of fires and subsequently determine the type of plant community present and how it is structured (Mitchell et al., 2009). Depending on factors such as resilience or the number of disturbances affecting an ecosystem, fires could result in the transformation of an ecosystem into a different state. The response of vegetation to fire disturbance is dependent on each species' sensitivity to heat (Catry et al., 2010). An example of a fire-related ecosystem transformation was shown in the oak-conifer in the southern Cascades, transforming from being dominated by *Pinus pinaster* to being dominated by *Quercus pyrenaica*. Although *Quercus* was not dominant in the historic state, its presence reduced the chance of high-intensity fires which helped many of the other plants to survive in the ecosystem (Torres et al., 2016). In the study, they suggested that overtime many areas that were once heavily managed may begin to move towards historic states or alternative states that no longer need intensive management strategies.

Areas impacted by severe fire disturbances have been known to encourage non-native, invasive species that can alter the ecosystem dynamics of an area (Wagner & Fraterrigo, 2015). Some invasive plants are adapted to thrive in areas that experience frequent fires, for example, *Microstegium vimineum* a non-native species that prosper in areas affected by fire due to its high flammability and fast recuperation (Wagner & Fraterrigo, 2015). Invasive species possess traits that enable them to quickly recolonize severely disturbed areas such as self-pollination, low shade tolerance, and short generation time (Zouhar et al., 2008). The presence of invasive plants can change the types of nutrients entering the soil from dead plant matter and root exudates, increase the use of herbicides by managers, and change the types of soil organisms present in the soil (Weidenhamer & Callaway, 2010). Maintaining a healthy population of native vegetation is an effective means of discouraging the presence of invasive species (Wagner & Fraterrigo, 2015).

Plants are not the only inhabitants in soils that are impacted by fire events. There are soil macro-organisms like mammals and insects, and smaller soil microorganisms like bacteria and fungi. Macro-organisms typically escape from the area or burrow deep into the soil to escape from fires (Engstrom, 2010). Microorganisms cannot so easily escape a fire and many of the ones near the surface will be incinerated when fires occur. Microorganisms enhance the fertility of soils and contribute to healthy plant growth (Altomare & Tringovska, 2011). High severity fires decrease microorganisms, whereas low severity fires have been found to enhance soil microorganisms (Andersson et al., 2004; Dean et al., 2015).

Human activities have changed and degraded tropical forests around the globe and caused significant biodiversity loss (Gibson et al., 2011). Managers are focusing on creating more heterogeneous forest stands based on the assumption that “pyrodiversity begets diversity” (Parr & Andersen, 2006). Pyrodiversity refers to the heterogeneity of an area that is created by fire (He et al., 2019). Higher levels of pyrodiversity resulted in more pollinator-plant interactions within an area (Ponisio et al., 2016). Managers try to encourage pyrodiversity through “patch mosaic burning,” which is designing spatially and temporarily different patches within forests while burning (Parr & Andersen, 2006). Forest management strategies for encouraging pyrodiversity need to become more structured to ensure prescribed burns are effectively meeting the goals of creating healthy, native, biodiverse ecosystems (Parr & Andersen, 2006).

Fires play a role in influencing carbon storage and cycling and consequently, the global climate. Soils represent one of the largest reservoirs of carbon on the Earth's surface, three times the amount that is present in the atmosphere (Lal, 2004). Fires result in the conversion of terrestrial carbon into atmospheric carbon and thus affect carbon sequestration in soils (Bird et al., 2000). When fires occur, the complete combustion of organic matter produces atmospheric carbon whereas incomplete combustion results in the formation of pyrogenic carbon, also known as black carbon (Bird et al., 2015), that influences various processes in the soil. For example, the amount of black carbon influences nutrient availability and retention, which influences CEC. A study evaluating the correlation between black carbon and CEC in Anthrosols found that surface oxidation of black carbon resulted in higher CEC per unit C and a higher charge density in black carbon-rich soils (Liang et al., 2006). Pyrogenic carbon has also been shown to be positively correlated with the decomposition rate and increased uptake of nitrogen compounds by plants (Kuzyakov et al., 2009).

Phosphorus is a vital nutrient for many plants and microorganisms that live in soils despite being limited in most ecosystems (Baker et al., 2015; Richardson & Simpson, 2011). Large amounts of phosphorus can become available in soils after fires occur (Debano, 1991). Fire can have a mineralizing effect on phosphorus (Certini, 2005; Saa et al., 1993), by converting organic P to biologically available inorganic forms. A study looking at fire in the *Quercus coccifera* shrublands found that nitrogen and phosphorus were more available in soils after recurring fires (Ferran et al., 2005). Fires can also cause significant changes to other soil chemical elements like Ca & Mg (Arocena & Opio, 2003) that encourage healthy plant growth (He et al., 2001). A deficiency of these minerals in the soil can, therefore, reduce ecosystem productivity. Other nutrients such as sodium (Na) can have negative impacts when present in high concentrations in soils such as reducing germination success and plant health (Bernstein, 1975). High Na levels can result in toxic ions and osmotic stress that reduces soil microbial activity and plant growth (Yan et al., 2015). Sodium occurs in many ecosystems around the world but it is not abundantly used by plants (Maathuis, 2014). The effects of fire on soil Na concentration seem to vary depending on soil type and fire intensity, with some studies showing a considerable decrease in concentration after a fire occurs (Smith, 1970) while others show an increase in concentration after a fire (Badia & Marti, 2002).

Soil texture can influence how fire interacts with soil. Bird et al., 2000 found that soil texture does impact carbon particles when a fire occurs. In soils with high sand content, larger carbon particles can move into the soil more easily than in clay soils. In clay soils, small particle size results in the trapping of larger carbon particles at the surface until they are broken down into smaller particle sizes by fire, resulting in increased pyrogenic carbon formation (Bird et al., 2000). In a wooded-shrubland ecosystem, it was found that prescribed fire changed the texture of soils through aerial deposition of silt particles (Chief et al., 2012). Aerial deposition of silt can have varying impacts depending on the porosity of the underlying soils. For example, in larger sized particles with larger pores, soil hydrology can be reduced by a thin layer of ash (Woods & Balfour, 2010). Soils with high CEC typically have high amounts of clay and low porosity, whereas soils with low CEC typically have sandier textures and high porosity(Aprile & Lorandi, 2012). High porosity in soils can result in leaching of valuable ionic elements.

Many forests require intervention through management because of past and current human activities that threaten their survival. Forests that have been altered largely by fire suppression, fire ignition, changing climate, and many other endeavors need intervention. In the U.S., many forests are currently at risk of severe forest fires. Thankfully we are now more aware

0f the dangers of fire suppression to both human interests and natural ecosystems. Therefore, managers strive to promote healthy forests by incorporating fires in their management strategies, there is a need for more studies exploring the ecological impacts of fires. Understanding how fire impacts the soil's chemical and physical properties will help researchers understand which fire dynamics most benefit soils. The effects of fires on plant communities have been well studied whereas studies looking at the impact of fire on soil chemical and physical properties are still lacking. Understanding how different fires impact soil properties which subsequently influences plant communities will help to provide the knowledge needed to ensure that the use of fire as a management approach is optimized to yield the most benefit. Based on what’s in the literature, we hypothesized that soil samples collected from areas impacted by the high-intensity wildfires will have significantly different soil characteristics, especially when compared with soils from the prescribed fire areas.

Research Objectives

The main goal of this study was to investigate the soil characteristics of areas that have experienced different fire regimes (no fire, prescribed fire, and natural wildfire) on Sapelo Island, GA. The specific objectives were:

1) Compare soil acidity and cation-exchange capacity in soil samples experiencing different fire regimes.
2) Analyze concentrations of important nutrient elements like phosphorus (P), potassium (K), calcium (Ca), magnesium (Mg), and sodium (Na) in soil samples from each area of interest.
3) Compare total organic matter and soil texture in soil samples from each area of interest.

Chapter 3 : Study Site

Located on the eastern coast of the United States, Sapelo Island is the fourth largest barrier island in the central region of Georgia's coastline (Figure 3-1). The island has a subtropical climate where winters are brief with mild temperatures, whereas summers are hot with humid conditions (Chambers, 1997). Soils on the island developed from quartz and are typically highly permeable, qualities that result in high drainage and encourage leaching of nutrients (Gaddis et al., 2013). According to the USDA classification, the island soils fall in two main orders, Spodosols (soils rich in aluminum oxides) and Entisols (soils lacking diagnostic horizons). The specific Spodosol suborder is Orthods which are described as relatively freely drained with a moderate accumulation of organic carbon and naturally infertile. The main Entisol suborder is Aquents or wet Entisols (USDA, 1998).

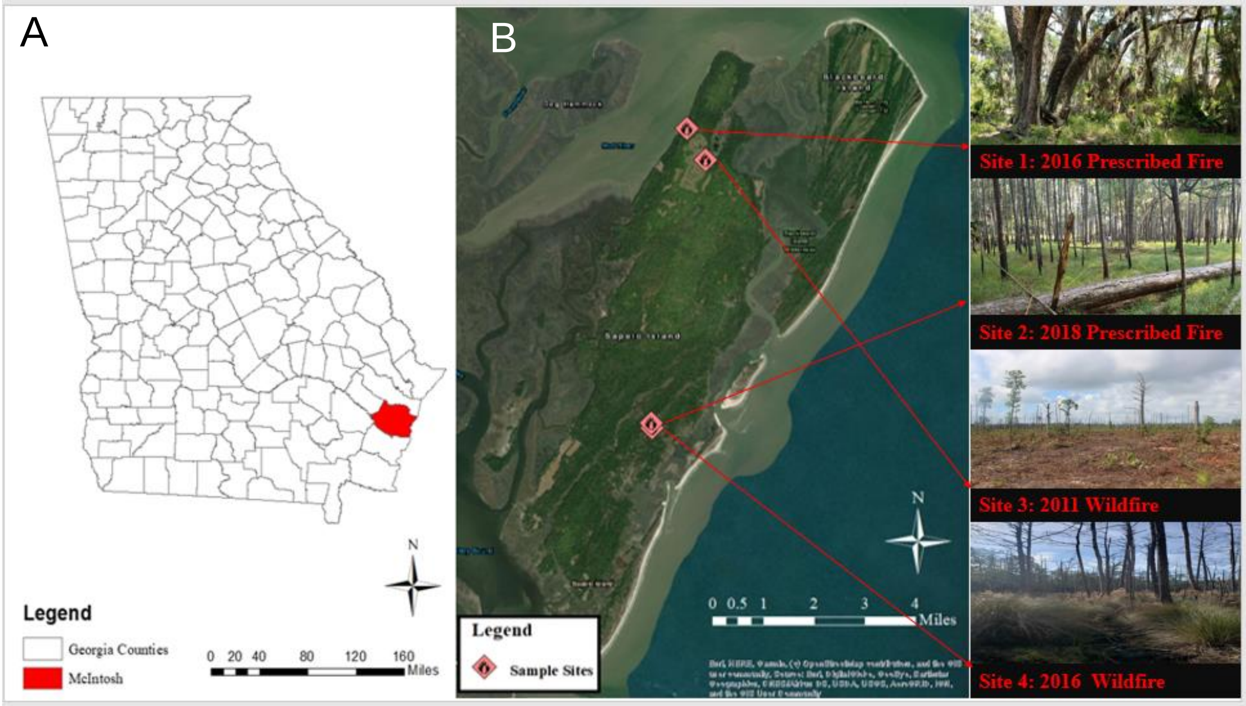

Figure 3-1: *A) Map of Georgia Counties with Mcintosh County highlighted. B) Map of sample sites located on* **Sapelo** *Island in Georgia.*

The island was originally inhabited by Native Americans who used fire to manage the landscape (Chambers, 1997). When colonizers arrived, they took possession of the island, and it passed between the Spanish, French, and British. Eventually, Thomas Spalding owned the island and owned slaves that worked on the plantations, growing staple crops like sea island cotton. After the Civil War freed slaves, agriculture was significantly reduced on the island (Chambers, 1997). Today, the island houses the University of Georgia Marine Institute, an office of the Georgia Department of Natural Resources Coastal Resources Division (DNR), and a small population of about 70 residents that reside on the south side of the island in the Hog Hammock community. Majority of the Hog Hammock community residents are direct descendants of Africans shipped to the island as slaves for Spalding's plantations in the late 1700s (Gaddis et al., 2013).

As stated in the 2008-2013 Sapelo Island National Estuarine Research Reserve Management Plan, the island is protected under the Coastal Zone Management Act of 1972, which allows scientists to research the various ecological processes that occur in the estuarine ecosystem (Gaddis et al., 2013). Today, the island is mostly undisturbed making it a prime location for ecological research. The study sites for this project were located in the upland maritime forest, or wooded forests that occasionally experience spray or overflow from the ocean (Bellis, 1995). Dominant species in the forests consist of live oak (*Quercus virginiana*), laurel oak (*Quercus laurifolia*), water oak (*Quercus nigra*), bay *(Laurus nobilis*), holly (*Ilex aquilifolium*), magnolia (*Magnolia grandiflora*), red cedar (*Juniperus virginiana*), sabal palm (*Sabal palmeto*), and loblolly pine (*Pinus taeda).* The understory is predominantly panic grass *(Panicum L.)*, wax myrtle (*Myrica cerifera*), broomsedge (*Andropogon virginicus*), and saw palmetto *(Serenoa repens*) (Gaddis et al., 2013). Some parts of the island have open grasslands, which is the result of previous agricultural practices and domesticated animal foraging (Gaddis et al., 2013).

Prescribed fires are conducted on the island by DNR from December through May (B. Tyler, personal communication, December 17, 2018). The fires are conducted on a 2-3-year fire interval (Figure 3-2). Prescribed fires need to remain contained by managers, therefore, winter (December-February) and spring (March-May) offer the best conditions because they are not too hot or dry. If fires become uncontained, they put lives and property at risk and could negatively impact ecosystems. Natural wildfires commonly occur during the summer months between June and August.

Prescribed burns are conducted on the island to encourage fuel heterogeneity and the presence of native species, and to reduce fuel loads (B. Tyler, personal communication, May 13, 2019). To ensure that fire management practices meet desired outcomes, managers must provide full plans on how they intend to execute each prescribed fire. Managers must identify pre-burn factors which include crew size, equipment, and smoke screening (for classifying areas where smoke could be a danger). A record of the previous burns for that area must be evaluated. A description of the stand including standardized species, growth classification (fires are not allowed at certain growth stages), and the standard fire behavior model. Managers use the Rothermel’s Surface Fire Spread Model to predict fire behavior and potential impacts (Scott & Burgan, 2005). The model inputs include live and dead fuel load, surface-area-to-volume ratio, heat measure, depth of fuel bed, and moisture within dead fuel. Burn plans also contain objectives of burns, weather factors, and fire factors (ex. flame length). After the fires, managers must report a post-fire evaluation of potential insect and disease threats to tree mortality and a biologist evaluation of the fire effects on the ecosystem.

Source: Esri, DigitalGlobe, GeoEye, Earthstar Geographics, CNES/Airbus DS, USDA, USGS, AEX, Getmapping, Aerogrid, IGN, IGP, swisstopo, and the GIS User Community

Figure 3-2: *Map of fire sites on the island provided by Blaine Tyler.*

Managers on the island use delayed aerial ignition devices (DAID) like the PyroShot High-Speed hand launcher and the Mark V Plastic Sphere Dispenser (released from a helicopter). DAID releases a combination of polystyrene balls and water-glycerol to create a chemical reaction that ignites within 30 seconds of being released (B. Tyler, personal communication, May 13, 2019).

Fire is not the only management approach used on Sapelo Island. DNR also uses mechanical and chemical treatments to manage some areas. The island managers used roller chopping in areas that had high amounts of standing dead biomass. Garlon® is a chemical used to manage invasive species on the island like Bahia grass (*Paspalum notatum)* and the Lantana butterfly bush (*Buddleja davidii)* (B. Tyler, personal communication, May 13, 2019).

In this study we selected four sites that experienced different types of fires regimes and had vastly different ecosystems. Sites 1 and 2 experienced low intensity, light severity prescribed fires while sites 3 and 4 experienced high intensity, deep severity wildfires.

Site 1: 2016 Prescribed Fire Site

This site experienced a prescribed fire during the 2016-2018 fire season. Based on the United States Department of Agriculture (USDA) soil survey, the soil type in this area is Palm Beach fine sand, dark (Soil Survey Staff, 2020). Palm Beach fine sand is very well-drained and extends deep into the soil profile (Gaddis et al., 2013). The ecosystem can be characterized as a mixed live oak maritime forest with a saw palmetto understory (Figure 3-3). Many areas are dominated by monocultures of live oak and saw palmetto, but the understory plant community has a mixture of various trees, shrubs, and herb species. A qualitative assessment based on our field observation showed that this site had the highest species richness in this study. The intensity of the fire that occurred in this area can be characterized as low to moderate (B. Tyler, personal communication, May 13, 2019). According to the Ryan & Noste severity classes, the severity of the fire would be categorized as light (Ryan, 2002). For simplicity, this site is referred to in this study as "*2016 prescribed fire.*"

Figure 3-3: *Photos A and B are of the 2016 prescribed fire site ecosystem.*

Site 2: 2018 Prescribed Fire Site

This site experienced a more recent prescribed fire during the 2018-2019 fire season. According to the USDA soil survey the soil in the area is classified as Rutledge fine sand (Soil Survey Staff, 2020). Rutledge fine sand is highly acidic and not well-drained (Gaddis et al., 2013). The site can be characterized as a pine forest with a grass understory (Figure 3-4). The intensity of the fire that occurred in this area is also characterized as low to moderate (B. Tyler, personal communication, May 13, 2019). According to the Ryan & Noste severity classes, the severity of the fire would be categorized as light (Ryan, 2002). In this study, this site is referred to as “*2018 prescribed fire.”*

Figure 3-4*: Photo of the 2018 natural fire site ecosystem*

Site 3: 2011 Wildfire Site

This site experienced a natural wildfire in 2011, which was a severe disturbance that the area has struggled to recover from. The USDA soil survey classifies soils at this site as St. Johns fine sand (Soil Survey Staff, 2020). St. Johns fine sand is highly acidic with very low drainage (Gaddis et al., 2013). Many areas lack vegetation throughout the year and many standing tree carcasses remain from the severe fire (Figure 3-5). The pre-fire community is characterized as a mixed pine and live oak forest with a shrub understory. The wildfire that occurred in this area is characterized as high intensity. According to the Ryan & Noste severity classes, the severity of the fire would be categorized as deep (Ryan, 2002) due to the full incineration of litter and vegetation. Managers conducted roller chopping in 2018 in an effort to rehabilitate the area. We refer to this site here as “2011 wildfire.”

Figure 3-5: *Photo of 2011 wildfire site ecosystem in spring 2019.*

Site 4: 2016 Wildfire Site

This site experienced a natural wildfire in 2016. The USDA soil survey classifies this area as having Rutledge fine sand which is the same soil as at site 2 that experienced a prescribed fire in the 2016 period. The pre-fire community is characterized as a pine forest with a grassy understory. At the time of this study, the dead trees were still standing but the understory was dominated by muhly grass (*Muhlenbergia capillaris*) but included other shrubs, grasses, other herbaceous vegetation, and a few small saplings (Figure 3-6). This site is characterized as experiencing a high-intensity fire. According to the Ryan & Noste severity classes the severity of the fire would be categorized as deep (Ryan, 2002) because the dead trees imply that the fire incinerated the vegetation. In this study, this site was referred to as "*2016 wildfire*."

Figure 3-6: *Photo of the 2016 natural wildfire site.*

Chapter 4 : Methodology

Field sampling was conducted between May and October 2019. First, general areas of interest were identified, based on their fire regime, using a map provided by DNR and assessments during field visits. Within the areas of interest, the four sites chosen included two that had experienced prescribed fires and two that experienced natural wildfires. Sites 1 and 2 both experienced prescribed fires. Site 1 experienced a prescribed fire during the 2016-2018 fire seasons and site 2 experienced a prescribed fire during the 2018-2019 fire seasons. Sites 3 and 4 both experienced natural wildfires. Site 3 experienced a high-intensity natural fire in the summer of 2011 and site 4 experienced a natural wildfire in the summer of 2016. To assess the possible impact of fire on soil characteristics, we needed a basis for comparison to act as a control. Since we did not experimentally administer any fires, our selection of sampling sites was deliberately aimed at areas in which a fire boundary separating burned and unburned areas were easily discernible and in close enough proximity that the general plant community was the same. At each sampling site, two locations close to each other were selected so that one location was within the fire boundary and therefore, referred to in this study as “burned.” The second nearby location was outside the fire boundary and therefore referred to in this study as “unburned.” Two horizontal transects (100 m) were established and sample plots (1m x 1m) placed along each at equal intervals (Figure 4-1) for a total of 15 samples per site.

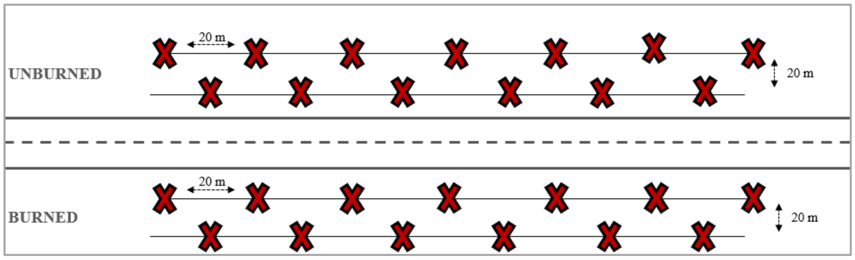

Figure 4-1: *Diagram of the sample collection methods.*

Geographical coordinates were taken at each plot using a Montana 650 GPS. Subsamples from three locations within the sampling plot were collected using a 3 ¼ inch (8.2 cm) diameter mud auger (Figure 4-2). Litter was removed from the surface before the auger was used to collect the soil. The samples were then thoroughly mixed (removing any plant roots, twigs, and rocks) and a composite sample placed in a plastic storage bag. The total number of soil samples collected was 120, (4 sites x burned vs unburned x 15 samples each).

Figure 4-2: *Photos of sampling procedures for collecting soil samples.*

Soil samples were transported to the lab at Georgia College & State University (GCSU) for processing (Figure 4-3). Soils were air dried in a greenhouse and sieved using a 2 mm sieve. A portion of each soil sample was sent to Clemson University's agricultural service lab in South Carolina for a standard soil test which included soil pH, and extractable phosphorus, K, Ca, Mg, Zn, Mn, Cu, B, and Na (all measured in ppm).

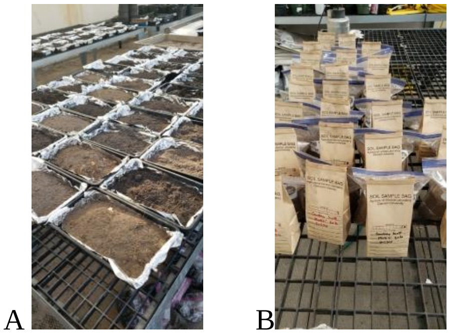

Figure 4-3: *Processing soils in the greenhouse. A) Soils air drying. B) Soils processed and packaged into Clemson soil analysis bags and Ziplock bags.*

Texture analysis (Figure 4-4A) was conducted at GCSU on a randomly selected subsample of five soils for each site and location using a Gilson Company soil hydrometer (model SA-2) to determine the percent sand/clay/silt content by analyzing how the soil particles disperse in a solution (Robertson, 1999). Soil organic matter (OM) content of each sample was also analyzed at GCSU using the loss on ignition (LOI) method (Robertson, 1999). The LOI method measures weight loss of samples after heating them at specific high temperature to calculate organic matter content (Heiri et al., 2001). One gram of each soil sample was added to a ceramic crucible, then weighed before and after being heated to 550 °C for four hours in a Thermolyne furnace by Thermo Fischer Scientific (Figure 4-4B).

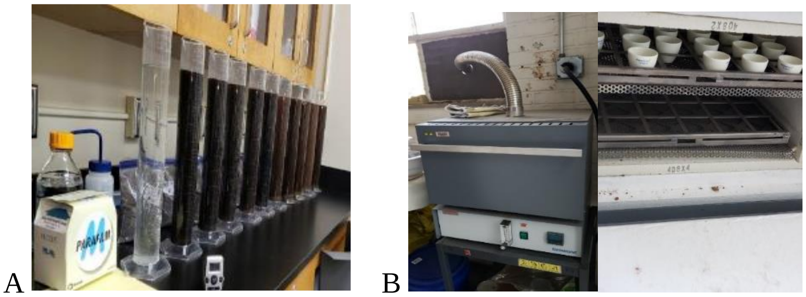

Figure 4-4: *Lab procedures: A) determining particle size distribution in each sample, B) soil analysis to determine organic matter composition.*

A multivariate analysis of variance (MANOVA) was used to compare the multiple soil characteristics measured in this study to determine whether the measured variables differed significantly between burned and unburned samples as well as between prescribed and wildfires. It is assumed that each soil characteristic is influenced by fire as well as other soil characteristics being tested. MANOVA tests relationships between the dependent (soil characteristics) and independent variables (burned or unburned and prescribed or wildfire), as well as between the independent variables *(*Scheiner, 1998). The tests were run under the assumption of normal distribution in the dependent variable, linearity among all couplings of dependent variables, equal variance throughout the range of predictors, and that covariances are homogeneous throughout the data in the model (Huberty & Olejnik, 2006; Scheiner, 1998). The Wilks' Lambda (Λ) test statistic was used to test the null hypothesis that there were no differences in the means of the soil variables when compared between sites. Other test statistics computed in the MANOVA include the Hotelling's Trace, the Pillai Bartlett test, and the Roy's Largest root test. The Tukey HSD post hoc test was used for comparisons between groups where mean differences were significant. All statistical analyses were performed using SPSS (IBM SPSS V24).

Chapter 5 : Results

The results from the multivariate test for pH, OM, CEC, P, Na, Ca, K, and Mg show that the null hypothesis of no difference in these soil characteristics among the different samples should be rejected (Table 1). The Wilks' Lambda value of 0.001 indicated that the site differences (burned or unburned, and prescribed or wildfire) were important in explaining differences between the soil characteristics. This was also supported by the other MANOVA test statistics (Pillai's trace, Hotelling's trace, and Roy's Largest Root) all of which were significant ($P < 0.0005$).

Table 1: Results from the MANOVA analysis for pH, Organic Matter, CEC, P, Na, Ca, K, and Mg between sites.

Effect		**Value**	**F**	**Hypothesis df**	**Error df**	**Sig**
Intercept	Pillai's Trace	.999	10291.441[a]	8	105	<0.0005
	Wilks' Lambda	.001	10291.441[a]	8	105	<0.0005
	Hotelling's Trace	784.110	10291.441[a]	8	105	<0.0005
	Roy's Largest Root	784.110	10291.441[a]	8	105	<0.0005
SITE	Pillai's Trace	3.793	16.410	56	777	<0.0005
	Wilks' Lambda	0.001	29.701	56	570	<0.0005
	Hotelling's Trace	20.476	37.766	56	723	<0.0005
	Roy's Largest Root	9.284	128.821[b]	8	111	<0.0005

[a] Exact statistic, [b] The statistic is an upper bound on F that yields a lower bound on the significance level

The multiple comparisons for soil organic matter (OM) results showed widely variable outcomes between prescribed and wildfire as well as between burned and unburned samples within the sites (Figure 5-1). Among the prescribed fire sites, the burned samples from the older 2016 prescribed fire site had significantly more soil OM ($p < 0.0005$). Whereas in the 2018 prescribed fire site, the burned samples had significantly less soil OM ($p < 0.0005$). Among the wildfire sites, the burned samples from the more severe 2011 wildfire site had significantly lower amounts of soil OM (p <0.03), but in the 2016 wildfire site, there was no significant difference between burned and unburned samples.

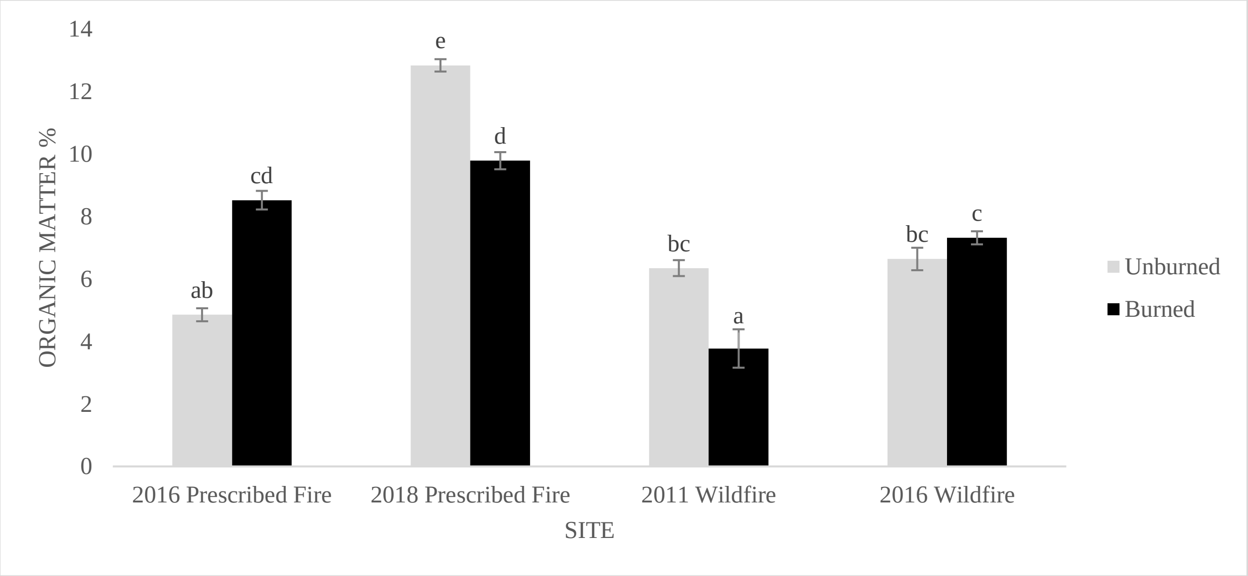

Figure 5-1: *Percent soil organic matter by site. The same letter indicates no difference, different letters indicate a significant difference in means. Error bars are ±SE.*

Multiple comparisons of soil CEC results showed that there was no significant difference between burned and unburned samples among the prescribed fire sites, although in both, the burned samples had slightly higher CEC than the unburned samples. For the natural wildfire sites, there was a significant difference in CEC between burned and unburned samples. In the 2011 wildfire site the burned samples had significantly lower CEC than the unburned samples (p <0.0005). This contrasted with the 2016 wildfire site where the burned samples had significantly more CEC than the unburned samples (p <0.0005). Both the high-intensity fire areas had significantly different soil characteristics between burned and unburned areas, however, they had opposing outcomes (Figure 5-2).

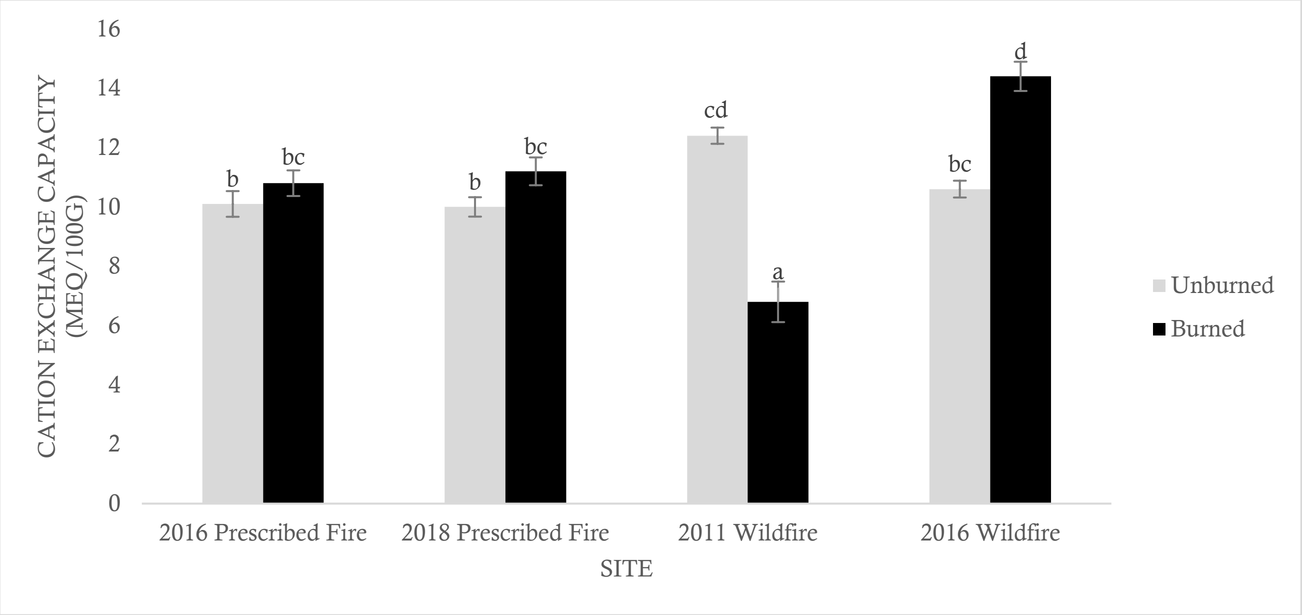

Figure 5-2 *Cation-exchange capacity (CEC) at each site (meq/100g). The same letter indicates no difference, different letters indicate a significant difference in means. Error bars are ±SE.*

All the sites had varying soil Na concentrations (Figure 5-3). The 2016 prescribed fire, 2018 prescribed fire, and the 2011 wildfire did not have significant differences in soil Na between burned and unburned samples. The more recent 2016 wildfire site had significantly higher soil Na concentration in burned samples than unburned samples ($p < 0.0005$). Both the 2018 prescribed fire and 2016 wildfire had high concentrations of soil Na when compared to the 2016 prescribed fire site and the 2011 wildfire site (Figure 5-3).

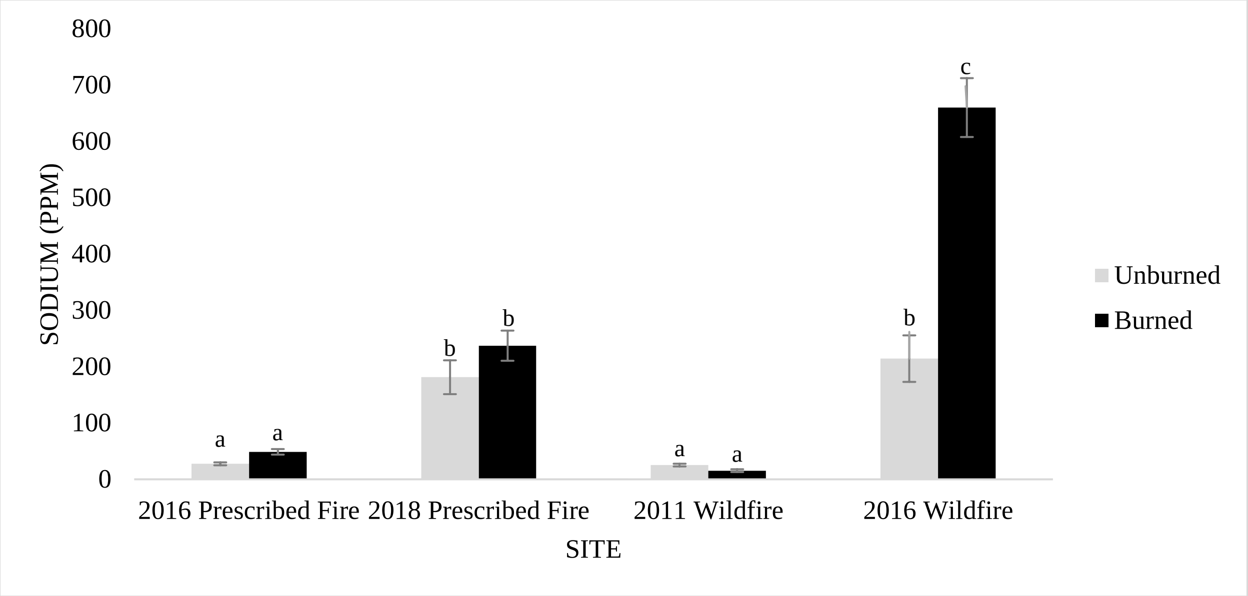

Figure 5-3*: Soil Na concentrations in parts per million at each site. The same letter indicates no difference, different letters indicate a significant difference in means. Error bars are ±SE.*

Within individual sites, soil phosphorus in the older 2016 prescribed fire site was significantly lower in the burned than unburned samples (p <0.0005). In the more recent 2018 prescribed fire site, there was no significant difference in concentration between burned and unburned samples (Figure 5-4). Soil phosphorus displayed opposing results among the wildfire sites. Samples from the older 2011 wildfire site had significantly lower soil phosphorus concentrations in the burned than unburned samples (p <0.0005). Overall, the 2016 prescribed fire samples had significantly higher concentrations of soil phosphorus than the 2018 prescribed fire and the 2016 wildfire sites. The unburned samples from the older 2011 wildfire site had much higher phosphorus concentrations than all the other samples (Figure 5-4).

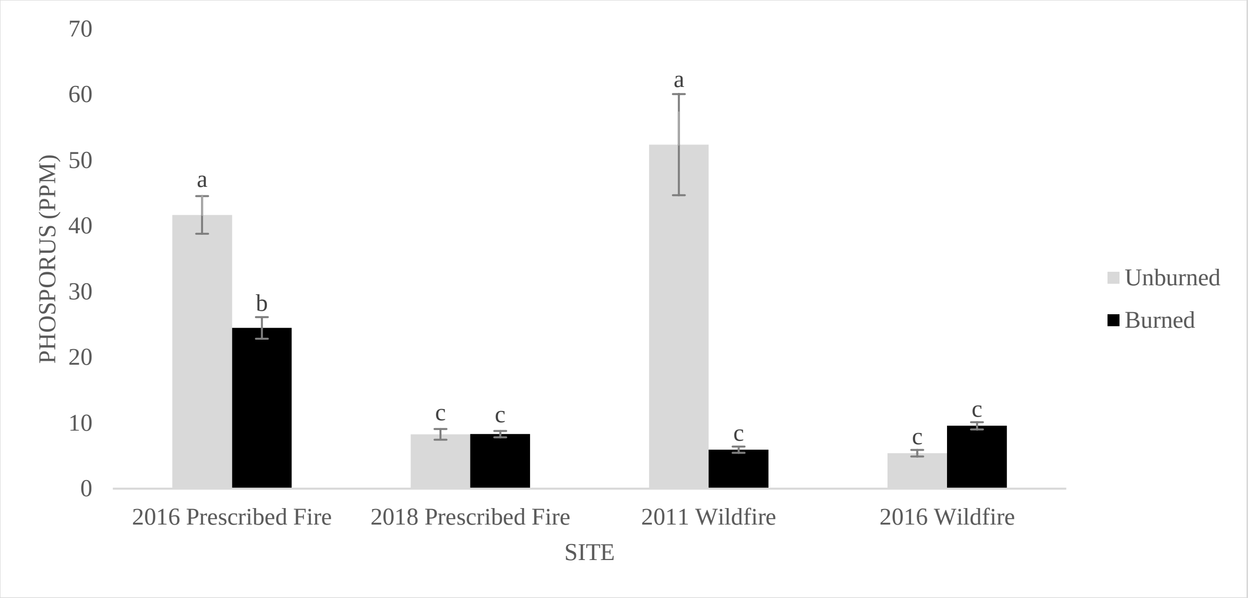

Figure 5-4: *Soil phosphorus concentrations in parts per million at each site. The same letter indicates no difference, different letters indicate a significant difference in means. Error bars are ±SE*

Within sites, concentrations of soil Ca in the 2016 prescribed fire were significantly lower in the burned samples than the unburned ($p < 0.0005$). In the 2018 prescribed, 2011 wildfire, and the 2016 wildfire sites there was no difference in concentration between burned and unburned samples (Figure 5-5). Comparison between sites showed that the unburned samples from the 2016 prescribed fire site had unusually high soil Ca concentrations (Figure 5-5).

Results of other soil chemical characteristics and nutrient concentrations are summarized in Table 2. Overall, all the samples were generally acidic with pH ranging from a high of 5.4 to a low of 3.8. The 2016 prescribed site had significantly lower pH thus higher acidity in the burned soils ($p < 0.0005$). The 2018 prescribed fire, 2011 wildfire site, and 2016 wildfire site had no significant difference in soil pH but had higher acidity in burned soil samples. Regarding K, the 2016 prescribed fire, 2018 prescribed fire, and 2016 wildfire sites did not have significant differences in soil K between burned and unburned samples. However, the 2016 wildfire had significantly higher soil K in burned samples ($p < 0.0005$). The only site that had significantly

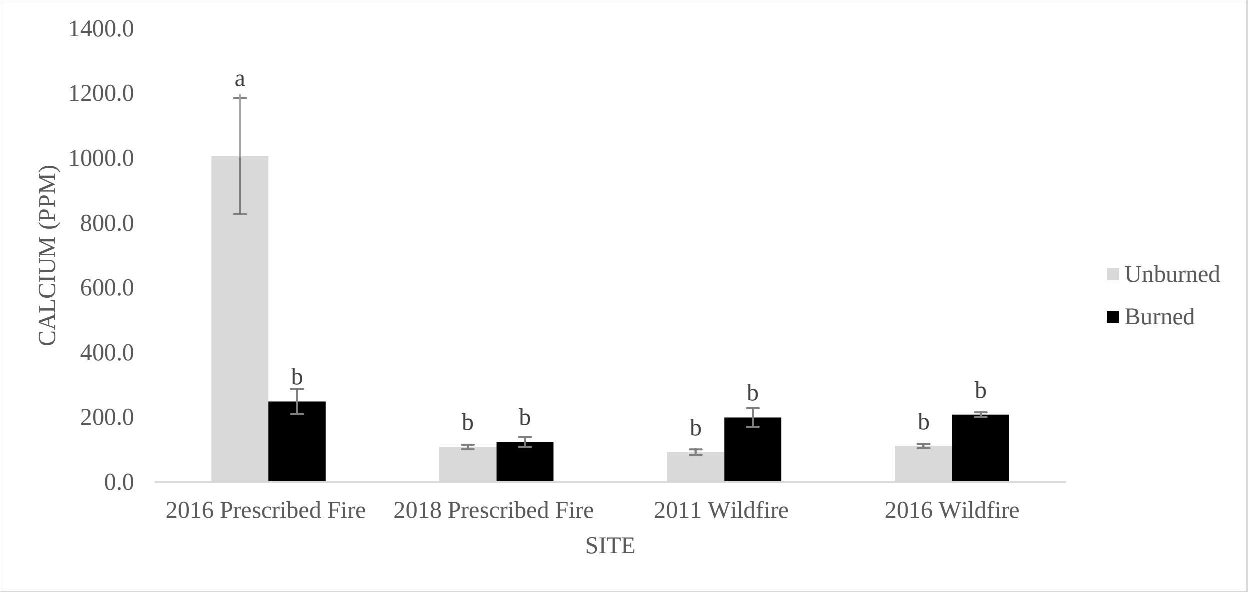

Figure 5-5: *Soil Ca concentrations at each site in ppm. The same letter indicates no difference, different letters indicate a significant difference in means. Error bars are ±SE.*

different concentrations of Mg between burned and unburned areas was the 2016 wildfire site which had significantly higher Mg concentrations in burned samples ($p < 0.0005$). Concentrations of B and Zn were generally very low across all samples and did not differ between burned and unburned samples in all the sites. For Mn, only one site, the 2016 prescribed fire site, had significantly lower Mn in burned than unburned samples. The rest of the sites had very low Mn levels and no difference in concentration between burned and unburned samples (Table 2).

A separate MANOVA was conducted for soil textural characteristics because only a random subsample of each site was analyzed for texture. The Wilks' Lambda value was low (0.09) and the p-value significant, hence, we rejected the null hypothesis of no difference. This was also supported by the other test statistics (Pillai's trace, Hotelling's trace, and Roy's Largest Root) all of which were significant ($p < 0.0005$) (Table 3).

Table 2: Soil characteristics (pH, Acidity, Mg, Ca, K, Zn, Mn, B) at each site. Numbers in parenthesis ±1 standard deviation. Asterisk (*) indicates significant differences in mean (* P < 0.05, ** P < 0.01, ***P < 0.001).

Soil Characteristics by Site	**pH**	**Acidity**	**Magnesium** (ppm)	**Potassium** (ppm)	**Zinc** (ppm)	**Manganese** (ppm)	**Boron** (ppm)
2016 Prescribed – Unburned	5.4 (± 0.2) *	3.9 (± 0.3) ***	111.7 (± 12.0)	34.3 (± 2.6)	1.0 (± 0.3)	**33.6 (± 3.78) *** **	0.4 (0.1)
2016 Prescribed – Burned	**3.8 (±0.0) * **	**8.6 (± 0.4) *** **	**74.2 (± 9.0)**	**42.3 (± 3.2)**	**0.8 (± 0.1)**	**2.1 (± 0.4) *** **	**0.2 (± 0.0)**
2018 Prescribed – Unburned	4.2 (± 0.0)	8 (± 0.3)	74.2 (± 4.9)	33.1 (± 1.7)	0.2 (± 0.0)	0.1 (± 0.1)	0.5 (± 0.1)
2018 Prescribed – Burned	**4.3 (± 0.1)**	**8.8 (± 0.4)**	**77.2 (± 7.8)**	**38.1 (± 3.2)**	**0.3 (± 0.1)**	**0.6 (± 0.5)**	**0.4 (± 0.0)**
2011 Wildfire – Unburned	3.9 (± 0.0) ***	11.5 (± 0.2) **	29.1 (± 3.5)	24.6 (± 2.4)	0.3 (±0.0)	0.3 (± 0.1)	0.0 (± 0.0)
2011 Wildfire – Burned	**4.2 (± 0.1) *** **	**5.2 (± 0.5) ** **	**55.8 (± 9.4)**	**28.0 (± 3.4)**	**0.4 (±0.0)**	**1.2 (± 0.2)**	0.0 (± 0.0)
2016 Wildfire – Unburned	4.4 **(± 0.1)**	8.5 (± 0.2)	69.6 (± 6.3) ***	17.0 (± 1.2) ***	0.3 (±0.1)	0 (± 0.0)	0.1 (±0.0)
2016 Wildfire – Burned	**4.4 (± 0.1)**	**8.7** (± 0.2)	**204.2 (± 8.2) *** **	**57.7 (±3.0) *** **	**0.6** (±0.1)	**0 (± 0.0)**	**0.5** (± 0.0)

Table 3: Results from the MANOVA analysis of sand, silt, and clay fractions between sites.

Effect		**Value**	**F**	**Hypothesis df**	**Error df**	**Sig**
Intercept	Pillai’s Trace	.999	1272.664[a]	2	31	<0.0005
	Wilks’ Lambda	.012	1272.664[a]	2	31	<0.0005
	Hotelling’s Trace	82.107	1272.664[a]	2	31	<0.0005
	Roy’s Largest Root	82.107	1272.664[a]	2	31	<0.0005
SITE	Pillai’s Trace	1.197	6.820	14	64	<0.0005
	Wilks’ Lambda	0.090	10.300 [a]	14	62	<0.0005
	Hotelling’s Trace	6.878	14.738	14	60	<0.0005
	Roy’s Largest Root	6.379	29.160[b]	7	32	<0.0005

[a] Exact statistic, [b] The statistic is an upper bound on F that yields a lower bound on the significance level.

Based on the USDA Soil Texture Class Boundaries (USDA, 2009), the 2016 prescribed fire site and both of the wildfire sites fall under the sand texture class, while the 2018 prescribed fire site falls under the loamy sand texture class (Figure 5-6). However, there were some differences in the specific sand, silt, and clay fractions. At the 2016 prescribed fire site sand fraction was lower in burned areas (p <0.0005), whereas, the clay and silt content did not significantly differ between burned and unburned areas (Figure 5-6). There were no significant differences found in soil texture at the 2018 prescribed fire, 2011 wildfire, and 2016 wildfire.

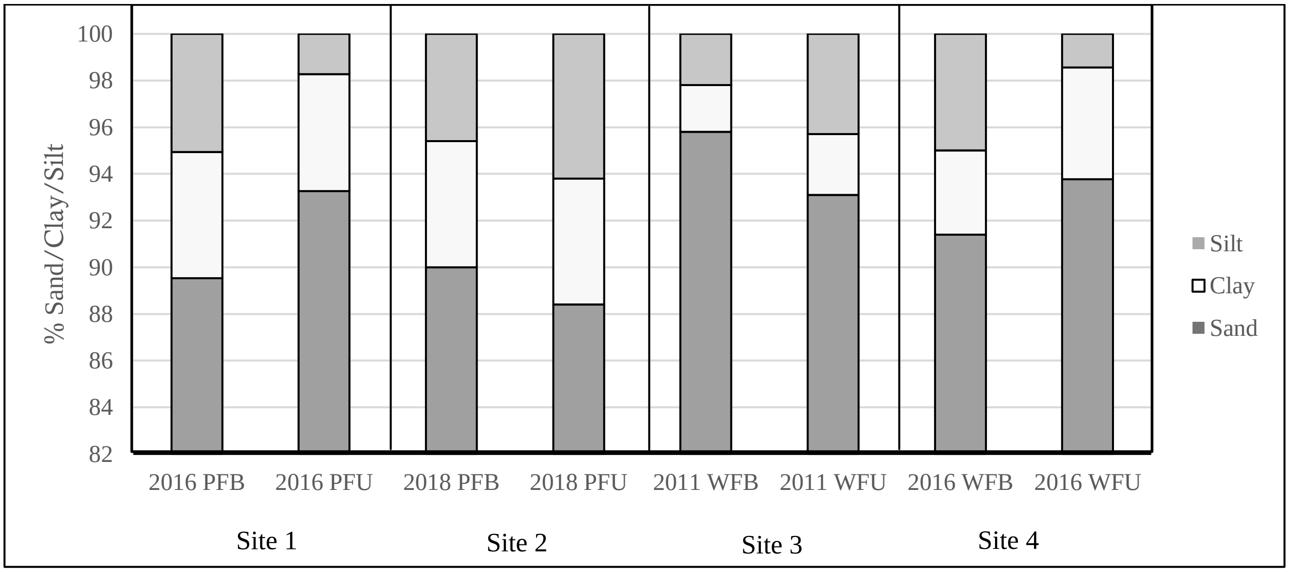

Figure 5-6: *Soil texture by site (PFB=Prescribed Fire Burned, PFU=Prescribed Fire Unburned, WFB=Wildfire Burned, WFU=Wildfire Unburned).*

Chapter 6 : Discussion

Soil organic matter is one of the major soil characteristics that is significantly impacted by fire. In this study, soil organic matter content varied considerably between the different fire regimes as well as between burned and unburned samples. Among the prescribed fire sites, the older 2016 prescribed fire site had significantly higher organic matter in the burned samples while the relatively recent 2018 prescribed fire site had significantly lower soil organic matter in the burned samples. In the wildfire sites, the older and relatively less severe 2016 wildfire did not significantly differ in OM content between burned and unburned samples whereas the much older and more severe 2011 wildfire site showed significantly less OM content in the burned samples. Soil organic matter content is dependent on a multitude of factors including fire intensity, moisture content, and composition of burned biomass and litter (Gonzalez-Perez et al., 2004). Various studies have shown that when the intensity of the fire is high enough, fires decrease soil organic matter due to complete oxidation of the organic matter (Alban, 1977; Badia & Marti, 2002; Certini, 2005). However, when vegetation recolonizes after the fire, organic matter is usually restored and can potentially be higher than the pre-fire levels if the fire results in increased primary productivity (Certini, 2005). This suggests that severe fire may temporarily result in reduced OM content within soils. Based on our findings, we hypothesized that at the time of their occurrences, both the 2016 and 2011 wildfires had high intensities to significantly reduced soil OM. While the 2016 site possibly reaccumulated OM, the 2011 site has not, perhaps an indication of a prolonged impact of the fire. Meanwhile, among the prescribed fire sites, the significantly higher OM in the burned samples of the 2016 prescribed fire may be an indication that either the fire did not affect OM levels or that there has been enough time for re-accumulation while at the relatively recent 2018 prescribed fire site, this re-accumulation has not occurred yet.

Soil OM is often influenced by the soil texture and this may be another possible explanation for the differences in OM among these sites. With the exception of the unburned samples from the 2018 prescribed site which had loamy sand, all the soils collected from the island for this study were classified as sand. Soil texture plays a significant role in influencing other soil chemical properties. Soils with higher proportions of clay minerals have higher surface areas for organic matter to be adsorbed onto and be decomposed by soil microorganisms (Robertson & Paul, 1999), whereas sandy soils encourage leaching of organic minerals due to low surface area (Aprile & Lorandi, 2012). The 2016 site was the only site that exhibited a significant difference in soil texture, with the sand fraction being significantly lower in burned areas and significantly higher OM. It is worth noting that, the 2011 wildfire site had the highest sand fraction and the lowest OM of all the sites.

Another soil chemical property often impacted by fire is soil CEC which is a valuable metric when measuring soil fertility. CEC is a particle's capacity to exchange positive bases (Ca^{2+}, Mg^{2+}, Na^{+}, and K^{+}) within its environment. Overall, the CEC levels were consistent with the nature of coastal plains soils that have a high sand content and low CEC levels typically below 6 meq/100g (Kissel & Sonon, 2002). Leaching of the ionic elements that alter soil CEC is higher in soils with higher sand fractions (Aprile & Lorandi, 2012) and partially contribute to low CEC levels. Soils collected from the two prescribed fire sites did not differ in the amount of CEC when compared to the nearby unburned samples. This is not unusual because depending on the soil type, CEC is either not significantly impacted or is reduced by fires of low to moderate intensity due to the thermal destruction of organic matter (Certini, 2005). However, soils collected from the two wildfire sites exhibited opposite outcomes in soil CEC levels between burned and unburned areas. The 2011 wildfire site had significantly lower CEC in burned samples while the 2016 wildfire site had significantly higher soil CEC in soil samples from burned areas. These contrasting results provide further support for our above proposed hypothesis regarding the differences in the nature of the two fires and potential long-lasting impacts of the older 2011 wildfire. A study evaluating fire effects on CEC found that higher temperatures resulted in greater loss in soil CEC but this is often restored once biomass replenishes soil OM (Ulery et al., 2017). In our study, the high CEC in the burned soil samples from the 2016 wildfire may be an indication that the soil CEC has had time to be replenished if the fire had impacted CEC at the time of its occurrence.

On the other hand, the significantly lower CEC in the soils from the much older wildfire of 2011 may be a sign that the fire was more intense than the 2016 wildfire. While the 2011 wildfire site may have had more than adequate time for the CEC to recover from any fire effect, the low CEC in burned soils might indicate that forest fires can be so severe, potentially resulting in longer-lasting mineral alteration that recovery cannot occur. Intense forest fires can cause the combustion of soil layers which results in significant changes to soil properties, for example, soil minerals can become altered into gaseous or liquid states, and subsequently decreases in soil CEC can occur due to soil mineral alteration (Badia & Marti, 2002; Ulery et al., 2017). A possible indication of such an alteration in our study is the soil textural analysis results. Although the soils were generally classified as sand, the sand fraction at the burned sites of the 2011 wildfire was notably higher than all the other sites. High temperatures disrupt the organic cements and cause fusion of clays into sand-sized particles and subsequently increase the sand fraction (Badia & Marti, 2002). Soils with high CEC typically have high amounts of clay and low porosity, whereas soils with low CEC typically have sandier textures and high porosity (Aprile & Lorandi, 2012).

Soil OM and CEC are highly correlated since OM is the main source of the exchangeable bases, and soils rich in organic matter tend to have higher CEC values (Aprile & Lorandi, 2012). Some of the results in our study showed this correlation. The burned samples from the 2011 wildfire site had the lowest OM and soil CEC of all sites. The burned samples from the 2016 wildfire and prescribed fire sites had significantly higher soil CEC and insignificant differences in soil OM between burned and unburned plots. The burned samples from the 2018 prescribed fire had lower concentrations of organic matter but CEC levels did not differ between burned and unburned samples.

When fire impacts soil organic matter, it also affects soil nutrient concentrations since OM is an important source of nutrients. When fires burn through an area, many soil nutrients are mineralized and become available in ash near the surface where they have increased risk of being lost from runoff or erosion (Wienhold & Klemmedson, 2009). During a fire, the addition of ash to soil surfaces also contributes to the increase in soil Ca, Mg, P, and K (Kennard, 2001). However, unlike soil organic matter that is often reduced after a fire and that such a reduction can persist in soils longer, nutrients especially P, K, Mg, and Ca are often increased immediately after a fire (Rodríguez et al., 2009; Simard et al., 2001) but such spikes in nutrients are often short-lived (Certini, 2005). While we found site differences in nutrient concentrations, the short-lived changes in nutrient concentrations following a fire as well as, the duration since the fires occurred imply that those differences are more likely an indication of differences in site characteristics rather than the possible impact of the fires. In regard to P, the burned samples from the 2016 prescribed fire and unburned samples from the 2011 wildfire sites both had significantly lower P concentrations. All other samples had no significant differences in their P concentrations between burned and unburned samples. The burned samples from the 2016 prescribed fire site had significantly lower Mn and higher P and Na. The burned samples of the 2018 prescribed fire site did not have any significant differences in soil nutrients. At the 2011 wildfire site, soil Mg, Ca, and Zn were significantly higher, and P and Na were significantly lower in areas that experienced the fire.

Soil sodicity influences the dispersion of clay from aggregation and reduces soil structure stability (Rengasamy & Marchuk, 2011). In our study, the primary determinant of Na concentrations is most likely hydrology and proximity to the ocean. The 2018 prescribed fire site and the 2016 wildfire sites are both located on the south end of the island close to the Cabretta beach and both had significantly higher soil Na than the other two sites. Sodium levels in the unburned soil samples were similar between the two sites but distinctly different in the burned soils. For the 2018 prescribed fire site, Na levels did not differ between burned and unburned areas. However, the 2016 wildfire site had significantly higher concentrations of Na in burned samples, nearly 300% higher. Fire may have contributed to this increase directly or indirectly by influencing other site characteristics. The fact that the 2016 wildfire site has this drastically high amount of Na in burned areas is not consistent with the other soil qualities exhibited at this site which appears to be in an early recovery stage of the pine tree stand that once inhabited the area.

Overall, nutrient concentrations were not always consistent with other site characteristics, leading to some unexpected results. For example, the 2016 prescribed fire site had significantly lower soil P in burned areas. However, at the 2011 wildfire site, the unburned samples had significantly higher P concentrations while also being significantly more acidic than the burned samples. Available soil P is influenced by soil pH, usually highest at a pH of 6.5 (Certini, 2005) and availability decreases at high and low soil pH. Therefore, the high P under acidic conditions was unusual. Another unusual result was the significantly higher concentrations of Mg and Ca in the burned samples of the 2011 wildfire which were also the samples that had the highest percent sand. This was an inconsistency since large particle sizes promote the leaching of nutrients from soils. Highly sodic soils typically exhibit low concentrations of Ca and Mg because Na causes flocculation of the particles (Rengasamy & Marchuk, 2011). At the 2016 wildfire site, soil Mg, Ca, and K were significantly higher in the burned samples as well as unusually high Na concentrations than all the other samples. These unexpected results require further investigation to understand the processes going on.

Since this study was assessing various interacting soil characteristics long after the fires occurred, it is not possible to unequivocally determine what the impacts of the fires were. However, often the impacts of the fires can be deduced from the post-fire plant communities. The 2016 prescribed fire site was dominated by live oak and saw palmetto, but also had a fairly rich community consisting of various grasses, shrubs, and other tree species. Qualitatively, the site can be described as being the most diverse or species-rich and heterogeneous plant community of all the sites in this study. Soils from areas that experienced the 2016 prescribed (low intensity, scorched severity) fire were lower in soil Ca and Mn but higher in Na, K, Mn, and organic matter in burned areas. The plant community at the 2018 prescribed fire site was a young fairly homogeneous pine stand with mixed grass species making up the ground cover. Soils from the areas that experienced the 2018 prescribed (low intensity, scorched severity) fire had significantly lower OM in burned areas than nearby unburned areas but all other soil characteristics were similar in burned and unburned areas. Overall, soils from areas that experienced prescribed fires showed the most significant differences in soil OM and nutrient availability. The 2016 prescribed fire had higher soil OM in areas that experienced fire whereas, the 2018 prescribed fire had lower OM in areas that experienced fire. The 2016 prescribed site had lower Ca and Mn but significantly higher Na and P, whereas the prescribed fire did not exhibit any differences in nutrient availability between burned and unburned areas. Differences in soil characteristics between burned and unburned areas at the prescribed fire sites were less pronounced than at the wildfire sites. Overall, when considering the possible impacts of prescribed fires based on results of soil characteristics, our findings appear to agree with other research that has found that areas that experience prescribed fires typically have fewer differences in soil qualities (Alcañiz et al., 2018).

Both the 2011 and 2016 wildfire sites have had ample time (8 and 3 years respectively) to recover from the fires, but the 2011 site had large patches with no vegetation while the 2016 wildfire currently had a thriving community of shrubs, grasses, and pine saplings. The 2016 wildfire site was originally dominated by mature pine trees and could be in the process of returning to a historic state. Areas that experience natural wildfires tend to have high amounts of dry fuel which burns and spreads quicker resulting in more severe and inconsistent effects in impacted areas (Certini, 2005; Flannigan et al., 2000). The site impacted by the 2011 wildfire (high intensity, deep severity) has exposed, bare soils, with unleveled ground, and the standing remains of the trees killed during the fire. Its soils were low in CEC, P, organic matter, and Na, but higher in Mg and Ca in burned areas. The combination of the soil properties that are important for plant development could be characterized as unfavorable in burned areas when compared to soils from nearby areas that were not affected by the fire. The 2011 wildfire site exhibited characteristics similar to the 2002 Hayman Fire, a severe fire that occurred in Colorado in which impacted areas experienced significant changes in soil characteristics, some areas that lost all OM took more than decades to recover (Graham, 2003). The 2016 wildfire (high intensity, moderate severity) killed the majority of the standing pines although, at the time of sampling, recolonization seemed to be well underway. Soils from the impacted areas had higher CEC, Na, P, Ca, K and silt fraction than soils from nearby areas not impacted. Most soil properties that are important for plant development were more favorable in burned areas than neighboring unaffected areas. This site demonstrates that some high intensity wildfires may not negatively impact soils. This was also demonstrated in a study investigating tropical dry forest in Bolivia that found that soils had higher nutrient availability and tree seedling growth rate following high intensity fires (Kennard, 2001).

Chapter 7 : Conclusions

Soil chemical and physical properties were evaluated on soil samples obtained from areas that experienced prescribed and natural wildfires and compared to soils from neighboring locations that did not experience those fires. We deduced that the sites experienced different fire regimes based on site characteristics. We classified the two prescribed fire sites as having low-intensity fires and light severity. The two wildfire sites were both classified as having experienced high intensity, deep severity fires but we characterized the older 2011 wildfire as having a greater severity and possibly long-lasting negative impacts on the soils when compared to the 2016 wildfire. Vegetation at the site of the 2011 wildfire had still not recovered at the time of this study whereas the site of the 2016 wildfire already had shrubs, grasses, and countless pine saplings. This difference in severity between the sites suggests that the 2016 wildfire fire was less intense than the 2011 wildfire.

Differences in soil characteristics were more pronounced in areas that experienced wildfires than areas that experienced prescribed fires. The results indicate that overall low intensity prescribed fires had insignificant impacts on soil characteristics. However, more research evaluating soil characteristics before and immediately after prescribed fires is needed to be able to confirm these findings. With such information, managers could determine if current prescribed fire practices are suitable methods for managing fuel loads in the forest to prevent severe wildfires. Fires that do not alter soil and chemical properties can have beneficial impacts on long term soil health (Heydari et al., 2017).

It was concluded that wildfire impacts on soil characteristics are dependent on the intensity and severity of the fire. High-intensity fires can be devastating to the plant community without impacting soil characteristics, the most positive soil characteristics were observed in areas that experienced a high-intensity wildfire. However, at a certain temperature gradient, the high-intensity fires can become so severe that they destroy parts of or an entire ecosystem beyond natural recovery. Areas that experience high-intensity fires may require rehabilitation if impacted areas do not recover naturally.

The findings supported the hypothesis that soil samples collected from areas impacted by wildfires would have significantly different soil qualities, especially when compared with soils from the prescribed fire area. Wildfires and prescribed fires differ in the potential impact that they can have on soil characteristics. These results suggest that prescribed fires can be a useful resource for managing fuel loads, but more research is needed to determine the best procedures to ensure healthy soils. More research needs to be conducted comparing high-intensity wildfires to prescribed burns to better understand what elements of high-intensity fires result in positive and negative impacts on soil quality. That knowledge can then be applied to how managers conduct prescribed burns. Numerous forest fires occur on Sapelo island but due to limited resources, we could only investigate a limited number of sites. This study provides a starting point for others to build upon. As more sites representing different fire histories are studied, we will have a better understanding of the potential impacts of fire on soil characteristics.

Chapter 8 References

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