Spring 2023

Projecting the Effects of Climate Change and Urbanization on Longleaf Pine Stands in the Florida Flatwoods

Lilian Grace Hutchens

Projecting the Effects of Climate Change and Urbanization on Longleaf Pine Stands in the Florida Flatwoods

by

Lilian Grace Hutchens

Bachelor of Science
University of South Carolina, 2021

Submitted in Partial Fulfillment of the Requirements

For the Degree of Master of Science in

Geography

College of Arts and Sciences

University of South Carolina

2023

Accepted by:

John A. Kupfer, Director of Thesis

Michael E. Hodgson, Reader

Peng Gao, Reader

Cheryl L. Addy, Interim Vice Provost and Dean of the Graduate School

DEDICATION

I am so grateful to have had so many wonderful people both inside and outside of the department who have helped me through this process. This is dedicated to all of you.

To Chris who has been by my side through all of this, who bore my stress amidst all of his own, I love knowing that we can get through such difficult times together. I know I'll look back on this time and this place where we met with so much fondness.

To my family who have gotten me to this point, I never could have started any of it without your love and support. Mom and Dad, thank you for always hearing me and for believing in me when I couldn't. Everyone learns so much from their parents but I am so lucky that you both understand this process and have helped me through it.

To the friends that I made here, especially Stafford Mullin and Grant Farmer who welcomed me that first year and Derek Matchette who came back to support me even when he had already moved beyond the walls of Callcott, thank you. Sharing this experience with you all and learning from you got me through many tough days.

To my committee, Dr. Michael Hodgson, Dr. Peng Gao, and Dr. John Kupfer, I feel so fortunate to have learned from you all over the years. Your feedback and support have shaped this document and given me confidence in my work. Dr. Kupfer, your generosity with your time and support is not lost on me. I am so glad that I chose to stay and learn from you. I know I'll bring all that you've taught me to me wherever I go next.

ACKNOWLEDGEMENTS

I would like to thank my committee, Dr. John Kupfer, Dr. Peng Gao, and Dr. Michael Hodgson for their thoughtful feedback and support which improved the quality of my thesis. Special thanks to Dr. Peng Gao who provided the FSim model output used in this paper and provided a great deal of technical support during the process. I would also like to thank Dr. Georgina Sanchez at the Center for Data Analytics at North Carolina State University for providing the FUTURES model output used as the core urbanization model in this paper. This project was funded by the Tall Timbers Research Station and Land Conservancy.

ABSTRACT

The southeastern United States once held millions of hectares of highly connected longleaf pine ecosystem. In a dramatic range reduction, longleaf pine now occupies less than 5% of its original extent, its remnant patches existing within a matrix of human-dominated land uses. Conservation planning for longleaf pine ecosystems is complicated given the ecosystem's reliance on fire and the broad spatial and temporal scales at which longleaf pine management must operate. Planning timelines for longleaf pine management extend into the end of the 21st century, a period during which climate, fire regimes, and land cover are all expected to change, influencing longleaf pine ecosystems. In this study, I analyzed the impacts of future changes in climate, the fire regime, and urbanization on the range of longleaf pine within the Florida flatwoods pyrome, an area covering much of central and northern Florida. I compiled data on possible scenarios of change from existing models of longleaf pine-relevant variables. In a GIS-based analysis, those variables were individually and collectively applied to known longleaf pine patches within the Florida flatwoods pyrome to help anticipate how longleaf pine stands may be differentially (or similarly) affected by future conditions. This study provides insight into the spatial distribution of longleaf pine persistence or loss and possible strain on management actions. The information produced from this study may be used to guide future longleaf pine management decisions by locating areas at particular risk of degradation, aiding in resource allocation and conservation prioritization.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

CHAPTER 1

INTRODUCTION

The southeastern United States today bears little resemblance to its pre-colonial landscape which once held millions of hectares of highly connected longleaf pine ecosystem. In a dramatic range reduction, longleaf pine (Pinus palustris Mill.) now occupies less than 5% of its original extent, its remnant patches existing within a matrix of human-dominated land uses (Oswalt et al. 2012). Awareness of this endangered ecosystem has grown, mobilizing conservation managers to pursue the protection and restoration of longleaf pine. With a growing understanding of its value as a commodity, its ecological importance, and its cultural legacy, managers are met with ample reason to advocate for the conservation of longleaf pine. However, such advocacy is complicated by the broad spatial and temporal scales at which longleaf pine management must operate.

Because of their complexity and reliance on fire, longleaf pine-dominated ecosystems have been the focus of much effort to develop best practices for ecosystem management. However, progress has been hindered by persistent management difficulties including conflicting stakeholder interests, high initial costs of restoration and management, and limited federal support. Today, managers grapple with a combination of stressors including fire suppression, climate change, urbanization, and fragmentation as uncertain future conditions pose a unique challenge for conservation managers (Kupfer et al. 2022).

Planning timelines for longleaf pine management extend into the end of the 21st century, a period during which climate, fire regimes, and land cover are all expected to change, influencing longleaf pine ecosystems. Current conditions and future projections of longleaf pine-relevant variables (e.g., temperature, relative humidity, wind direction, wildfire likelihood, burn window, land cover) are available from existing data and models, but such variables are rarely considered in combination for their cumulative impacts on the range of longleaf pine, albeit with some exceptions (Costanza et al. 2015, Vorhees 2015). In this study, I seek to analyze the impacts of future changes in climate, the fire regime, and urbanization on longleaf pine stands within the Florida flatwoods pyrome, which covers much of central and northern Florida.

Specifically, I address the following research questions: 1) to what degree may projected changes in urbanization, climate, and the fire regime impact the extent of longleaf pine ecosystems in the Florida flatwoods pyrome?, 2) how much are the land cover, the climate, and the fire regime expected to change in the Florida flatwoods pyrome between now and the end of the 21st century?, 3) how much longleaf pine is expected to be lost or degraded due to urbanization, reduction in the number of suitable burn days, and altered wildfire risk? Based on my results I seek to address the implications of changes in urbanization, climate, and the fire regime on longleaf pine ecosystem restoration and other management initiatives in the Florida flatwoods pyrome.

To do so, I used a geospatial approach, compiling data on possible scenarios of change from existing models of longleaf pine-relevant variables. Those variables were individually and cumulatively applied to known longleaf pine patches within the Florida flatwoods pyrome to help anticipate how longleaf pine stands may be differentially (or similarly) affected by future conditions. Such analysis provided insight into the spatial distribution of longleaf pine persistence or loss, the degree of longleaf pine ecosystem fragmentation, and possible strain on management actions. The information produced from this study may be used to guide future longleaf pine management decisions by identifying major management concerns and locating areas at particular risk of degradation, aiding in resource allocation and conservation prioritization.

CHAPTER 2

BACKGROUND AND LITERATURE REVIEW

2.1 LONGLEAF PINE ECOLOGY

Longleaf pine was once found across an estimated 24 - 36 million ha in large portions of Florida, Georgia, South Carolina, North Carolina, Alabama, Mississippi, and parts of Texas, Louisiana, and Virginia (Oswalt et al. 2012) (Figure 2.1). The species occupies both flatwood environments, lower elevation areas on the Atlantic and Gulf Coastal Plains, and upland environments, including higher elevation areas in piedmont regions with limited extents in montane regions (ALRI 2009, Brockway et al. 2005).

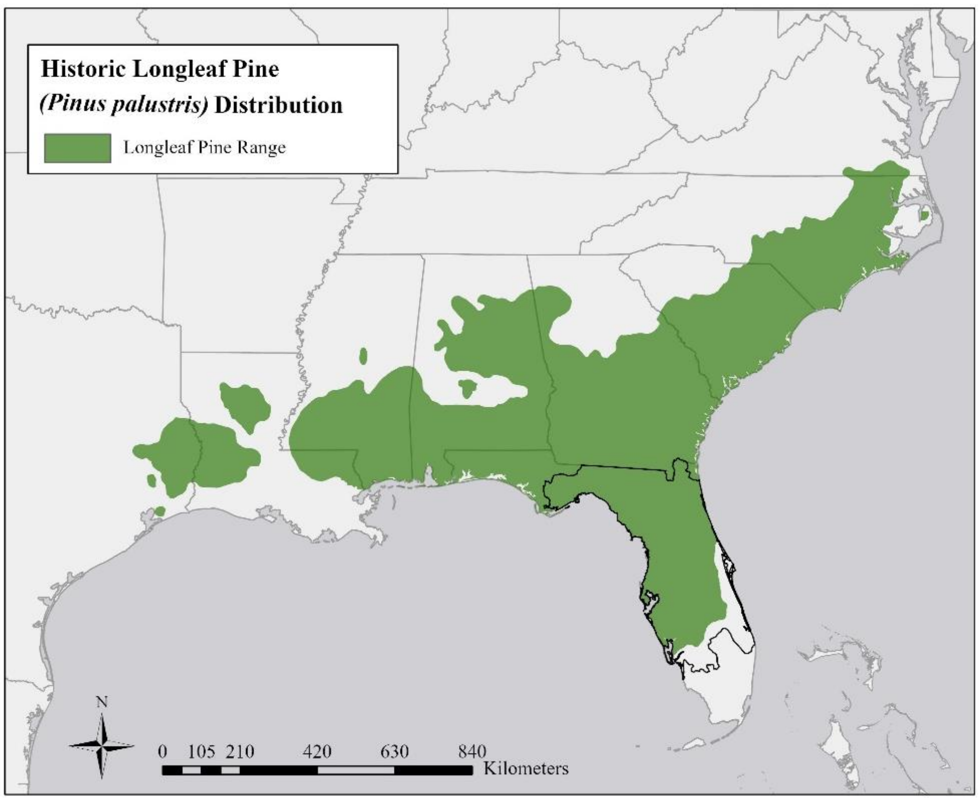

Figure 2.1. Historic range of longleaf pine. (Modified from Kupfer et al. 2022)

The ecological importance of longleaf pine ecosystems is widely documented. Healthy longleaf pine ecosystems exhibit incredibly high biodiversity and are recognized as a part of the North American Coastal Plain Biodiversity Hotspot (Brudvig et al. 2021). Of particular interest are the many endemic species of conservation concern that inhabit longleaf pine ecosystems, including 29 federally endangered or threatened species such as the red-cockaded woodpecker, gopher tortoise, and numerous vascular plants (ALRI 2009, Walker 1993).

With the exception of its seedling stage, longleaf pine is highly resilient to fire and relies on disturbances to maintain its population (Brockway 2005, Zion 2019). In many areas, healthy longleaf pine ecosystems are characterized by an overstory of open canopy longleaf pine and an herbaceous understory dominated by wiregrass (Astrida stricta Michx. and Astrida beyrichiana Trin and Rupr) (Oswalt et al. 2012). This two-layered forest structure is maintained through frequent low-intensity surface fires that remove hardwoods from the midstory, improve nutrient availability, and reduce competition (Brockway et al. 2005, Jose et al. 2006). Longleaf pine and many shrubs are shade-intolerant so an open canopy is crucial for ensuring that sunlight can reach juvenile longleaf pine and associated understory vegetation (Platt et al. 1988, Varner et al. 2005). Without periodic fire, hardwoods (especially oaks) build up in the midstory, shading out shorter vegetation, thereby limiting the potential for new longleaf pine growth and changing the species composition of the ecosystem (Grand and Kleiner 2016, Provencher et al. 2001).

2.2 FACTORS CONTRIBUTING TO THE CONDITION OF LONGLEAF PINE ECOSYTEMS

Prior to colonial settlement, longleaf pine ecosystems in the Southeast were subjected to fire started by lightning strikes or Native American land clearing efforts every 1-5 years (Frost 2006, Oswalt et al. 2012, Platt et al. 1988). After settlement and exacerbated by industrialization, the United States adopted strict fire suppression policies to limit the human risk of exposure to wildfire (Frost 2006, Vorhees 2015, Zion 2019). The detrimental effects of persistent fire suppression on longleaf pine ecosystems have been widely reported. Long unburned areas exhibit closed-canopy structures and reduced biodiversity as a result of hardwood invasion and the buildup of shrubs and fuels in the understory and midstory that shade out the diverse understory species characteristic of open canopy longleaf pine (Varner et al. 2005, Provencher et al. 2001). Many of the species that exhibit declining populations are dependent on longleaf pine ecosystems and, by extension, periodic fires to maintain suitable habitat conditions. These longleaf pine-reliant species have been negatively impacted by degradation due to fire suppression. Today, greater recognition of the role of fire in maintaining longleaf pine ecosystems has encouraged the reintroduction of prescribed fire or controlled burning to meet management goals, yet much longleaf pine acreage remains unburned, particularly on private lands (Costanza et al. 2013).

The extent of longleaf pine ecosystem reached a record low of 1.34 million ha in 2012 with much of that habitat considered to be of poor or degraded quality as assessed by Forest Inventory Analysis data (Oswalt et al. 2012). The historic decline in longleaf pine has been attributed to overharvesting by the timber industry, land conversion to agriculture, urbanization, fire suppression, and replacement with slash (Pinus elliottii Engelm.) and loblolly (Pinus taeda L.) pines (ALRI 2009, Frost 2006, Oswalt et al. 2012). Beginning in the 1990s, recognition of the severity of longleaf pine ecosystem loss arose with new interest in its protection and restoration (Peet and Allard 1993, Outcalt and Sheffield 1996). This interest was partly sparked by the listing of the red-cockaded woodpecker as endangered in 1970 (Brockway et al. 2005). The species is endemic to old-growth longleaf pine ecosystems, indirectly providing funding for the protection of its habitat. However, mobilization of broad-scale, ecosystem-based longleaf pine conservation efforts solidified later with the formation of America's Longleaf Restoration Initiative (ALRI) in 2005 and the subsequent publication of the Range Wide Conservation Plan for Longleaf Pine in 2009 which sought to increase the range of longleaf pine to 3.24 million hectares by 2025 (ALRI 2009).

Academic research and planning projects on longleaf pine conservation grew following this publication as conservation managers across federal, state, and local governments, as well as non-governmental organizations (NGOs) and private industries, recognized the ecological and economic value of longleaf pine maintenance and restoration. Despite concerted efforts to protect longleaf pine, continued losses of longleaf pine to clearing have offset expansion of the range (McIntyre et al. 2018). In the most recent status report released by ALRI, the current extent of longleaf pine is estimated to be between 1.82 and 1.90 million ha, far below the stated goal of 3.24 million ha of longleaf pine by 2025 (Ballinger et al. 2020, Oswalt and Guldin 2021).

2.3 CURRENT CONSERVATION EFFORTS AND EXISTING CHALLENGES

In addition to continued losses of longleaf pine ecosystems to land conversion and fire suppression, managers report other major challenges to existing longleaf pine conservation efforts. Forest management in the Southeast must operate within a landscape of complex land use history, considerable fragmentation, and variable ownership. Currently, managers seek to maintain good condition, open canopy longleaf pine, improve degraded longleaf pine ecosystems, and restore longleaf pine in areas where it was previously excluded (ALRI 2009). While efforts were initially centered around the maintenance of existing longleaf stands, concerns regarding the minimal progress in range expansion over the last 10 years have led some managers to extend their resources and look to restoration efforts within and outside of the historic range of longleaf pine (McIntryre et al. 2018). Restoration, or the establishment of new longleaf pine, is particularly complex but is widely considered to be necessary to achieve management goals given the extent of ecosystem loss (McIntyre et al. 2018).

2.3.1 *Outreach to Private Landowners*

Many broad-scale longleaf pine restoration initiatives take place on publicly owned land, primarily under the direction of the United States Department of Agriculture (USDA) Forest Service (McIntyre et al. 2018, Oswalt et al. 2012). However, an estimated 60% of the existing longleaf pine acreage exists under private ownership (Ballinger et al. 2020). While there is significant interest in longleaf pine conservation on private lands, steep learning curves for proper management and high costs of restoration and maintenance can limit longleaf pine conservation initiatives in the private sector (Costanza et al. 2013).

Conservation initiatives must contend with a perception among private landowners and timber harvesters that longleaf pine is difficult to maintain and less economically ‘efficient’, which has led to the preferential planting of other southern pines, especially slash and loblolly pines, in place of longleaf pine (Koo 2010). However, conservation outreach personnel have begun to communicate the considerable economic value that longleaf pine can provide to private landowners through recreation, for example, through the creation of high-value hunting areas or sustainable timber harvesting bolstered by the desirability of longleaf pine trees for its high-quality wood (ALRI 2009, Zion 2019).

Despite such economic potential, the initial costs of restoration through the application of prescribed fire (often in conjunction with chemical and mechanical management tools such as herbicide applications and thinning) can remain cost-prohibitive for many private landowners (Brockway et al. 2005). Federal incentive programs that can help reduce up-front costs of longleaf pine restoration, including the Longleaf Stewardship Fund, Environmental Quality Incentives Program, and Wildlife Habitat Incentive Program, have been implemented with some success, albeit limited by federal funding (Zion 2019). Conservation easements offer an additional method of incentivizing the protection of existing swaths of longleaf pine by providing tax breaks to private landowners who are willing to protect their land from urbanization in perpetuity (ALRI 2009).

In addition to financial assistance, agencies and NGOs offer technical assistance to private landowners and distribute expertise on proper longleaf pine ecosystem management (ALRI 2009). Extensive literature on the development of best practices for maintenance and restoration of longleaf pine has supported more successful longleaf pine management efforts on private lands in recent years (Brockway et al. 2005, Jose et al. 2006, Platt et al. 1988). As a result of the proliferation of financial and technical support programs, the majority of new longleaf pine establishment has occurred on private lands rather than public lands in all ALRI status reports released since 2013.

2.3.2 *Restrictions on Prescribed Burning*

There is a sizable literature on best practices for prescribed burning of longleaf pine, offering guidance on seasonality, length, and severity of the prescribed burn (Brockway et al. 2005, Waldrop and Goodrick 2012) Managers may only burn during certain times of the year when optimal environmental conditions are met. Thus, the burn window defines a range of suitable climatic and environmental conditions that ensure the spread of fire without excessive risk to people or surrounding lands (Kupfer et al. 2020).

Atmospheric conditions that influence smoke dispersion and air quality also delimit burning opportunities (Wade and Mobley 2007). The Clean Air Act requires compliance with air quality standards when burning near residential or urbanized areas to protect public health (Williams 2021). However, strict air quality standards are widely understood to severely limit opportunities to conduct prescribed burns (Brockway et al. 2005, Grand and Kleiner 2016).

Social concerns further complicate and limit burn opportunities. The academic and conservation community has expanded its knowledge of best practices for prescribed burning in recent decades, yet the frequency and extent of prescribed burns remains low (Costanza et al. 2013). The public, including residents who live near proposed sites of prescribed burns, often have a limited understanding of the role of prescribed fire and view management as a threat to safety, slowing manager's abilities to conduct burns and increasing burn practitioners' fears of legal repercussions for possible damages (Costanza et al. 2013, Costanza and Moody 2011, Kobziar et al. 2015). Additionally, a reported shortage of prescribed burn practitioners limits managers' abilities to conduct prescribed burns (Costanza et al. 2013, Kobziar et al. 2015, Vorhees 2015).

It is particularly challenging to manage public perception, air quality standards and steep economic requirements when proposing prescribed burns in long unburned systems, as is often the case in longleaf pine restoration and improvement efforts. The accumulation of fuels due to fire suppression increases the risk of conducting prescribed fires as large fuel loads may lead to the rapid spread of high-intensity fire (Kobziar et al. 2015, Varner et al. 2005). Introduction or reinstatement of fire to long unburned systems to enable longleaf pine growth requires considerable expertise and resources to ensure fuel loads are safely reduced (Varner et al. 2005, Waldrop and Goodrick 2012). As a consequence of such complicating factors, burning of longleaf pine on private land is particularly limited, with just 24% of reported prescribed burns taking place on private lands in 2020 (Ballinger et al. 2020).

2.3.3 *Fragmentation*

Rapid urbanization and land conversion in the southeastern United States has produced an additional challenge to the prescribed burning of longleaf pine ecosystems by creating landscapes in which undeveloped land cover is highly discontinuous and fragmented by human-dominated land uses. Habitat fragmentation refers to the degree to which natural landscapes become subdivided by other land use types, often urban or agriculture, to produce smaller, more isolated patches of habitat with reduced ecological value (Fahrig 2003). Much of the remaining acreage of longleaf pine exists in small remnant patches with old-growth stands being particularly limited in extent (ALRI 2009, Brockway et al. 2005, Kirkman and Mitchell 2006). In a 1996 report on longleaf pine conditions conducted for Florida, Georgia, South Carolina, and North Carolina, it was discovered that an estimated 45 to 60% of all longleaf pine existed in patches smaller than 20 ha (Outcalt and Sheffield 1996). These smaller, more isolated habitat patches produced by fragmentation support fewer species and limit the mobility of organisms across the landscape (Fahrig 2003). Additionally, patch isolation makes populations more vulnerable to stressors such as invasive species or disease outbreaks (Simberloff 1993).

Fragmentation also threatens the ability of managers to conduct prescribed burns. Increased proximity of habitat to encroaching developed land heightens the complexity of prescribed burn planning as the safety of nearby residents must be considered. The subdivision of private lands into smaller patches (‘parcelization’) also increases the cost of conducting prescribed burns and the difficulty of restricting fire to a limited area, further discouraging private landowners from maintaining or improving longleaf on their property (Brockway et al. 2005). Despite the expense and difficulty of prescribed burning on small fragments, recent literature expresses the importance of fire management even in small areas as further loss of longleaf pine acreage must be minimized (ALRI 2009, Heuberger and Putz 2003). Efforts to conduct prescribed burns in fragmented suburban areas have been undertaken but to a limited degree (Heuberger and Putz 2003).

2.4 FUTURE MANAGEMENT CONCERNS

Given the lifespan of longleaf pine and the long planning timelines that are necessary for its management, conservation managers must consider future conditions in the planning process. Rapid urbanization and altered climatic conditions are expected throughout the Southeast within the next century, meaning managers may need to adapt to operate within the new conditions. However, high degrees of uncertainty in the severity and spatial distribution of such changing conditions complicate future planning. While longleaf pine planning documents have largely improved with time due to the establishment of higher planning standards by federal and state governments, many management organizations fail to include detailed information on future conditions due to lack of funding for study and uncertainties in projections (Clark et al. 2018, Foster et al. 2019). Though uncertainties in future conditions persist, literature on longleaf pine demonstrates a relative consensus as to the major threats to longleaf pine ecosystem management within the next century.

2.4.1 *The Resilience of Longleaf Pine to Climate Change*

Despite setbacks and limited expansion of longleaf pine extent over the last 10 years, recent research has fostered optimism for longleaf pine persistence, predicting that it may be more resilient to climate change and its threats of altered moisture regimes, high temperatures, and invasive beetles, than other southern tree species (Costanza et al. 2015, Koo 2010). Although there is variability among emissions scenarios and uncertainty in climate modeling, it is expected that the southeastern United States will experience higher temperatures, prolonged drought events, and more severe storms under climate change (Beckage et al. 2006, Hopke 2020). Recent research suggests that these changing climatic conditions may lead to an expansion of the range of longleaf pine northward without a substantial corresponding contraction in its southernmost extent (Beckage et al. 2006, Koo 2010, Peters et al. 2020). Additionally, longleaf pine exhibits greater tolerance to drought and high temperatures, is less susceptible to blowdown from hurricanes, and possesses higher resistance to invasive species like the southern pine beetle than other southern pine species including slash, loblolly and shortleaf pines (ALRI 2009, Johnsen et al. 2009, Peters et al. 2020, Samuelson et al. 2012). However, while climate change may not pose significant direct risks to longleaf pine, secondary impacts such as those associated with disturbance regimes (especially those related to fire) may prove to be more complicated.

2.4.2 *Wildfires and Prescribed Burning Under Climate Change*

In recent years, public awareness of wildfire risk has risen in response to highly publicized wildfire events in the western United States (Hopke 2020). Increasing public attention has fostered the growth of literature on the response of wildfire to climate change in the United States, much of which predicts more frequent, higher severity wildfires under warmer, drier climate change conditions (Costanza et al. 2015, Liu et al. 2013, McKenzie and Littell 2017, Prestemon et al. 2016). However, there remains considerable uncertainty as to the degree and spatial distribution of wildfire response to climate change, particularly in the southeastern United States. (Costanza et al. 2015).

Recent research argues that potential changes in the wildfire regime are of lesser importance to longleaf pine ecosystem health in the southeastern United States than changes in prescribed fire opportunity. Costanza et al. (2015), for example, suggest that changes in the wildfire regime under climate change will have little impact on longleaf pine conservation but that prescribed burning, specifically a doubling of current prescribed burning levels, will be necessary to counteract the fire suppression practices that result in longleaf pine ecosystem degradation.

More than 3.0 million ha of land undergo prescribed burning each year in the southeastern United States (Melvin 2018, Melvin 2020), an area significantly larger than the average annual area burned by wildfire which falls below a million hectares a year (Lee et al. 2014). The optimism of a potentially resilient longleaf pine is counteracted by projections of severe seasonal limitations on prescribed burning opportunities under climate change (Kupfer et al. 2020). Specifically, prescribed burning, an already complex process with existing challenges, is necessary to reduce wildfire risk and to maintain, improve, and restore longleaf pine ecosystems, so its potential constraint under climate change is of major concern to conservation managers. The number of days that fall into a suitable prescription burn window and meet the legal requirements for conducting a burn is expected to decline (in some places, substantially) under climate change (Kupfer et al. 2020). Recent research by Kupfer et al. (2020) reports that elevated temperatures under climate change will significantly decrease the number of prescribed burning opportunities in the spring and summer and reduce reliability in the late spring and early fall. Such severe reductions in prescribed burn opportunity will complicate management and potentially further restrict burning and inhibit longleaf pine ecosystem conservation.

2.4.3 *Urbanization*

Limitations on prescribed burning are expected to be further exacerbated by urbanization in the coming years. In addition to climate change considerations, managers must consider future land-use change, particularly given that the Southeast is expected to experience rapid urban growth and increased fragmentation within the next century (Terando et al. 2014). This acceleration of urbanization in the southeast has occurred more recently in comparison to other regions of the United States with the population in the southeast increasing 40% faster than the rest of the United States between 1950 and 2010 (Terando et al. 2014). Some argue that urban growth may be more damaging to longleaf pine conservation efforts than climate change (Costanza et al. 2015). Widespread urbanization is expected to result in further loss of longleaf pine ecosystem acreage and further restrict opportunities for prescribed burning (ALRI 2009, Costanza et al. 2015).

Particular concern has been expressed about the expansion of the wildland-urban interface (WUI), the area in which human development meets an undeveloped area with natural vegetation, resulting in heightened wildfire concerns (Stewart et al. 2007, Radeloff et al. 2018). Burning in or near the WUI presents a greater risk of human-started wildfire and pushback against burning from residents (ALRI 2009, Grand and Kleiner 2016, Hawbaker et al. 2013, Radeloff et al. 2018). Working with the public to ensure safety and to inform residents of the risks and rewards of prescribed burning may provide an additional burden to longleaf pine managers. Researchers are seeking to better plan prescribed burns in small, highly fragmented areas within urban and suburban lands (Heuberger and Putz 2003). With opportunities for prescribed burning already constrained by increasing temperatures under climate change, further limitations due to proximity to urban and suburban land cover would threaten the ability of longleaf pine ecosystem managers to achieve conservation goals.

.

CHAPTER 3

METHODS

Assessment of the literature on management concerns for longleaf pine produced three overarching variables known to impact conservation of longleaf pine: urbanization, the prescription burn window, and wildfire occurrence. A complete picture of the future of longleaf pine management would therefore consider changes to all three variables. Models of each variable are available, but they have not previously been applied to longleaf pine and, given the complexity of each variable and the uncertainty of forward projection, an integrative model of all three variables is not available. I seek to consider the variables cumulatively by mapping and analyzing each variable and its spatial relationship to longleaf pine patches in the Florida flatwoods pyrome. Such an analysis provides pyrome-wide trends and longleaf pine patch-specific insights that can be used to support longleaf pine management. The methods below (Figure 3.1) describe the models and techniques used to produce a connection between independent models of each variable and known longleaf pine.

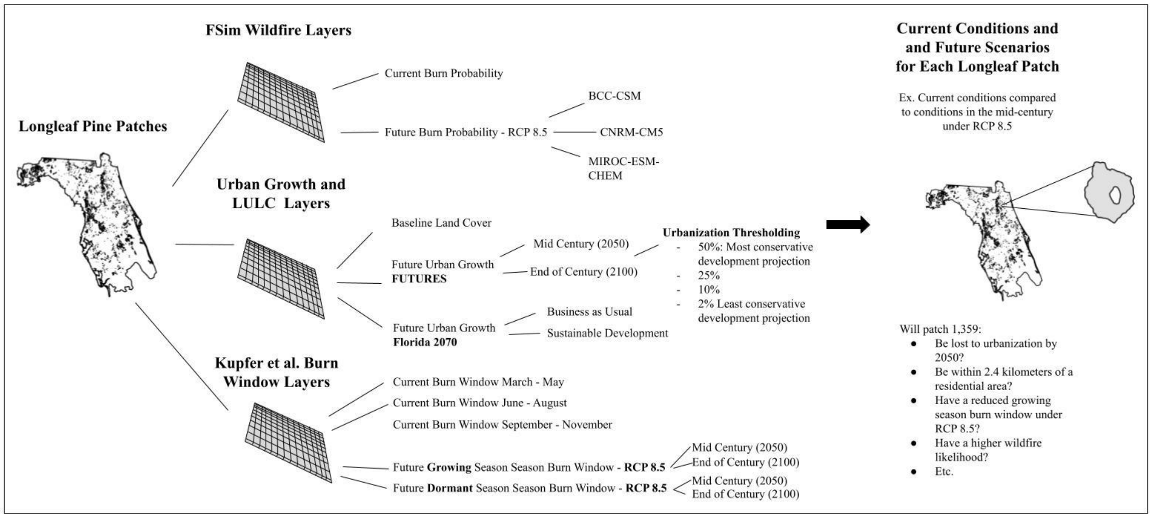

Figure 3.1: Process of organizing layers, applying values of the variables of interest to longleaf pine patches, and conducting data analysis. Branches of the tree diagram indicate iterations of the variables.

3.1 STUDY AREA: THE FLORIDA FLATWOODS PYROME

Given data availability and modeling capacity, this study is centered on the Florida flatwoods pyrome, which offers an ideal case study for research on current and future threats to longleaf pine ecosystem management. Much like biomes, pyromes represent areas of shared ecological characteristics, in this case, a shared fire regime (Short et al. 2020). The Florida flatwoods pyrome is an over 12-million-hectare area that is dominated by longleaf pine savanna covering the northern half of Florida and a portion of Georgia (Short et al. 2020) (Fig. 2.1). However, for the purposes of this study, the pyrome has been restricted to the boundaries of the state of Florida and has therefore been reduced to an extent of approximately 10.2 million ha.

Of the southeastern states, Florida holds the largest extent of longleaf pine ecosystems (Outcalt and Sheffield 1996) and is home to the highest number of longleaf pine-associated endangered and threatened vascular plants (Van Lear et al. 2005). Additionally, of all the states which have longleaf pine, Florida is the only one in which the majority is under public land ownership (Outcalt and Sheffield 1996). Considerable mobilization of conservation management and research on longleaf pine ecosystems has taken place for the area, enabling the creation of large, high-resolution datasets on longleaf pine ecosystem locations and conditions, namely the Longleaf Pine Ecosystem Database released in 2018 by the Florida Forest Service and Florida Natural Areas Inventory (Florida Forest Service 2018).

3.2 DATA SOURCES

To study the impacts of projected changes in urbanization, burn window availability, and fire regime on ecological patterns and processes of longleaf pine in the Florida flatwood pyrome through the next four decades, I needed datasets that addressed each of those factors. These are described below.

3.2.1 *The Florida Longleaf Pine Ecosystem Geodatabase*

The Florida Longleaf Pine Ecosystem Geodatabase (LPEGDB) offers an extensive repository of longleaf pine ecosystems in the state of Florida. Over 3.5 million ha of land were assessed, and 956,867 ha of longleaf pine were located and mapped by the Florida Forest Service (FFS), the Florida Natural Areas Inventory (FNAI), and partners. Of the longleaf pine sites identified, over 600,000 ha fall within the Florida flatwoods pyrome (Florida Forest Service 2018). Currently, no other state has an equivalent database of systematically identified longleaf pine patches. In fact, an ongoing effort to develop a longleaf pine database for the entire southeastern United States has been modeled after the Florida Longleaf Pine Ecosystem Geodatabase and is in the initial phases of data collection (Florida Natural Areas Inventory 2022). Data quality of the geodatabase has been assessed and documented, enabling confidence in sites of confirmed longleaf pine, supporting the decision to use the LPEGDB as the basis for this geospatial study on current and future threats to longleaf pine ecosystems and their management.

The database consists of two vector shapefiles, one of which contains the longleaf pine occurrence status of all land assessed for the LPEGDB, including land where longleaf pine is absent (or presence is unknown), while the other contains only polygons where longleaf pine is confirmed or highly likely to occur. When data are available, confirmed longleaf pine polygons include supplemental information describing the ecological characteristics, condition, and ownership of the individual longleaf pine patches. Such supplemental information allows for discernment between natural and planted pine, private and public ownership, high quality and degraded systems, and longleaf dominant and non-dominant areas. However, availability of attribute data is not consistent for all confirmed patches of longleaf pine. For example, dominance classes were undetermined for more than 79,000 ha, and another 392,688 ha were not assigned a condition rank of poor, fair, or good. Despite some limitations to the availability of information on ecological condition, all confirmed longleaf pine patches had attribute data describing the owner type and a confidence level describing whether the user can be certain of longleaf pine presence in a given polygon.

The LPEGDB contains over 40,500 polygons in which longleaf pine has been confirmed or is highly likely to be present, including 26,630 in the Florida flatwoods pyrome study area. However, not all longleaf pine polygons included in the database are appropriate for this study. For example, in accordance with the conservation management goals of this study, longleaf pine patches should be ecologically valuable, relevant to conservation, and appropriate targets for management. Longleaf pine patches under a certain size are unlikely to support the species and ecological functions of interest for conservation. Likewise, very small patches of longleaf pine are perhaps less likely to receive proper management through prescribed burning or removal of hardwoods and undergrowth given resource limitations. As a consequence, only longleaf pine patches above 40 ha were included as units for analysis. Vorhees (2015) defines ecologically relevant longleaf pine patches as larger than 40 ha based on the minimum habitat size requirement for red-cockaded woodpeckers, an endangered species indicative of good-condition longleaf-pine ecosystems. Though this criterion may exclude small patches of ecologically-relevant longleaf pine, a 40-hectare minimum patch size is likely needed to necessitate management and offer adequate habitat to species of interest in longleaf pine ecosystems. While the management of small longleaf pine fragments is possible and there is increasing interest in such endeavors (see Heuberger and Putz 2003), such small-scale management is beyond the scope of this study.

The Florida Longleaf Pine Ecosystem Geodatabase offers attribute data describing the condition (poor, fair, excellent/good) and dominance (absent, occasional/rare, co-dominant, dominant) of individual longleaf pine patches. However, the attribute data on dominance and condition is not available for all longleaf pine presences. The management goals of this study necessitate the consideration of all sites that are highly likely to contain longleaf pine. Excluding polygons where presence of longleaf pine is confirmed but dominance or condition is not known may risk the exclusion of significant sites of longleaf pine that were not extensively surveyed. Therefore, the dominance and condition attributes were not used to further restrict the definition of longleaf pine patches in this study. A complete flowchart of the process used to refine the longleaf pine dataset is shown in Figure 3.2.

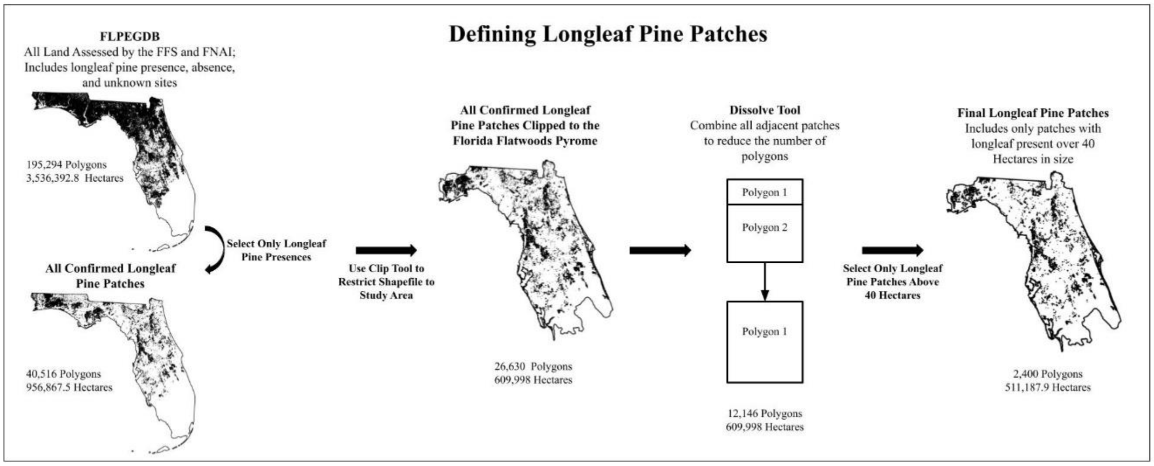

Figure 3.2. Process for defining the longleaf pine patch layer, including the total number of polygons and hectares at each stage of data preparation.

3.2.2 *Urbanization*

Data from three sources were used to represent urban land cover and its future changes: 1) the U.S. Geological Survey's National Land Cover Database (NLCD), 2) outputs from runs of the FUTure Urban-Regional Environment Simulation (FUTURES) model, and 3) the Florida2070 urban growth dataset. Each provided a baseline of current urban land coverage in the study area, though for slightly different years.

The 2019 National Land Cover Database (NLCD) provides nationwide data on land cover and land cover change at a 30m resolution (Dewitz 2019). Land cover rasters are divided into 20 land cover classes derived from the Anderson Level II classification system (Jin et al. 2019). NLCD land cover data was selected for its documented accuracy of 86.4% (Wickham et al. 2021) and differentiation between different degrees of land development. Further, differentiation of the developed land cover class into Anderson II subclasses of Developed – Open Space, Developed – Low Intensity, Developed –

Medium Intensity, and Developed – High Intensity enabled a more detailed assessment of current urban land in the Florida flatwood pyrome. These data were downloaded from: https://www.mrlc.gov/data/nlcd-2019-land-cover-conus.

The FUTure Urban-Regional Environment Simulation (FUTURES) is a sophisticated urban growth model with a history of usage in landscape-scale urbanization studies (Meentemeyer et al. 2013; Van Berkel et al. 2019; Sanchez et al. 2020). FUTURES does not assume homogeneity in urban growth patterns but, rather, incorporates variation in urban growth patterns, for example, at the county-level assuming differences in zoning for urban land cover. Such accounting for spatial heterogeneity is appropriate for the large, pyrome-scale study area used in this study. FUTURES is a stochastic model meaning that each model run used in this study will exhibit some degree of variation attributable to randomness. For this study, I received early access to 50 model runs of FUTURES for the Florida flatwoods pryome study area from Dr. Georgina Sanchez in the Center for Geospatial Analytics at North Carolina State University. Each model run is represented by a raster with pixel values denoting projected urban growth for each year between 2019 and 2100. The baseline urban land cover is given for the year 2019. For the purposes of this study, the rasters were reclassified to represent three time periods, the baseline urbanization, mid-century urban growth projections up to the year 2050 and an end of the century urban growth projections up to the year 2100.

The Florida 2070 Project is a spatial dataset of Florida-specific urbanization scenarios for the year 2070 developed by the Florida Department of Agriculture and Consumer Services, 1000 Friends of Florida, and the University of Florida's Geoplan

Center (1000 Friends of Florida 2017, Carr and Zwick 2016). The dataset provides a baseline of developed land from the year 2010, a “trend 2070” urbanization scenario for the year 2070 if urban growth continues at the expected rate concurrent with population growth, and an “alternative 2070” urbanization scenario in which more land is protected, and sprawl is reduced through creation of higher density urban areas. The project dataset also includes shapefiles of protected areas under the baseline, “trend 2070”, and “alternative 2070” scenarios. The Florida 2070 dataset offers urban growth projections that have been used in numerous landscape-scale conservation studies (Davis et al. 2021, Romañach et al. 2020). For the purposes of this study, the Florida 2070 dataset will primarily serve as a comparison point to the FUTURES urban growth projections.

3.2.3 *Climate Change and Fire*

Prior to widespread fire suppression, frequent fires maintained the open-canopy structure characteristic of most longleaf pine stands (e.g., Glitzenstein et al. 2003; Rother et al. 2020) and supported high levels of vascular plant species richness (Peet and Allard 1993). Exposure to wildfire continues to affect the ecological condition of some fire-dependent longleaf pine ecosystems (Brockway et al. 2005), and the likelihood that a given area will be exposed to wildfire may influence the decisions of burn managers. The U.S. Forest Service developed the software FSim, a spatially-discriminant simulation that uses weather and climate conditions, topography, and fuels data to estimate the probability that a given location will be affected by wildfire over a multi-year period (Finney et al. 2011). The location and spread of individual wildfires are simulated using weather conditions that influence the direction and spread of wildfire (e.g., temperature, relative humidity, wind speed, direction) and different ignition sites. FSim allows for stochasticity to account for the unpredictability of fire behavior, ignition, and weather by completing tens of thousands of model runs. Annual burn probabilities calculated by the model represent the annual likelihood of burning given a specified landscape and set of weather conditions (which can include historic weather data or output from global climate models), while fire ignitions and fire perimeters represent a plausible event set of wildfires given the same (Riley et al. 2018). In this study, I used output from FSim for baseline climate conditions (1979-2005) as well as mid-century conditions predicted by three global climate models (GCMs) under two representative concentration pathways (RCPs) to estimate changes in annual burn probabilities resulting from projected 21st century climate change.

As important as wildfires historically were to the health of longleaf pine and other southeastern ecosystems, far more area is now burned annually through prescribed fires (Melvin 2018, Melvin 2020). Prescribed burning is a critical management tool both for restoring and managing longleaf pine ecosystems and for reducing wildfire risks. To examine how projected climate changes may influence the ability of fire managers to conduct prescribed burns in longleaf pine ecosystems, we used current and future burn window data developed for the Southeast by Kupfer et al. (2020). In that study, a set of burn window criteria (suitable weather conditions within which burning may occur based on maximum daily temperature, daily average relative humidity, and daily average wind speed) were applied to projections from an ensemble of GCMs under two greenhouse gas emission scenarios, as well as past observations for comparison (Kupfer et al. 2021). The data, which were downloaded from the US Geological Survey's Science Base website, are provided as decadal output for observed conditions and for individual GCM results for the historical climate scenario and the two future climate scenarios.

3.3 ANALYSES

3.3.1 *Impacts of Development and Urbanization on Longleaf Extent*

Initial analysis of longleaf pine extent and its potential future change included a characterization of the current land cover of all known longleaf pine patches used for study. Of particular interest was any known longleaf pine that was classified as ‘developed’. Areas of overlap where current longleaf pine was classified as developed could indicate an error in the urbanization database, the LPEGDB, or represent true longleaf pine loss. Furthermore, such overlap between land classified as longleaf pine and land classified as developed could influence the results of a comparison between the baseline 2019 urbanization conditions and the modeled mid-century and end-of-century urbanization conditions. For this analysis, I used the 2019 National Land Cover Database (NLCD) to determine the land cover characteristics of known longleaf pine patches as derived from the LPEGDB. After downloading and clipping the 2019 NLCD data to the Florida Flatwoods Pine study area, I used the Zonal Statistics Tool to identify the dominant land cover class for each longleaf pine patch.

The potential effects of urbanization on the persistence of longleaf pine patches was modeled using FUTURES. Two time frames, mid-century (2050) and end of century (2100), were selected for their relevance in long-term longleaf pine conservation planning and for their alignment with the time frame of the burn window model used in this study. Fifty (50) FUTURES runs were provided and used in this analysis. Due to a user-side data error, one model run was eliminated for a total of 49 model runs. I did not create or run FUTURES; rather, I analyzed the output within the Florida flatwoods pyrome study area. Each model run is represented by a raster layer with pixel values representing land developed in the 2019 baseline or land classified as developed each year between 2019 and 2100. To account for the stochastic components of the model, I created a new raster that combined all model runs and included the number of times a given pixel was developed across the 49 model runs. For example, if a pixel was classified as developed in 5/49 model runs, the pixel value was assigned as 0.102, indicating that it was projected for urbanization in 10.2% of model runs.

To do so, each run was reclassified into a binary raster using the Reclassify tool. Then, all of the runs were added together using the Raster Calculator tool. For example, to create a binary raster of one model run for the mid-century, a pixel value of 1 was assigned for areas classified as developed by 2050 and a 0 was assigned for all other values. Forty-nine (49) reclassified rasters were created displaying mid-century urbanization, one binary raster per model run. I then used the Raster Calculator tool to add each of the 49 model runs together, creating a raster representing the probability of pixel urbanization. Urbanization rasters were converted to polygons for ease of area calculation and assessing the spatial relationship of urbanization to longleaf pine patches.

Four urbanization thresholds were used to identify longleaf pine at different degrees of risk of future urbanization as a means of reconciling our goal of identifying expected longleaf pine loss with the stochasticity of FUTURES. For example, a longleaf pine patch might be lost to urbanization in one model run, but due to the stochastic elements of FUTURES, it may not be projected to urbanize in the other 48 runs. A pixel projected to be urbanized in 25 out of 49 model runs (51% of model runs) would thus have a higher likelihood of future urbanization than a pixel that was projected to be urbanized in 1 out of 49 model runs (2% of model runs). Correspondingly, I examined the probability of urbanization for each cell in FUTURES using four urbanization thresholds. In the most inclusive threshold (2%), a pixel that was urbanized in any model run was considered to be developed. In the most restrictive threshold (50%), a pixel was only considered to be developed if it was urbanized in 25 model runs or more. Two additional cutoffs, 10% (5-12 model runs) and 25% (13-24 model runs), were selected as intermediate urbanization thresholds.

To further explore the potentialities of urban expansion in the Florida flatwoods pyrome, the Florida 2070 dataset developed by 1000 Friends of Florida was analyzed and included as a comparison point for the FUTURES urbanization dataset. The Florida 2070 dataset differs from FUTURES in its time frame, offering an urbanization outcome for the year 2070. Two scenarios are available: Florida 2070 Trend demonstrating business-as-usual, sprawling urban expansion, and Florida 2070 Alternative, demonstrating more compact urbanization centered around city centers and accounting for additional protection of public lands. Inclusion of the Florida 2070 urbanization projections offered a counterpoint to FUTURES while helping to gauge its utility in ecological studies.

Lastly, I considered the proximity of longleaf pine to developed land, a variable that provides additional insight into the difficulty of prescribed burning. Burn managers typically refer to the Wildland Urban Interface (WUI) when discussing limitations on prescribed burning produced by safety concerns for nearby residents. Because defining and modeling the WUI is complex, I used a simplified approach adapted from the federal definition of WUI and related publications wherein I identified all longleaf pine within

2.4 km of developed areas at a given time (Healthy Forests Restoration Act of 2003, Stewart et al. 2007). Developed areas within a distance of 2.4 km from burnable vegetation has frequently been used in studies of the WUI to identify communities at-risk of exposure to fire (Healthy Forests Restoration Act of 2003, Stewart et al. 2007). I then selected and analyzed all longleaf pine within that 2.4 km buffer of developed areas as having additional strain on prescribed burning and a higher potential for degradation.

3.3.2 *Changing Fire Regimes and Burn Windows*

To examine the potential effects of changing climate on wildfire occurrence in longleaf pine patches into the 21st century, FSim was run for the Florida flatwoods pyrome study area using future climate projections from three GCMs. FSim output included the current burn probability modeled based on meteorological conditions observed between 1979 and 2005 and future burn probability for the mid-century for 2040-2069. Multiple model runs were conducted using three GCMs: BCC-CSM, CNRM-CM5, and MIROC-ESM-CHEM; to reduce bias and account for variability in future climate, the three GCMs were averaged for use in this study. Historical and future FSim rasters were clipped to the study area boundary, and the average burn probability was calculated for each longleaf pine patch using the Zonal Statistics tool. All FSim runs were performed by Dr. Peng Gao (UNC-Wilmington) as part of a larger collaborative study on future fire regimes in the Florida flatwoods pyrome.

Finally, because prescribed burning is so central to the persistence of good condition longleaf pine, I mapped changes to the number of days that fall into the burn window for the Florida flatwoods pyrome study area and the existing longleaf pine patches by overlaying rasters representing burn window characteristics on the longleaf pine patch layer derived from the Florida Longleaf Pine Ecosystem Geodatabase. The burn window dataset compiled by Kupfer et al. (2021) provides raster data on observed historic and future burn windows modeled for multiple GCMs and two climate scenarios for monthly and seasonal periods throughout the 21st century. I used data for RCP 8.5 to correspond with FSim data availability. Burn window data reflects the average of several GCMs to account for the variability in possible environmental conditions affecting longleaf pine and prescribed burning in the future. Seasonal rather than monthly burn windows were used as they capture possible difference between growing and dormant season conditions while reducing the potentially unmanageable number of future scenarios that would result from the use of monthly data.

Four burn window rasters were downloaded for each season: Season 1, March through May, Season 2, June through August, Season 3, September through November, and Season 4, December through February. Burn window data were available for each decade between 2010 and 2100. I selected the years 2050 and 2100 to represent mid-century and end of century burn windows, which correspond with the FUTURES urbanization time frames. Each raster was clipped to the Florida flatwoods pyrome. The mean, minimum, and maximum burn window observed across the pyrome was recorded and mapped. Burn window values were subsequently averaged for each longleaf pine patch through Zonal Statistics.

CHAPTER 4

RESULTS

4.1 BASELINE LAND COVER ASSESSMENT OF KNOWN LONGLEAF PINE PATCHES

The presence of developed areas influences the presence of longleaf pine and the difficulty of managing it. Therefore, characterization of the land cover on longleaf pine patches can provide insights into the health or quality of longleaf pine ecosystems and serves as an important benchmark for monitoring future changes related to urbanization. My initial assessment of longleaf pine patches and their associated land cover classification demonstrates that longleaf pine can persist alongside developed areas, albeit rarely (Table 4.1). Only a small area of the mapped longleaf pine patches (12,168 ha, or 2.41% of the total area in longleaf pine patches) was located on land classified as developed by the 2019 NLCD dataset, the majority of which was classified as low-intensity developed areas. The figures were similar for land classified as developed by the FUTURES baseline (24,146 ha, 4.73%). A notably higher percentage of longleaf pine areas (45,944 ha; 8.99%) were located on land classified as developed by the Florida 2070 baseline.

Visual assessment using air photos demonstrates that some of the longleaf pine located on developed land cover may be attributed to classification error, either in identifying an area as having longleaf pine when it does not or identifying an area as being developed when it is not. However, in some instances, it is the result of sparse urbanization in rural or suburban areas where longleaf can persist, typically within sporadic housing development. Variation between the three developed area baselines was also clearly apparent. For example, the comparatively high amount of longleaf pine overlapping with developed areas using the Florida 2070 baseline is likely a result of an overestimation of current developed area. Rudimentary accuracy assessment of the three datasets suggests a higher frequency of land classified as developed when it is undeveloped in the Florida 2070 baseline, in particular.

Of the 24,146 ha of longleaf pine occurring on land classified as developed by the FUTURES baseline dataset, almost all of it (97.97%) was privately owned. Further, on 51.75% of that land, longleaf pine was classified as either codominant or rarely occurring. Therefore, while longleaf pine may persist alongside developed areas, longleaf pine overlap with developed areas may be an indicator of lower-quality longleaf pine stands where longleaf pine may be present but is interspersed with competing vegetation.

Table 4.1 Known Longleaf Pine Extent on Land Classified as Currently Developed by NLCD, FUTURES, and Florida 2070 baselines.

Land Cover Class	**Longleaf Pine Extent (ha)**	**Percentage of Total Longleaf Extent**
NLCD - Developed Open Space	12,105	2.40%
NLCD - Developed Low Intensity	63	0.01%
NLCD - Developed Medium Intensity	0	0.00%
NLCD - Developed High Intensity	0	0.00%
NLCD - Developed Overall	12,168	2.41%
FUTURES – Developed	24,146	4.73%
Florida 2070 - Developed	45,944	8.99%

4.2 PROJECTED LOSSES OF LONGLEAF PINE TO URBANIZATION

The above results parallel other findings which show that developed areas are largely incompatible with longleaf pine persistence (Costanza et al. 2015, Vorhees et al. 2015). Thus, urbanization within the Florida flatwood pyrome can be considered a threat to longleaf pine and was quantified in this study. A location identified as having longleaf pine at the baseline and subsequently classified as developed by the urbanization models was considered to be a direct loss of longleaf pine to urbanization.

The area of developed land cover across the Florida flatwoods pyrome increased into the mid to late 21st century, with the projected extents dependent on the model used (FUTURES or Florida 2070) and the threshold or scenario selected (Table 4.2). Loss of longleaf pine responded accordingly as scenarios projecting more expansive urban growth resulted in more severe loss of longleaf pine (Table 4.3, Figure 4.1). Using the FUTURES 50% threshold (the most restrictive threshold given that the majority of model runs must agree to assign a pixel as developed) resulted in a 19,084 ha (1.16%) increase in developed area by 2050. The small area projected to be urbanized under this threshold indicates relatively limited agreement between model runs and considerable variation in the area projected to be urbanized. Correspondingly, this threshold resulted in a small loss of longleaf pine and a negligible decline in average patch area. Though small in area, the longleaf pine lost at the most restrictive thresholds is of particular note because it is the most likely to be lost (given model projections), and therefore may be of greater concern for managers. Areas with the highest degree of agreement and, thus, the highest likelihood of urbanization and longleaf pine loss were clustered around major metropolitan areas, mainly the greater Orlando area.

In contrast, use of the 2% model threshold (meaning that a cell projected to urbanize in any of the 49 FUTURES iterations) resulted in a 115.9% increase in urban area. Such an extreme expansion of developed area is likely a major overestimation of added urban area, but it allows for the identification of additional longleaf pine at risk of loss. At the 2% threshold, 44,649 ha of longleaf pine were lost by 2100, 9.18% of the current range of longleaf pine. The average patch size declined from 204.1 ha to 187.3 ha. Relatedly, the extent of longleaf pine within patches under 40 ha, the minimum patch area necessary to sustain high-quality longleaf pine and longleaf-pine dependent species, increased across the study period. This acreage is not considered to be a direct loss of longleaf pine as the longleaf pine has not been directly converted to a developed land cover. Rather, it may be understood as indirect loss of longleaf pine or conversion to a degraded ecosystem that is no longer able to sustain full ecosystem function.

The Florida 2070 Trend development scenario (which is characterized by uncontrolled, business-as-usual sprawl) and the alternative Florida 2070 scenario (which is characterized by compact growth and greater land protection) both produced estimates of urban area increase closer to the lowest thresholds (2% and 10%) thresholds of the FUTURES model projects. This indicates that projections from the Florida 2070 model are in line with the more liberal estimations of future urban growth from the FUTURES model. Notably, while the percent increase in urbanization in the FUTURES model and the Florida 2070 model were comparable, the urbanization baseline in the Florida 2070 model was far larger than the FUTURES baseline, with 50.16% more hectares of developed areas identified prior to forward projection. The high estimate of current developed land cover may serve to explain the high estimates of urban area from Florida 2070 despite comparable rates of urbanization increase.

Table 4.2 Extent of Developed Land in the Florida Flatwoods.

Urbanization Threshold	**Year**	**Urbanized Area (ha)**	**Development Added Since Baseline (ha)**	**Percent Increase**
FUTURES				
Baseline	2019	1,644,560		
50% (25 model runs)	2050	1,663,644	19,084	1.16%
	2100	1,716,823	72,263	4.39%
25% (13 model runs)	2050	1,758,416	113,856	6.92%
	2100	1,879,796	235,236	14.30%
10% (5 model runs)	2050	2,049,292	404,732	24.61%
	2100	2,271,255	626,695	38.11%
2% (1 model run)	2050	3,192,317	1,547,757	94.11%
	2100	3,543,880	1,899,320	115.49%
Florida 2070				
Baseline	2010	2,469,415		
Development Trend (Sprawl)	2070	4,555,698	2,086,283	84.48%
Development Alternative (Compact)	2070	3,831,380	1,361,965	55.15%

Table 4.3 Total Longleaf Pine Area, Longleaf Pine Loss, and Patch Area Resulting from Modeled Urbanization for FUTURES and Florida 2070.

Urbanization Threshold	Year	Longleaf Pine Area (ha)	Average Patch Area	Longleaf Pine in Patches Under 40 ha	Longleaf Pine Directly Lost (ha)
FUTURES					
Baseline	2019	486,356	204.1	3,103	24,146[a]
50% (25 model runs)	2050	486,043	204.0	3,146	313
	2100	485,246	203.6	3,339	1,110
25% (13 model runs)	2050	484,690	203.4	3,462	1,666
	2100	482,391	202.5	3,623	3,965
10% (5 model runs)	2050	479,757	201.4	4,128	6,599
	2100	475,494	199.8	4,166	10,862
2% (1 model run)	2050	452,496	191.2	5,588	33,860
	2100	441,707	187.3	6,198	44,649
Florida 2070					
Baseline	2010	464,558	195.0	4,717	45,944[a]
Development Trend (Sprawl)	2070	414,400	174.2	7,001	50,158
Development Alternative (Compact)	2070	439,647	184.6	5,614	24,911

[a]Values represent overlap between known longleaf pine patches and baseline developed land. This area is likely a cumulative result of classification error, longleaf pine intermix with development, and true longleaf pine loss.

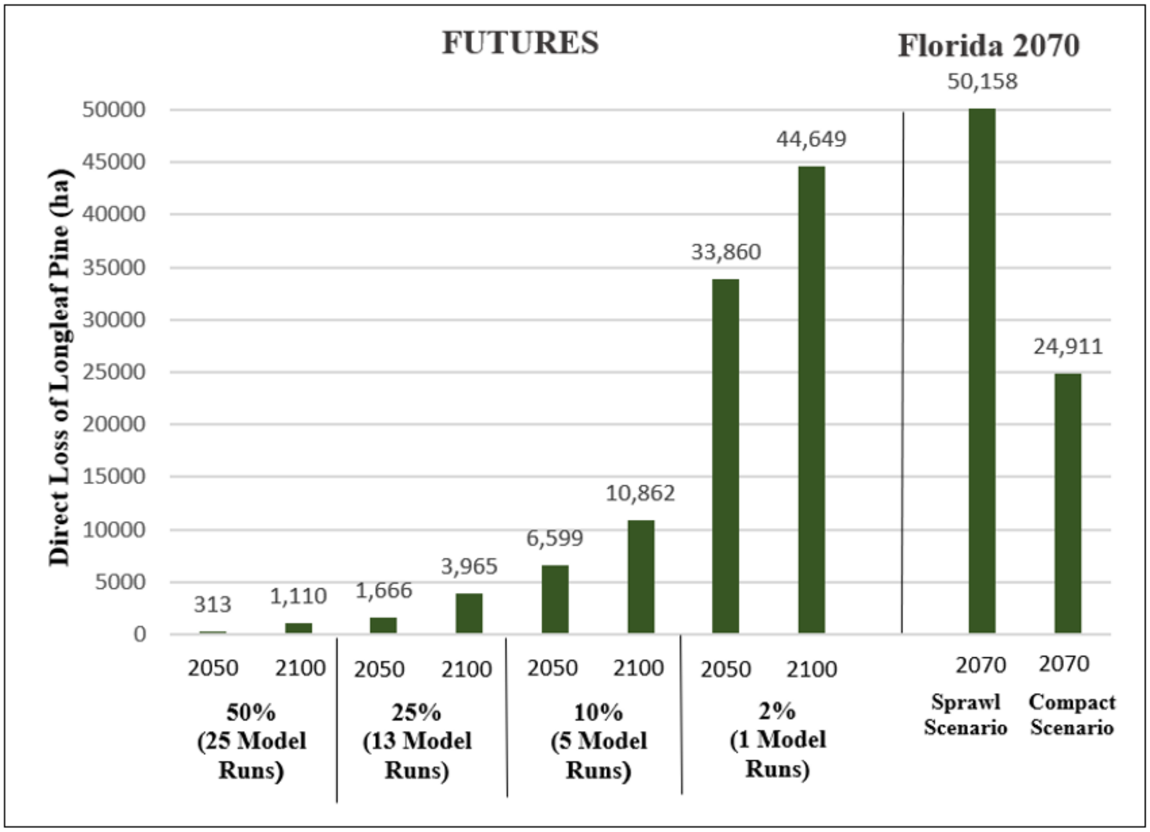

Figure 4.1: Graphical comparison of total longleaf pine loss in hectares for the FUTURES and Florida 2070 model under different urbanization thresholds and scenarios.

In addition to causing the direct loss of longleaf pine through land use conversion, urbanization poses a threat to the practice of prescribed burning as the encroachment of developed land increases the difficulty of and places greater restrictions on prescribed burning. Encroachment on longleaf pine forests is already extremely severe with the majority of current longleaf pine patch area being within 2.4 km of developed land, the distance commonly used to define the WUI (Table 4.4) (Stewart et al. 2007). Using the FUTURES urbanization baseline for 2019, 85.85% of longleaf pine acreage was within 2.4 km of developed land. For both models and nearly all urbanization thresholds, the total extent of longleaf pine located within 2.4 km of developed land cover declines into the century. This is likely because any increase in the amount of longleaf pine in close proximity to development was offset by direct loss of longleaf pine through conversion to developed land. The proportion of longleaf pine within 2.4 km of developed land out of the total longleaf pine extent for that year remained relatively constant, at about 85 - 86%. The FUTURES model indicated a slightly higher proportion of longleaf pine acreage located within 2.4 km of developed land compared to the Florida 2070 model. Likewise, the extent of longleaf pine within 2.4 km of development was smaller overall in the Florida 2070 model. This may be a result of the higher direct loss estimates of longleaf pine in the Florida 2070 model.

Table 4.4: Extent of Longleaf Pine Within 2.4 Km of Developed Land Projected into the Late 21st Century by the FUTURES and Florida 2070 Model.

Urbanization Threshold	**Year**	**Development Shadow (2.4 Km)**	**Area Not In 2.4 Km Buffer**
FUTURES			
Baseline	2019	417,535 ha (85.85%)	68,821 ha
50% (25 model runs)	2050	417,319 ha (85.86%)	68,724 ha
	2100	416,620 ha (85.86%)	68,626 ha
25% (10 model runs)	2050	416,074 ha (85.84%)	68,616 ha
	2100	413,836 ha (85.78%)	68,555 ha
10% (5 model runs)	2050	411,720 ha (85.81%)	68,037 ha
	2100	407,986 ha (85.80%)	67,508 ha
2% (1 model run)	2050	391,782 ha (86.58%)	60,714 ha
	2100	382,304 ha (86.55%)	59,403 ha
Florida 2070			
Baseline	2010	379,252 ha (81.63%)	85,306 ha
Development Trend (Sprawl)	2070	343,115 ha (82.79%)	71,285 ha
Development Alternative (Compact)	2070	366,277 ha (83.31%)	73,370 ha

4.3 CHANGES IN SUITABLE BURN WINDOW CONDITIONS

The number of days that fall within the burn window offers an additional indicator of possible longleaf pine degradation. A decrease in the number of days within the burn window suggests increasing limitations on the opportunities for prescribed burning throughout the year. Given longleaf pine's reliance on fire to maintain its ecosystem structure, lack of prescribed burning may result in degradation of the ecosystem quality. Under RCP 8.5, the number of suitable burn days for the Florida flatwoods pyrome is projected to decline most dramatically in the summer months (June - August), with just 7% of days offering suitable conditions for burning by 2100 (Table 4.5). While there is some opportunity for prescribed burning during the summer at baseline (56% of days in 2010), opportunities drop off steeply into the century. During the spring (March - May) and fall (September - November), the number of days within the prescription burn windows are expected to decline, though less sharply than during the summer. The winter burn window (December - February), however, will maintain its reliability as a safe time to conduct prescribed burns with only a 1% reduction in the number of days within the burn window by 2100.

Reduction in the number of suitable burn days is not uniform across the Florida flatwoods pyrome (Figure 4.2). Near the coasts, especially on the Atlantic Ocean side of the Florida peninsula, the decline in suitable burn days is projected to be less severe. Continental locations away from the moderating effects of the ocean are projected to experience the greatest decline in days falling within the burn window, presumably due to warmer conditions that approach the upper burn window temperature threshold.

Table 4.5 Percentage of Days that Fall into Four Seasonal Burn Windows under RCP 8.5 and Projected into the Late 21st century.

Season	**Year**	**Min**	**Max**	**Mean**	**St Dv**
Spring: March – May	2010	71%	91%	82%	3.7%
	2050	66%	91%	78%	4.3%
	2100	53%	84%	65%	5.2%
Summer: June – August	2010	32%	90%	56%	9.9%
	2050	15%	76%	31%	8.6%
	2100	2%	34%	7.2%	3.2%
Fall: September – November	2010	62%	87%	76%	4.4%
	2050	53%	84%	69%	5.1%
	2100	38%	60%	54%	4.8%
Winter: December – February	2010	69%	89%	83%	3.1%
	2050	70%	90%	83%	2.9%
	2100	68%	90%	82%	3.3%

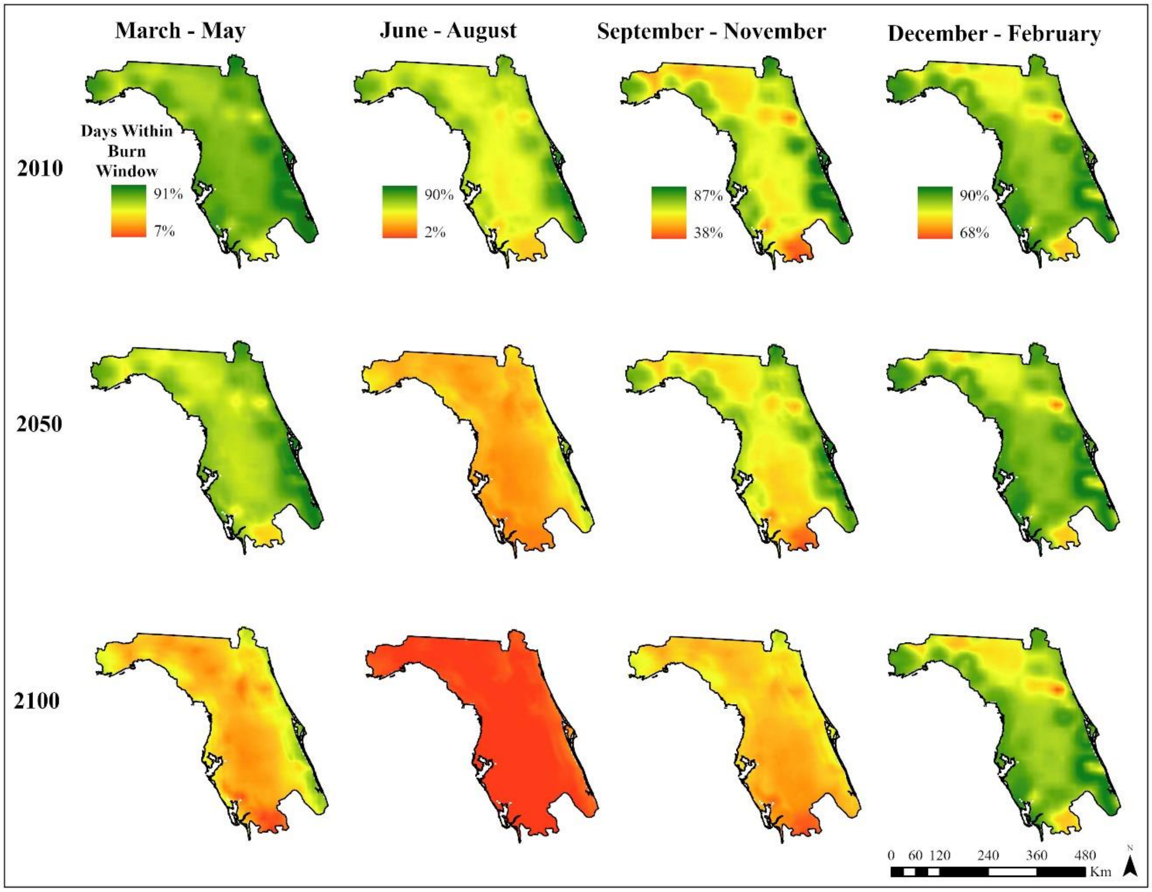

Figure 4.2 The percentage of days that fall within the prescription burn window under RCP 8.5 mapped across the Florida flatwoods pyrome. Results are displayed seasonally and for the baseline (2010), the mid-century (2050), and the end of the century (2100).

4.4 CHANGES IN WILDFIRE LIKLIHOOD

A change in the probability of wildfires in the Florida flatwoods pyrome has implications for the frequency of longleaf pine exposure to fire and for the decisions of burn managers. For example, an increase in wildfire likelihood may support the implementation of more frequent prescribed burning to combat the accumulation of fuels and prevent the spread of uncontrolled fire. Under historical climate conditions (1979-2005), the average wildfire burn probability for longleaf pine patches in the FFP is 0.00329, interpreted as approximately 3.29 fires for every thousand years. Note that the burn probability produced by the FSim model is lower than the widely accepted pre-colonial burn probability of one fire every 1-5 years (cf. Frost 2006, Oswalt et al. 2012, Platt et al. 1988) because FSim was calibrated using large fires which are rare occurrences in the southeastern United States.

The average burn probability increased into the mid-century, though to a small degree (Table 4.6). Under historical conditions, more than half (57.51%) of longleaf pine acreage had a wildfire probability between 0 and 0.003. However, by the mid-century, just under half of the longleaf pine had a burn probability between 0 and 0.003. The distribution of burn probability across the longleaf pine acreage shifted toward higher burn probabilities with maximum burn probability reaching 0.0283 or 2.8 fires for every 283 fires for every 1000 years.

Table 4.6 Wildfire Probability of Longleaf Pine Patches Modeled for Historic and Future Conditions

Wildfire Probability of Longleaf Pine Patches		
	Historic (1979-2005)	**Future (2040-2069)**
Mean	0.003287	0.003863
Min	0.000087	0.000153
Max	0.022744	0.028389
Hectares of Longleaf Pine Within a Given Burn Probability Range		
0 - 0.003	293,572 (57.51%)	251,980 (49.36%)
0.003 - 0.006	123,901 (24.27%)	143,512 (28.11%)
0.006 - 0.009	43,014 (8.43%)	38,348 (7.51%)
0.009 - 0.012	14,614 (2.86%)	29,835 (5.84%)
0.012 - 0.015	14,296 (2.80%)	14,410 (2.82%)
0.015 - 0.018	10,216 (2.00%)	11,243 (2.20%)
0.018 - 0.021	4,036 (0.79%)	4,179 (0.82%)

0.021 - 0.024	6,854 (1.34%)	7,175 (1.41%)
0.024 - 0.027	0 (0.00%)	9,355 (1.83%)
0.027 - 0.03	0 (0.00%)	466 (0.09%)

4.5 CHANGES AT THE LOCAL SCALE

Observed and analyzed separately, urbanization, the number of suitable days for prescribed burning, and wildfire probability are all projected to change over the course of the 21st century in ways that have implications for the future condition and management of longleaf pine in the Florida flatwoods pyrome. Though modeled separately, changes in each variable will have a cumulative impact on longleaf pine patches. The accumulation of threats is particularly apparent at the local-level where longleaf pine management is most likely to take place. To demonstrate, I selected three locations to serve as case studies for the modeled changes in urbanization, burn window, and wildfire likelihood: an area centered on Camp Blanding Joint Training Center (Site A), an area located in the outskirts of Orlando near Hal Scott Preserve (Site B), and an area located near Englewood and Myakka State Forest (Site C) (Figure 4.2). Each site features a combination of protected and unprotected longleaf.

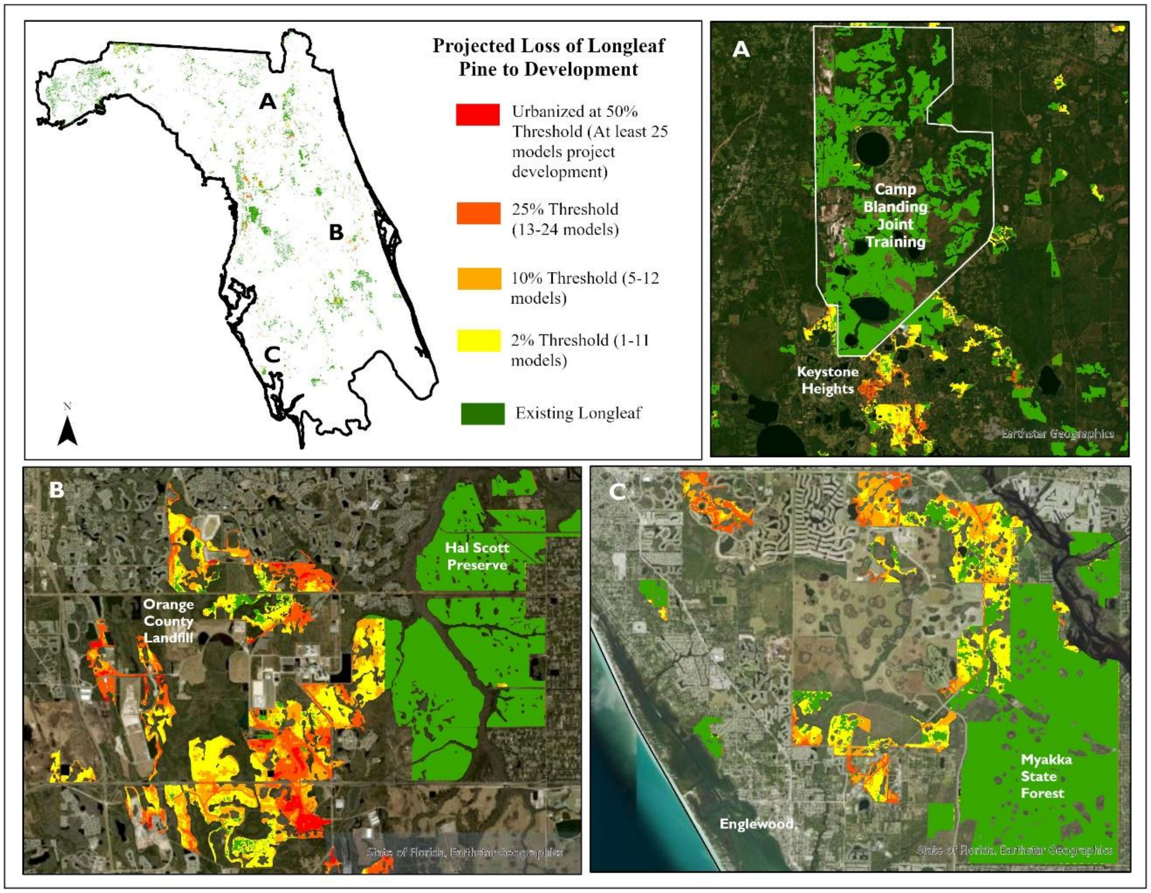

Figure 4.2 Projected Loss of Longleaf Pine to Urban Growth across the Florida flatwoods pyrome and local-scale sites (panels A-C). Site locations are denoted by their corresponding letter on the broader scale pyrome map.

Table 4.7 Comparison of Longleaf Pine-Relevant Variables at Each Case Study Site

Direct Loss of Longleaf Pine (Ha)				
Threshold	**Year**	**A**	**B**	**C**
Total Longleaf Pine Area Before Loss	2019	19,068	4,997	4,459
50%	2050	0 (0.0%)	18.8 (0.3%)	0 (0.0%)
	2100	1.44 (0.0%)	124.2 (2.5%)	0 (0.0%)
25%	2050	592.8 (3.1%)	453.3 (9.1%)	159.5 (3.6%)
	2100	622.0 (3.3%)	745.8 (14.9%)	218.4 (4.9%)
10%	2050	729.0 (3.8%)	1,011.2 (20.2%)	356.1 (7.9%)
	2100	913.6 (4.8%)	1,413.6 (28.3%)	596.8 (13.4%)

2%	2050	2,438.8 (12.8%)	2,027.2 (40.6%)	1,065.5 (23.9%)
	2100	2,891.5 (15.2%)	2,230.8 (44.6%)	1,171.7 (26.3%)
Percentage of Days that Fall into the Burn Window				
Season	**Year**	**A**	**B**	**C**
Season 1 (Mar – May)	2019	80%	80%	84%
	2050	80%	80%	84%
	2100	67%	67%	71%
Season 2 (Jun - Aug)	2019	56%	58%	60%
	2050	31%	33%	27%
	2100	8%	7%	4%
Season 3 (Sept – Nov)	2019	77%	78%	81%
	2050	72%	70%	70%
	2100	58%	53%	52%
Season 4 (Dec – Feb)	2019	82%	84%	88%
	2050	84%	85%	88%
	2100	82%	84%	88%
Wildfire Probability				
Time Period	**Year**	**A**	**B**	**C**
Historical Baseline	1979 - 2005	0.00224	0.00626	0.00472
Future	2040 - 2069	0.00270	0.00744	0.00569

Site A, located southwest of Jacksonville and about 65 km inland of the coast, includes the largest amount of longleaf pine of the three study areas, most of which is located within Camp Blanding Joint Training Center. The fragmented, but large swath of longleaf pine within the training center remains protected in all urbanization scenarios while adjacent, unprotected longleaf pine stands are at risk of conversion to developed land. The training center thus provides a core area of longleaf pine that can be expected to persist while urban expansion just outside of the military installation would likely reduce overall connectivity of the forest. The importance of the military base in conserving longleaf pine ecosystems in the area is clear as, without such protections, urban growth poses a threat to much of the longleaf pine present in the area. Likewise, of the three sites, Site A has the lowest percentage of direct loss of longleaf pine (Table 4.7). Less than 5% of the total longleaf pine acreage is lost by 2100 at all urbanization thresholds of 10% or higher. At the least restrictive (2%) urbanization threshold, 15% of the longleaf pine is lost (areas in yellow in Figure 4.2), revealing further at-risk longleaf pine, albeit, with a lower confidence in that risk. Such loss is by no means insignificant, but the presence of the military base with a large proportion of the area under protections ensures longleaf pine persistence. Given the lower risk of direct loss, managers in the area might focus their attention on restrictions on prescribed burning driven by encroachment of urban land cover and climate change-induced reduction in the number of suitable burn days.

The greatest degree of agreement between urbanization model runs occurred outside of major urban centers where non-compact, sprawling urban land cover is common. Such high agreement between model runs indicates high likelihood of urbanization or higher risk of longleaf pine loss. Site B, located on the outskirts of Orlando in Orange County, exemplifies such a situation. Longleaf pine in the area is afforded some protection in Hal Scott Preserve but a large amount of the acreage exists under private ownership, surrounded by encroaching developed area. At the least restrictive urbanization threshold, nearly half (44.6%) of all longleaf pine acreage in Site B is lost by 2100. More restrictive thresholds (10% and 25%) indicate similarly large proportions of longleaf pine loss by 2100 (28.3% and 14.9%). Risk of loss due to urbanization is, in this case, the greatest threat to longleaf pine in this area. Reduction in the number of days that fall into the prescription burn window that makes burning entirely unsafe during the summer months and unreliable in the transitional months (March - May and September - November) exacerbate the situation. Limitations on prescribed burning caused by warmer, drier climate change conditions and the encroachment of urban areas could strain management and result in degradation of any longleaf pine that is not directly lost due to conversion to developed land cover. Additionally, the probability of wildfires in Site B is above the average for longleaf pine in the FFP and is expected to increase into the mid-century. This further supports the need for prescribed burning to limit wildfire potential. Threats to longleaf pine in Site B accumulate with consideration of each variable suggesting that the likelihood of persistence of healthy longleaf pine in Site B is tenuous.

Site C, located on the Gulf coast abutting the suburb of Englewood demonstrates a geographic and conservation circumstance largely unique to Florida. A large protected area of longleaf pine, Myakka State Forest, and the adjacent undeveloped wetland are surrounded by high-value suburban housing near several golf courses and clubs advertised for their natural beauty and proximity to wildlife (Myakka Pines Golf Club 2018, Sarasota National 2023). The unfragmented swath of longleaf pine in Myakka State Forest (perforated by small wetland depressions) will persist into the late century given its protections. However, conservation plans for the state forest already express the extreme care needed to undergo safe prescribed burning and maintain air quality standards in the area given its proximity to urban land (Florida DOACS Division of Forestry 2010). Urban growth, reduction in the number of suitable burn days, and increase in wildfire probability all indicate increased difficulty in fire management beyond the already existing challenges. Urbanization is expected to fill in along existing roads and neighborhoods in the area, including areas directly adjacent to the borders of Myakka State Forest. Closer to Myakka State Forest, confidence in the likelihood of urbanization declines, with the majority of longleaf pine projected to be lost near the state forest only occurring at the least restrictive threshold of 2%. As with the entire pyrome, the summer is expected to be unsuitable for prescribed burning by 2100. When compared with the other two sites of interest, Site C has slightly higher opportunity for burning in the winter (Dec - Feb) and spring (March - May). This pattern exists at the baseline and into the mid and late 21st century. While longleaf pine is projected to be lost with moderately high confidence near areas of existing suburban housing and golf courses, the presence of the protected state forest and difficult to develop wetland to its west appear to lower the risk of longleaf pine loss. Encroaching development and climate-change induced changes to the fire regime and burn window will likely exacerbate the difficulty of prescribed burning for managers in the area.

CHAPTER 5

DISCUSSION

Results of this study suggest that projected changes in urbanization, climate, and the fire regime have the potential to impact longleaf pine ecosystems in the Florida flatwoods pyrome at several scales. At the broad, pyrome-wide scale, changes in longleaf-pine relevant variables are visible in the form of increasing urban growth, reductions in the number of days that fall into the burn window, and increases in wildfire burn probability and can indicate general concern for the future of longleaf pine from which recommendations can be made for its management. Results can be used to justify advocating for increased land protections for longleaf pine and expansion of funding and research on burn management given a future of greater need for prescribed burning amidst increasing limitations on burn opportunities and increased wildfire risk. Yet changes in these variables are not uniform across space. On the local level where most longleaf pine management occurs, important variation arises with different implications for management action in the future as demonstrated by the variation in the site-specific case studies above (Figure 4.2). These findings demonstrate the advantages of multi-scale analysis, work that is increasingly possible with improved capacity of geographic information systems and contribute to the abundant literature on multi-scale conservation management (Costanza et al. 2011, Felton et al. 2020, Gonthier et al. 2014, Razgour et al. 2011).

5.1 COMBINING INDEPENDENT MODELS: CHALLENGES AND INSIGHTS

Clear trends in each variable, urbanization, burn window, and wildfire probability, were visible when overlaid with longleaf pine stands, allowing for conclusions to be drawn about the future of longleaf pine management. However, conclusions must be considered tentative and understood with the high degree of uncertainty involved in the modeling process. Documented bias exists for each dataset and error in each dataset was compounded when attempting to determine their spatial relationships to one another. Communication of error, bias, and uncertainty to managers who make use of the results of such analyses is critical. However, communication of technical sources of error may be challenging if the user is not personally working with the data. Considering the cumulative results of independently created models also has considerable limitations. For example, the probability that a wildfire occurs is likely dependent on urban expansion. If urban expansion is very severe with much forested land cover converted to developed land cover, wildfires would likely not spread as easily, affecting the results. Yet the wildfire model outputs used in this study were not dependent on the changes projected by the FUTURES urbanization model.

Moreover, the combination of models designed to be used independently made it difficult to determine which dataset was the source of error, particularly given unfamiliarity with a study site or data sources. For example, at a broad scale it was difficult to determine whether overlap between longleaf pine and urbanization in the baseline was a product of misclassification of longleaf pine in the LPEGDB or misclassification of developed land cover in the NLCD, FUTURES, or Florida 2070 baselines. In many cases, the boundaries of a particular longleaf pine patch in the

LPEGDB may have been oversimplified and included developed area. Likewise, an urbanization dataset may have misclassified an area as developed when it is not truly developed. The challenge of quantifying confounding variables may result in biased conclusions about the degree of urban growth and its relationship to longleaf pine. However, at a local scale, it became easier to assess accuracy and correct or quantify data error, suggesting that the usage of such datasets may be most appropriate at the local scale and when the user has a strong knowledge of a particular area.

When attempting to combine multiple independent models and project them into the future, misalignment of the time frames of the models and the error inherent in modeling 25 to 75 years into the future can produce additional difficulty in interpretation of results. The burn window model and wildfire probability model provided output using different GCMs. By using the average of multiple GCMs and the same climate change scenario (RCP 8.5), some variability was accounted for. The wildfire model output from FSim, in particular, is a very recent dataset so results should be interpreted with care. The FSim data used here are preliminary outputs that are a part of an ongoing project to apply FSim to the Florida flatwoods pyrome by Dr. Peng Gao at the University of North Carolina -Wilmington. Bias results and accumulates when applied to longleaf pine patches.

Likewise, the future of urban growth is complex and difficult to model (Meentemeyer et al. 2013, Terando et al. 2014). Urbanization baselines varied between different datasets, affecting future projections of urban expansion (Table 4.2). Incorporating multiple urbanization models into the analysis allowed for comparison between possible scenarios of change in urban growth. While only two urbanization models were used, FUTURES and Florida 2070, this study supports the advantage of considering multiple urbanization models when projecting far forward into the future. The use of urbanization thresholds in the FUTURES model in particular allowed us to benefit from the model's stochasticity by identifying areas of agreement between model runs, indicating high probability of urbanization. While areas of model agreement were of significant interest, lower urbanization thresholds also captured additional longleaf pine at some degree of risk, limiting the potential for underestimation of loss due to urbanization. For the purposes of conservation management, erring on the side of overestimation of urbanization may be desirable as longleaf pine managers may be concerned with any degree of risk to longleaf from urban expansion. Projecting future urbanization and its risk to longleaf pine at the pyrome-scale provided insight into the severity of future longleaf pine loss, both at more and less conservative urbanization thresholds. Scaling down to the local level reveals site-specific urban growth patterns that may serve to guide the attention of conservation managers to particular areas at risk of loss.

Lastly, this study is limited by its exclusive consideration of longleaf pine loss. The accumulation of longleaf pine loss and degradation through the cumulative layering of each independent model presents a bleak outcome for longleaf pine without the protective and conservationist actions and plans currently being undertaken and developed by federal, local, and state governments, non-governmental organizations (NGOs) and private institutions. Florida, especially, has a robust action plan for longleaf pine management that goes unrepresented in the modeling efforts of this study (Florida Forest Service 2020). America's Longleaf Restoration Initiative has mobilized efforts to increase the extent of longleaf pine through restoration and improve degraded ecosystems by restoring fire regimes (ALRI 2009). These efforts have already begun to offset loss of longleaf pine acreage throughout its range and are projected to continue in the future (Ballinger et al. 2020). In Florida, approximately 6,780 hectares of longleaf pine were established between 2009 and 2020 as reported by ALRI (Ballinger et al. 2020). Increases in the amount of prescribed burning have been observed in the last several years which is not accounted for in this study (Melvin 2018, Melvin 2020). Likewise, additional land protections through mechanisms such as conservation easements will likely prevent new longleaf pine patches from future urbanization. Florida Forever and the Florida Natural Areas Inventory have developed priority lists for establishing land protections, many of which may be realized into the coming years, offsetting longleaf pine loss (FNAI 2010, FNAI 2018, FNAI 2020).

5.2 CONCLUSIONS AND FUTURE DIRECTIONS

Predictive modeling for the future of longleaf pine management requires simplification of a great deal of complexity given the many variables dictating longleaf pine persistence, narrowed in this study to urbanization, the burn window, and wildfire probability. Consideration of the cumulative effects of changes in multiple variables is desirable as longleaf pine managers must contend with a host of interacting threats to the persistence of longleaf pine. Spatial variation in the severity of changes to each longleaf pine-relevant variable necessitates the use of geospatial analysis to identify broad pyrome-wide trends while capturing individual, local-level concerns. However, the uncertainty of projection into the distant future combined with the error inherent in the modeling process make such endeavors difficult with results that carry numerous caveats and considerable potential for misinterpretation. Such uncertainty may be untenable when the purpose of modeling is actionable management with financial costs and direct consequences on longleaf pine persistence. Despite the realities of uncertainty, the results of the analyses discussed above paint a concerning picture for the future of longleaf pine and its management with great threat of loss due to urban growth and degradation due to fire regime changes. These results support the abundance of literature calling for increased protections and resource allocation for longleaf pine conservation management in order to prevent rapid declines in longleaf pine into the mid to late 21st century (ALRI 2009, Costanza et al. 2015, Kirkman and Mitchell 2006, Van Lear et al. 2005).

In spite of the above concerns, the possibilities for improvements in modeling for conservation management purposes are many. The creation of integrative models, for example, a wildfire model dependent on changes in urban land cover, or a suitability model where the relative importance of each variable is assessed by experts and ranked, may produce novel outcomes useful for conservation managers. Dr. Peng Gao is exploring such an integrative model by using the urbanization results of the FUTURES model as the input for the FSim model, results of which may be available in the near future. Though time consuming, studies using different climate change scenarios, an expanded number of GCMs, and more urbanization datasets and scenarios may account for the high degree of variability in scenarios of change for longleaf pine. Quantification of the accuracy of each variable of interest may also simplify decision making when selecting models and improve communication of possible errors to managers.

Interpretation of the results of this study would benefit greatly from examination by local conservation management experts who could verify or dispute the legitimacy of the results based on experience with the study area. Uncertainties in the modeling process are many, but the expertise and local knowledge of conservation managers would likely alleviate some of these concerns and enable usage of the results to justify future changes to longleaf pine management. GIS-based modeling studies produced in collaboration with subject-experts and experienced managers offer a practicable way of harnessing spatial technologies and techniques to support conservation management.

REFERENCES

1000 Friends of Florida, UF GeoPlan Center, & Florida Department of Agriculture. (2017). *Special Report: What is Your Vision for Florida's Future?* www.1000friendsofflorida.org/Florida2070.

ALRI (America's Longleaf Restoration Initiative). (2009). *Range-Wide Conservation Plan for Longleaf Pine*. www.americaslongleaf.org

Ballinger, R., Crate, S., Hertz, S., & Jones, K. (2020). *America's Longleaf Restoration Initiative 2020 range-wide accomplishments*. https://americaslongleaf.org/media/zelc21dp/2020-alri-accomplishment-report-final.pdf.

Beckage, B., Gross, L., & Platt, W. (2006). Modelling Responses of Pine Savannas to Climate Change and Large-Scale Disturbance. *Applied Vegetation Science*, 75–82. https://www.jstor.org/stable/4620464.

Brockway, D. G., Outcalt, K. W., Tomczak, D. J., & Johnson, E. E. (2005). Restoration of Longleaf Pine Ecosystems. Gen. Tech. Rep. SRS-83. Asheville, NC: U.S. Department of Agriculture, Forest Service, Southern Research Station. 34 p., 083. https://www.srs.fs.usda.gov/pubs/20672

Brudvig, L. A., Turley, N. E., Bartel, S. L., Bell-Dereske, L., Breland, S., Damschen, E. I., Evans, S. E., Gibbs, J., Hahn, P. G., Isaacs, R., Ledvina, J. A., Orrock, J. L., Sorenson, Q. M., & Stuhler, J. D. (2021). Large ecosystem-scale effects of restoration fail to mitigate impacts of land-use legacies in longleaf pine savannas. *PNAS*, *118*(17). https://doi.org/10.1073/pnas.2020935118/-/DCSupplemental

Carr, M. H., & Zwick, P. D. (2016). *Geoplan Center at the University of Florida*. 41. https://1000friendsofflorida.org/florida2070/wp-content/uploads/2016/09/florida2070technicalreportfinal.pdf

Clark, K. E., Chin, E., Peterson, M. N., Lackstrom, K., Dow, K., Foster, M., & Cubbage, F. (2018). Evaluating Climate Change Planning for Longleaf Pine Ecosystems in the Southeast United States. *JSAFWA Journal of the Southeastern Association of Fish and Wildlife Agencies*, *5*, 160–168. https://seafwa.org/sites/default/files/journal-articles/J5_22Clarketal151-168.pdf.

Costanza, J., & Moody, A. (2011). Deciding Where to Burn: Stakeholder Priorities for Prescribed Burning of a Fire-Dependent Ecosystem. *Ecology and Society*, *16*(1). https://doi.org/10.5751/ES-03897-160114

Costanza, J. K., Moody, A., & Peet, R. K. (2011). Multi-scale environmental heterogeneity as a predictor of plant species richness. *Landscape Ecology*, *26*(6), 851–864. https://doi.org/10.1007/s10980-011-9613-3

Costanza, J. K., Terando, A. J., McKerrow, A. J., & Collazo, J. A. (2015). Modeling climate change, urbanization, and fire effects on *Pinus palustris* ecosystems of the southeastern U.S. *Journal of Environmental Management*, *151*, 186–199. https://doi.org/10.1016/j.jenvman.2014.12.032

Costanza, J. K., Weiss, J., & Moody, A. (2013). Examining the knowing-doing gap in the conservation of a fire-dependent ecosystem. *Biological Conservation*, *158*, 107–115. https://doi.org/10.1016/j.biocon.2012.08.025

Davis, A. G., Cox, J. J., & Fei, S. (2021). Alternative 2070: Mitigating the effects of projected sea level rise and urbanization on Florida black bear and Florida panther habitat. *Journal for Nature Conservation*, *63*, 126052. https://doi.org/10.1016/j.jnc.2021.126052

Dewitz, J. (2019). *National Land Cover Database (NLCD) 2019 Land Cover Science Product (ver. 2.0, June 2021) | USGS Science Data Catalog*. Retrieved March 6, 2023, from https://data.usgs.gov/datacatalog/data/USGS:60cb3da7d34e86b938a30cb9

Fahrig, L. (2003). Effects of Habitat Fragmentation on Biodiversity. *Annual Review of Ecology, Evolution, and Systematics*, *34*, 487–515. https://doi.org/10.1146/annurev.ecolsys.34.011802.132419

Finney, M. A., McHugh, C. W., Grenfell, I. C., Riley, K. L., & Short, K. C. (2011). A simulation of probabilistic wildfire risk components for the continental United States. *Stochastic Environmental Research and Risk Assessment*, *25*(7), 973–1000. https://doi.org/10.1007/s00477-011-0462-z

Felton, A., Löfroth, T., Angelstam, P., Gustafsson, L., Hjältén, J., Felton, A. M., Simonsson, P., Dahlberg, A., Lindbladh, M., Svensson, J., Nilsson, U., Lodin, I., Hedwall, P. O., Sténs, A., Lämås, T., Brunet, J., Kalén, C., Kriström, B., Gemmel, P., & Ranius, T. (2020). Keeping pace with forestry: Multi-scale conservation in a changing production forest matrix. *Ambio*, *49*(5), 1050–1064. https://doi.org/10.1007/s13280-019-01248-0

Florida Department of Agriculture and Consumer Services Division of Forestry. (2010). *Ten Year Resource Management Plan for the Myakka State Forest*. https://www.fdacs.gov/content/download/4929/file/MYAKKA%2520FINAL%2520 2010%2520PLAN.pdf

Florida Forest Service. (2020). *Florida's Forest Action Plan 2020 Update*. Florida Forest Service, Florida Department of Agriculture and Consumer Services. https://www.fdacs.gov/ezs3download/download/96038/2641743/Media/Files/Florida -Forest-Service-Files/Florida-Forest-Action-Plan-2020-Update.pdf

Florida Forest Service & Florida Natural Areas Inventory. (2018). *Longleaf Pine Ecosystem Geodatabase v.4 Final Report*. https://www.fnai.org/PDFs/LPEGDB_v4_Final_Report_Sep2018_revFeb2019.pdf.

Florida Natural Areas Inventory (FNAI). (2010). *Florida Forever Conservation Needs Assessment*. Division of State Lands, Florida Department of Environmental Protection artment of Environmental Protection. https://www.fnai.org/PDFs/FFCNA_Summary_Report.pdf

Florida Natural Areas Inventory (FNAI). (2020). *Florida Forever Conservation Needs Assessment Overview Maps*. https://www.fnai.org/PDFs/FF_Needs_Assessment_Overview_Maps_Nov2020.pdf

Florida Natural Areas Inventory (FNAI). (2022). *Southeast Longleaf Pine Ecosystem Occurrences Geodatabase: Phase 1 Final Report to the U.S. Endowment for Forestry and Communities*. https://www.fnai.org/PDFs/SE_LEO_GDB_Phase_I_Final_Report.pdf

Foster, M., Peterson, M. N., Cubbage, F., & McMahon, G. (2019). Evaluating natural resource planning for longleaf pine ecosystems in the Southeast United States. *Forest Policy and Economics*, *100*, 142–153. https://doi.org/10.1016/j.forpol.2018.11.008

Frost, C. (2006). History and Future of the Longleaf Pine Ecosystem. In J. Shibu, E. Jokela, & D. Miller (Eds.), *The Longleaf Pine Ecosystem: Ecology, Silviculture, and Restoration* (pp. 9–42). Springer. https://link.springer.com/book/10.1007/978-0-387-30687-2

Glitzenstein, J. S., Streng, D. R., & Wade, D. D. (2003). Fire Frequency Effects on Longleaf Pine (Pinus palustris P. Miller) Vegetation in South Carolina and Northeast Florida, USA. Natural Areas Journal. 23 (1): 22-37. 2003. https://www.fs.usda.gov/research/treesearch/5266

Grand, J. B., & Kleiner, K. J. (2016). *Prioritizing Landscapes For Longleaf Pine Conservation*. http://www.usgs.gov/usgs-manual/500/502-3.html

Gonthier, D. J., Ennis, K. K., Farinas, S., Hsieh, H.-Y., Iverson, A. L., Batáry, P., Rudolphi, J., Tscharntke, T., Cardinale, B. J., & Perfecto, I. (2014). Biodiversity conservation in agriculture requires a multi-scale approach. *Proceedings of the Royal Society B: Biological Sciences*, *281*(1791), 20141358. https://doi.org/10.1098/rspb.2014.1358

Hawbaker, T. J., Radeloff, V. C., Stewart, S. I., Hammer, R. B., Keuler, N. S., & Clayton, M. K. (2013). Human and biophysical influences on fire occurrence in the United States. *Ecological Applications*, *23*(3), 565–582. https://doi.org/10.1890/12-1816.1

Healthy Forests Restoration Act of 2003, no. 108–148, Congress (2003). https://www.govinfo.gov/content/pkg/COMPS-1123/pdf/COMPS-1123.pdf

Heuberger, K. A., & Putz, F. E. (2003). Fire in the Suburbs: Ecological Impacts of Prescribed Fire in Small Remnants of Longleaf Pine (*Pinus palustris*) Sandhill. *Restoration Ecology*, *11*(1), 72–81. https://doi.org/10.1046/J.1526-100X.2003.09982.X

Hopke, J. E. (2020). Connecting Extreme Heat Events to Climate Change: Media Coverage of Heat Waves and Wildfires. *Environmental Communication*, *14*(4), 492–508. https://doi.org/10.1080/17524032.2019.1687537

Johnsen, K. H., Butnor, J. R., Kush, J. S., Schmidtling, R. C., & Nelson, C. D. (2009). Hurricane Katrina winds damaged longleaf pine less than loblolly pine. *Southern Journal of Applied Forestry*, *33*(4), 178–181. https://doi.org/10.1093/sjaf/33.4.178

Jose, S., Jokela, E. J., Miller, D. L., & Jokela, J. (2006). *The Longleaf Pine Ecosystem Ecology, Silviculture, and Restoration*. Springer. https://link.springer.com/book/10.1007/978-0-387-30687-2

Jin, S., Homer, C., Yang, L., Danielson, P., Dewitz, J., Li, C., Zhu, Z., Xian, G., & Howard, D. (2019). Overall Methodology Design for the United States National Land Cover Database 2016 Products. *Remote Sensing*, *11*(24), Article 24. https://doi.org/10.3390/rs11242971

Kirkman, L. K., & Mitchell, R. J. (2006). Conservation Management of *Pinus palustris* Ecosystems from a Landscape Perspective. *Source: Applied Vegetation Science*, *9*(1), 67–74. https://www.jstor.org/stable/4620463

Kobziar, L. N., Godwin, D., Taylor, L., & Watts, A. C. (2015). Perspectives on Trends, Effectiveness, and Impediments to Prescribed Burning in the Southern U.S. *Forests*, *6*(3), Article 3. https://doi.org/10.3390/f6030561

Koo, J. (2010). *Predicting Global Climate Change Impacts on Longleaf Pine (Pinus palustris) Distribution*. https://getd.libs.uga.edu/pdfs/koo_jeeyen_201008_ms.pdf

Kupfer, J. A., Lackstrom, K., Grego, J. M., Dow, K., Terando, A. J., & Hiers, J. K. (2022). Prescribed fire in longleaf pine ecosystems: Fire managers' perspectives on priorities, constraints, and future prospects. *Fire Ecology*, *18*(1), 27. https://doi.org/10.1186/s42408-022-00151-6

Kupfer, J. A., Terando, A. J., Gao, P., Teske, C., & Hiers, J. K. (2020). Climate change projected to reduce prescribed burning opportunities in the south-eastern United States. *International Journal of Wildland Fire*, *29*(9), 764–778. https://doi.org/10.1071/WF19198

Kupfer, J., Terando, A. J., Gao, P., & Tirpak, B. E. (2021). *Historical and Future Prescribed Burn Windows for the Southeast United States* [Data set]. U.S. Geological Survey. https://doi.org/10.5066/P95BV7GE

Lee, D., Quigley, T., & National Science and Analysis Team. (2014). *The National Strategy: The Final Phase in the Development of the National Cohesive Wildland Fire Management Strategy*. Department of the Interior and Department of Agriculture. https://www.forestsandrangelands.gov/documents/strategy/strategy/CSPhaseIIINationalStrategyApr2014.pdf

Liu, Y., Goodrick, S. L., & Stanturf, J. A. (2013). Future U.S. wildfire potential trends projected using a dynamically downscaled climate change scenario. *Forest Ecology and Management*, *294*, 120–135. https://doi.org/10.1016/j.foreco.2012.06.049

McIntyre, R. K., Guldin, J. M., Ettel, T., Ware, C., & Jones, K. (2018). Restoration of longleaf pine in the southern United States: A status report. *In: Kirschman, Julia E., Comp. Proceedings of the 19th Biennial Southern Silvicultural Research Conference; 2017 March 14-16; Blacksburg, VA. e-Gen. Tech. Rep. SRS-234. Asheville, NC: U.S. Department of Agriculture, Forest Service, Southern Research Station*, *2018*, 297–302. http://www.fs.usda.gov/treesearch/pubs/56973

Meentemeyer, R. K., Tang, W., Dorning, M. A., Vogler, J. B., Cunniffe, N. J., & Shoemaker, D. A. (2013). FUTURES: Multilevel Simulations of Emerging Urban–Rural Landscape Structure Using a Stochastic Patch-Growing Algorithm. *Annals of the Association of American Geographers*, *103*(4), 785–807. https://doi.org/10.1080/00045608.2012.707591

Melvin, M. A. (2018). *2018 National Prescribed Fire Use Survey Report*. National Association of State Foresters and the Coalition of Prescribed Fire Councils Inc. https://www.stateforesters.org/wp-content/uploads/2018/12/2018-Prescribed-Fire-Use-Survey-Report-1.pdf

Melvin, M. A. (2020). *2020 National Prescribed Fire Use Report*. National Association of State Foresters and the Coalition of Prescribed Fire Councils Inc. https://www.stateforesters.org/wp-content/uploads/2020/12/2020-Prescribed-Fire-Use-Report.pdf

McKenzie, D., & Littell, J. S. (2017). Climate change and the eco-hydrology of fire: Will area burned increase in a warming western USA? *Ecological Applications. 2017. 27(1): 26-36.*, *27*(1), 26–36. https://doi.org/10.1002/eap.1420

Myakka Pines Golf Club Intro Video. (2018, August 11). Myakka Pines Golf Club - About Us. https://www.myakkapinesgolfclub.com/intro-video/

Oswalt, C., & Guldin, J. M. (2021). *Status of Longleaf Pine in the South: An FIA Update*. https://www.srs.fs.usda.gov/pubs/gtr/gtr_srs2021.pdf

Oswalt, C. M., Cooper, J. A., Brockway, D. G., Brooks, H. W., Walker, J. L., Connor, K. F., Oswalt, S. N., & Conner, R. C. (2012). *History and Current Condition of Longleaf Pine in the Southern United States*. https://doi.org/10.2737/SRS-GTR-166

Outcalt, K. W., & Sheffield, R. M. (1996). *The Longleaf Pine Forest: Trends and Current Conditions*. https://www.srs.fs.usda.gov/pubs/rb/rb_srs009.pdf

Peet, R. K., & Allard, D. J. (1993). Longleaf Pine Vegetation of the Southern Atlantic and Eastern Gulf Coast Regions: A Preliminary Classification. *Proceedings of the Tall Timbers Fire Ecology Conference*. http://labs.bio.unc.edu/Peet/pubs/TTFEC-1993.pdf

Peters, M. P., Prasad, A. M., Matthews, S. N., & Iverson, L. R. (2020). *Tree Atlas—Climate Change Atlas—Northern Research Station, USDA Forest Service*. https://www.fs.fed.us/nrs/atlas/tree/

Platt, W. J., Evans, G. W., & Davis, M. M. (1988). Effects of Fire Season on Flowering of Forbs and Shrubs in Longleaf Pine Forests. *Oecologia*, *76*(3), 353–363.

Prestemon, J. P., Shankar, U., Xiu, A., Talgo, K., Yang, D., Dixon, E., Mckenzie, D., & Abt, K. L. (2016). Projecting wildfire area burned in the south-eastern United States, 2011-60. *International Journal of Wildland Fire*, *25*(7), 715–729. https://doi.org/10.1071/WF15124

Provencher, L., Herring, B. J., Gordon, D. R., Rodgers, H. L., Tanner, G. W., Hardesty, J. L., Brennan, L. A., & Litt, A. R. (2001). Longleaf pine and oak responses to hardwood reduction techniques in Fire-suppressed sandhills in northwest Florida. *Forest Ecology and Management*, *148*, 63–77. https://doi.org/10.1016/S0378-1127(00)00525-9

Radeloff, V. C., Helmers, D. P., Anu Kramer, H., Mockrin, M. H., Alexandre, P. M., Bar-Massada, A., Butsic, V., Hawbaker, T. J., Martinuzzi, S., Syphard, A. D., & Stewart, S. I. (2018). Rapid growth of the US wildland-urban interface raises wildfire risk. *Proceedings of the National Academy of Sciences of the United States of America*, *115*(13), 3314–3319. https://doi.org/10.1073/pnas.1718850115

Razgour, O., Hanmer, J., & Jones, G. (2011). Using multi-scale modelling to predict habitat suitability for species of conservation concern: The grey long-eared bat as a case study. *Biological Conservation*, *144*(12), 2922–2930. https://doi.org/10.1016/j.biocon.2011.08.010

Riley, K. L., Thompson, M. P., Scott, J. H., & Gilbertson-Day, J. W. (2018). A Model-Based Framework to Evaluate Alternative Wildfire Suppression Strategies. *Resources*, *7*(1), Article 1. https://doi.org/10.3390/resources7010004

Romañach, S. S., Benscoter, A. M., & Haider, S. M. (2020). Potential Impacts of Future Urbanization and Sea Level Rise on Florida's Natural Resources. *Journal of Fish and Wildlife Management*, *11*(1), 174–184. https://doi.org/10.3996/092019-JFWM-076

Rother, M. T., Huffman, J. M., Guiterman, C. H., Robertson, K. M., & Jones, N. (2020). A history of recurrent, low-severity fire without fire exclusion in southeastern pine savannas, USA. *Forest Ecology and Management*, *475*, 118406. https://doi.org/10.1016/j.foreco.2020.118406

Samuelson, L. J., Stokes, T. A., & Johnsen, K. H. (2012). Ecophysiological comparison of 50-year-old longleaf pine, slash pine and loblolly pine. *Forest Ecology and Management*, *274*, 108–115. https://doi.org/10.1016/j.foreco.2012.02.017

Sanchez, G. M., Terando, A., Smith, J. W., García, A. M., Wagner, C. R., & Meentemeyer, R. K. (2020). Forecasting water demand across a rapidly urbanizing region. *Science of The Total Environment*, *730*, 139050. https://doi.org/10.1016/j.scitotenv.2020.139050

Sarasota National Golf Club- Amenities. (2023). https://www.sarasotanationalgolf.com/Amenities

Short, K., Grenfell, I., Riley, K., & Vogler, K. (2020). *Pyromes of the Conterminous United States*. Forest Service Research Data. https://doi.org/10.2737/RDS-2020-0020

Simberloff, D. (1993). Species-Area and Fragmentation Effects on Old-Growth Forests: Prospects for Longleaf Pine Communities. *Proceedings of the Tall Timbers Ecology Conference*.

Stewart, S. I., Radeloff, V. C., Hammer, R. B., & Hawbaker, T. J. (2007). Defining the Wildland–Urban Interface. *Journal of Forestry*, *105*(4), 201–207. https://doi.org/10.1093/jof/105.4.201

Terando, A. J., Costanza, J., Belyea, C., Dunn, R. R., McKerrow, A., & Collazo, J. A. (2014). The Southern Megalopolis: Using the Past to Predict the Future of Urban Sprawl in the Southeast U.S. *PLOS ONE*, *9*(7), e102261. https://doi.org/10.1371/journal.pone.0102261

Van Berkel, D., Shashidharan, A., Mordecai, R. S., Vatsavai, R., Petrasova, A., Petras, V., Mitasova, H., Vogler, J. B., & Meentemeyer, R. K. (2019). Projecting Urbanization and Landscape Change at Large Scale Using the FUTURES Model. *Land*, *8*(10), Article 10. https://doi.org/10.3390/land8100144

Van Lear, D. H., Carroll, W. D., Kapeluck, P. R., & Johnson, R. (2005). History and restoration of the longleaf pine-grassland ecosystem: Implications for species at risk. *Forest Ecology and Management*, *211*(1–2), 150–165. https://doi.org/10.1016/J.FORECO.2005.02.014

Varner, J. M., Gordon, D. R., Putz, F. E., & Hiers, J. K. (2005). Restoring Fire to Long-Unburned *Pinus palustris* Ecosystems: Novel Fire Effects and Consequences for Long-Unburned Ecosystems. *Restoration Ecology*, *13*(3), 536–544. https://doi.org/10.1111/j.1526-100x.2005.00067.x

Vorhees, L. (2015). *Prioritizing Conservation Areas for Longleaf Pine Forests in North Carolina: A spatial analysis of 3 major threats (fire suppression, urbanization, and climate change)*. https://dukespace.lib.duke.edu/dspace/handle/10161/9691

Wade, D., & Mobley, H. (2007). Managing smoke at the wildland-urban interface. *Gen. Tech. Rep. SRS-103. Asheville, NC: U.S. Department of Agriculture, Forest Service, Southern Research Station. 28 p., 103*. https://doi.org/10.2737/SRS-GTR-103

Waldrop, T. A., & Goodrick, S. L. (2012). *Introduction to Prescribed Fire in Southern Ecosystems*. Government Printing Office. https://www.srs.fs.usda.gov/pubs/su/su_srs054.pdf

Walker, J. (1993). *Rare Vascular Plant Taxa Associated with the Longleaf Pine Ecosystems: Patterns in Taxonomy and Ecology*. https://talltimbers.org/wp-content/uploads/2014/03/Walker1993_op.pdf

Wickham, J., Stehman, S. V., Sorenson, D. G., Gass, L., & Dewitz, J. A. (2021). Thematic accuracy assessment of the NLCD 2016 land cover for the conterminous United States. *Remote Sensing of Environment*, *257*, 112357. https://doi.org/10.1016/j.rse.2021.112357

Williams, E. (2021). Reimagining Exceptional Events: Regulating Wildfires Through the Clean Air Act. *Washington Law Review*, *96*(2). https://digitalcommons.law.uw.edu/wlr

Zion, S. (2019). *The Right Tree, Right Now: Advantages, Values, and Benefits of Longleaf Pine (Pinus palustris) Ecosystem Management*. https://nau.edu/wp-content/uploads/sites/140/2019.SeanZionLongleafPineEcosystemManagement.pdf