THE RIGHT TREE, RIGHT NOW: ADVANTAGES, VALUES, AND BENEFITS OF LONGLEAF PINE (*PINUS PALUSTRIS)* ECOSYSTEM MANAGEMENT

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ABSTRACT

THE RIGHT TREE, RIGHT NOW: ADVANTAGES, VALUES, AND BENEFITS OF LONGLEAF PINE (*PINUS PALUSTRIS) ECOSYSTEM MANAGEMENT*

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Pinus palustris (longleaf pine) was once the dominant forest type in the southeastern United States. Over the course of the last century, longleaf pine forests have been reduced from 92 million acres to 3.2 million acres, significant efforts to restore 4.8 million acres by 2025 are underway. However, other pine species such as loblolly pine (*Pinus taeda*) and slash pine (*Pinus elliottii*) are still favored due to perceptions that longleaf pine has poor regeneration and slow growth. This review investigates the relationship of longleaf pine to climate change, carbon sequestration, disturbance resistance, biodiversity, and ecosystem services findings suggest that longleaf pine provides advantages, values, and benefits that could mitigate negative impacts inherent within each of the five major categories that this review investigates. Additional efforts to restore the current range and to improve natural resource management policies that favor the longleaf pine ecosystem are urgently needed.

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Introduction

Pinus palustris, commonly known as longleaf pine (Figure 1), found in the southeastern United States, once grew across 92 million acres, ranging from southern Virginia through central Florida and as far west as east Texas (Landers et al. 1995). Due to European colonization, conversion of forest land to agriculture, excessive commercial logging, centuries of fire suppression, urbanization, and misconceptions about its slow growth, longleaf pine has been reduced to three percent (or 3.2 million acres) of its historical range (Kelly and Bechtold 1990) (Figure 2). In its place, forests of loblolly pine (*Pinus taeda*) (Figure 3) and slash pine (*Pinus elliottii*) (Figure 4) were established in plantations on both, public and private lands (Zhang et al. 2010). This reduction and replacement ultimately led to the severe degradation of the ecosystem that evolved alongside longleaf pine (Jose et al. 2010).

Within this review, I highlight five environmental challenges and in turn, argue that longleaf pine is the most advantageous, valuable and beneficial tree species to overcome those challenges and improve forest ecosystem processes. This review focuses solely on longleaf pine and its (1) resistance to climate change, (2) capacity to sequester carbon, (3) disturbance resistance, (4) biodiversity of flora and fauna and, (5) value of ecosystem services provided. In the context of critical environmental challenges within our century, these will arguably be the most significant challenges for natural resource managers across the globe. However, this review specifically focuses on the southeastern United States. Restoring the longleaf pine ecosystem in this region requires changes to forest management and forest policies. The implications of restorations of longleaf pine woodlands, could reduce the impact of these environmental challenges and increase ecosystem resilience within the southeastern United

States. Overall, the values, advantages, and benefits of the longleaf pine ecosystem cannot be overstated and require further investigation, highlighted within this review.

A Review of the Literature

Although this review focuses on a specific region in the U.S., longleaf pine restoration may affect environmental and natural resource issues on a much larger scale. Climate profile models predict that even under a rapid emissions reduction scenario, the Midwest and the Northeast United States will likely see an increase in temperature of 3-5°F by 2099 (National Climate Assessment 2017) (Figure 5). Typical forest types within these regions will experience increased drought and heat stress, potentially increasing tree mortality (Allen et al. 2010). Additionally, tree species are expected to increase the likelihood of establishment in higher latitudes (Root et al. 2003). A warmer and drier climate in those regions could expand suitable longleaf pine habitat along the northern and western boundaries of its historical range (Koo 2007). Therefore, in addition to management implications within the Southeast, the potential increase of suitable longleaf pine habitat outlines the importance of this review for the Midwest and the Northeast United States.

Climate change and carbon sequestration share a close relationship. Carbon sequestered in living biomass, as well as wood products, reduces the amount of carbon released into the atmosphere (Kooten et al. 2002). Current plans from the National Resources Conservation Service (NRCS) to restore 1.6 million acres of longleaf pine forests by the year 2025 (USDA NCRS Longleaf Pine Restoration 2017) could potentially sequester an additional 2 million metric tons of carbon. Therefore, an overall change in forest management policy that promotes longleaf pine will only serve to sequester more carbon, further mitigating the effects of climate change (Canadell and Raupach 2008). Additionally, longleaf pine has exceptional wood quality that promotes high levels of carbon sequestration in commercial wood products (Meldahl and Kush 2006). Once used extensively for timber, utility poles, support beams, cabinetry, doors, and windows, the marked reduction in its range has limited its commercial use (Zhang et al. 2010). However, because it has a higher density than other southern pine species, more carbon is stored in longleaf pine wood products (USDA, Wood Handbook 2010). The high resistance to various disturbances also plays a role in the carbon sequestration of longleaf pine.

Whether through anthropogenic or natural causes, disturbances significantly influence forest type, structure, composition and can drastically alter ecosystem processes (Seidl et al. 2014). Within the southeastern U.S., five main disturbance regimes exist: southern pine beetle (*Dendroctonus frontalis*), fusiform rust (*Cronartium quercuum*), brown-spot needle blight caused by the fungus *Mycosphaerella dearnessii*, the windfall from hurricane events, and wildfires (Figure 6). Within each disturbance type, longleaf pine exhibits low fungal infection rates, low mortality rates, minimal blowdown and increased resistance to fire (Friedenberg et al. 2007; Schmidt 2003; Johnson et al. 2009; Boyer 1972). The research on the effects of climate change and humans on disturbance regimes suggests that the frequency, intensity, and severity of these events will likely increase (Dale et al. 2001). Longleaf pine reduces the risk of forest cover loss in the event these disturbances cause high rates of tree mortality (Slack et al. 2016, Martinson et al. 2007, Gresham et al. 1991). Increased longleaf pine restoration, in turn, should increase the ecosystem resistance and resilience to these damaging legacy disturbances.

Evidence shows that longleaf pine forests have high biodiversity, being rich and abundant in both animal and plant species. According to Landers et al. (2005), more than 30 federally endangered species depend on the longleaf pine ecosystem. Additionally, Sorrie et al. (2006) in their study of the vascular flora within a longleaf pine ecosystem in North Carolina found 143 families, 490 genera, and 1,206 rare species, of which~~,~~ 61 are federally endangered. Peet and Allard (1993) similarly documented 170 plant species in a 1000 square meter area of a North Carolina longleaf pine ecosystem. The sharp reduction of longleaf pine has had substantial adverse effects on critical wildlife and plant species (Lear et al. 2005). These varied and great numbers of living organisms are wholly dependent on the longleaf pine ecosystem. Increasing the acreage of longleaf pine forest could have a substantial, positive effect on biodiversity in the Southeast.

Climate change resistance, carbon sequestration, disturbance resistance, and biodiversity add considerable value to longleaf pine ecosystems. However, it is further bolstered by its outstanding wood quality and use in vital commercial wood products. Additionally, longleaf pine has considerable value for recreation. The vast array of wildlife promotes sustainable hunting, and an open understory (characteristic of a longleaf pine forest), and encourages running, hiking, mountain biking, and off-road vehicle use (Brockway et al. 2005). Adding the value of economic services provided through water resupply, groundwater recharge, pollination and aesthetics, the overall dollar amount estimate of ecosystem~~s~~ services provided by longleaf pine forests easily exceeds tens of billions of dollars (Platt 2012).

This review is the first of its kind to examine the connections to some of the most important environmental challenges of the 21st century and highlight how one tree species can help reduce the impact of their effects. Significant efforts from multiple government and non-governmental organizations, plan to restore the area of longleaf pine forest from 3.2 million to 4.8 million acres by 2025 (USDA, NCRS Longleaf Pine Restoration 2017). Since 2010, the National Resources Conservation Service has invested over $65 million in restoration efforts (USDA, NCRS Longleaf Pine Restoration 2017). The amount of restored longleaf pine forest and the amount of funds allocated, outline the extent and scale of the value placed upon longleaf pine. However, additional restoration efforts are needed to take advantage of this valuable tree.

This review highlights the key advantages of the longleaf pine ecosystem against the most significant environmental challenges we face today. Additionally, this review will provide substantial evidence of the effectiveness of longleaf pine to forest managers faced with the difficult challenges of managing forests in a changing climate. Arguably, this issue is the number one problem foresters will have to solve in the next century and longleaf pine may prove to be the right tree, right now.

Methods

I used Web of Science, CAB Abstracts, and Google Scholar to search for peer-reviewed scientific articles. I searched titles, abstracts, and keywords with no established date range. I conducted numerous searches utilizing various combinations of terms that included; "*Pinus palustris" OR* "longleaf pine", WITH "climate AND change", "carbon AND sequestration", "disturbance", "resistance", "fire", "pathogen", "wind", "bark AND beetle", "biodiversity" and "economic AND services". Resistance to disturbance was also broken down to include the major disturbance types of the southeast and was searched individually with "*Pinus palustris" OR* "longleaf pine."

To meet the scope of this review, I filtered the results for relevancy (rank orders articles that found the term searched in either the title, abstract, or keywords), the number of times cited and then selected all articles that fell within my major categories of interest. A total of 51 articles was identified that met the search criteria. Table 1 depicts the results and number of articles reviewed within each group.

Table 1. Search results from Web of Science, CAB Abstracts, and Google Scholar indicating the number of relevant articles within each major category of the review; climate change (CC), carbon sequestration (CS), disturbance resistance (DR), biodiversity (BD), and ecosystem services (ES). Articles that incorporated more than one category have been listed separately

CC	CS	DR	BD	ES	ES w/ CC	ES w/ CS	CC w/ CS	CC w/ DR
4	8	20	8	4	2	1	3	1

The Silvics and Developmental Pathway of Longleaf Pine

Understanding the supporting role longleaf pine plays in the resistance to climate change, capacity to promote carbon sequestration, disturbance resistance, maintenance or increase in biodiversity, and provision of ecosystem services provided, requires a baseline understanding of its growth, behavior, ecology, and developmental pathway. Additionally, because the geography, topography, climate, and soil types affect where and how longleaf pine grows and thrives, it is necessary to understand its environment.

The longleaf pine forest range is predominantly in the Atlantic and Gulf Coastal Plains from southern Virginia to eastern Texas, extending into south Florida (Boyer 1990) (Figure 2). However, the range also extends into the mountainous regions found in Alabama and Georgia, reaching elevations near 2,000 feet (Boyer 1990). The climate is hot, humid, and wet in the summer, with mild, relatively dry winters (Boyer and Peterson, 1990). Vast swaths of sandy soil exist within this region that is incredibly wet in months of high rainfall, and extremely dry in early summer months. Longleaf pine is tolerant of these fluctuations and grows well despite these extreme upper and lower limits of temperature and precipitation (Outcalt 2000). The soils within these regions have also been categorized as acidic, low in organic matter and relatively infertile (Boyer 1990).

Longleaf pine reaches reproductive maturity rather late, producing seed-bearing cones at approximately 30 years of age (Croker and Boyer 1975). Seeds typically germinate after 1 to 2 weeks and require bare mineral soil to establish (Croker and Boyer 1978). Longleaf pine has five stages of growth: the seedling stage/grass stage, bottlebrush stage, sapling stage, and mature stage (Boyer 1990) (Figure 7). During the seedling stage, it is most susceptible to fire, drought, and herbivory, and can take upwards to one year to reach, what is defined as the grass stage (Boyer 1990). However, it is important to note that during the grass stage, longleaf pine is still a seedling. In this grass stage, the tree exhibits exceptional resistance to fire because the bud is surrounded and protected by a tuft of needles. Also in this stage, longleaf pine places most of its resources into root growth, establishing a deep-seated taproot (Boyer 1990). The resources utilized in the grass stage to establish a well-developed root structure, significantly contribute to its wind--firm attributes. During this stage, it is most susceptible to mortality from competition and pathogens in the form of scrub-oaks and brown-spot needle blight, respectively (Boyer 1990).

Once the root collar reaches about 1 in. in diameter, the tree adds height and can easily reach 10 ft. in three years. This rapid upward growth is called “bolting”. At this point, the tree transitions from the grass stage to the bottlebrush stage (Boyer 1990). During this stage, the tree continues to add height, greater in proportion to diameter with no lateral branches, resembling a bottlebrush. The increase in height secures sunlight and ensures the height of the apical bud rapidly grows taller than the lethal heat of surface fires. It is not until the sapling stage that longleaf pine adds lateral branches. By this time, the canopy base height exceeds flame lengths associated with a low intensity, high-frequency fire regime (Platt 1991). Longleaf pine will remain in this stage for several years. It is during this stage that bark thickness is increased, furthering enhancing its fire-resistance. During its mature phase, longleaf pine exhibits an even higher resistance to fire and can reach ages greater than 450 years (Boyer 1990).

Characteristically in the Southeast U.S., longleaf pine competes against scrub oaks such as southern red oak (*Quercus falcate*), blackjack oak (*Quercus marilandica*), and turkey oak (*Quercus laevis*) to reach the overstory (Outcalt, 2000). Scrub oaks grow moderately fast but exhibit no significant resistant to fire. Fire kills and limits populations of scrub oaks, while longleaf pine matures and ultimately dominates the overstory (Outcalt, 2000). With a high frequency, low severity fire regime, scrub oaks are further reduced, and a vast array of flora will begin to dominate in the understory with wiregrasses at the forefront (Outcalt, 2000). Based on the silvics and developmental pathway of longleaf pine, it is not just extremely fire resistant; it is fire-dependent. Because the grass stage suppresses height growth, this shade intolerant tree cannot obtain the resources needed to enter the subsequent bottlebrush and sapling stages without fire-induced mortality to oak species. Due to damaging wildland fires in the early 1900s, the U.S. Forest Service instituted fire policies that suppressed fire during the first burning period, commonly known as "the 10:00 a.m. policy" (Loveridge 1994). This fire suppression policy eliminated the role of fire in longleaf pine ecosystems and partly explained why it had undergone such a marked reduction (Shappell and Koontz 2015, Brudvig et al. 2014, Hartnett and Krofta 1989).

Survival and Resistance in a Warming Climate

Arguably, one of the biggest hurdles natural resource managers will have to overcome in the future is managing forests in the face of climate change. Predicted changes in temperature within the lowest carbon emissions scenario (RCP 2.6) estimate that between the years 2071-2099 the Southeast U.S. will see an increase in temperature of 1-3°F (National Climate Assessment 2017) (Figure 5). Within the highest carbon emissions scenario (RCP 8.5), estimates fall within a temperature increase of 7-11°F (National Climate Assessment 2017) (Figure 5). A recent special report by the Intergovernmental Panel for Climate Change (IPCC) reported that without an immediate reduction of carbon emissions the world is on track to meet or exceed the RCP 8.5 model (IPCC 2018).

Longleaf pine exhibits natural traits that show a significant and positive potential to resist and thrive in a warmer, drier climate with more expected occurrences of droughts, floods, severe weather, and fire (Diop 2009). The historical range exhibits the tree's exceptional ability to withstand a large range of climatic conditions. For instance, the climate in northern Virginia varies significantly from the climate in eastern Texas. The long-term average maximum and minimum temperatures for Virginia from 1895-1998 were 66.7°F and 44.6°F, respectively. Average precipitation during this same period was 42.70 inches (NOAA 2019). Compared to eastern Texas, during the same period, the average maximum was 76.5°F, the average minimum was 55.3°F with 51.7 inches of precipitation (NOAA 2019). Despite these variations in climate, historically, longleaf pine has dominated these regions and is expected to withstand heat and drought stress induced by climate change within these regions (Samuelson et al. 2012). Furthermore, climate change is expected to increase the frequency of severe storms, wildfires, as well as insect and disease outbreaks (Stanturf et al. 2007, Johnson et al. 2009, Costanza et al. 2015, Martinson et al. 2007). Within each of these disturbance types, longleaf pine exhibited low rates of blowdown, high resistance to fire, as well low infestation and infection rates, significantly reducing the risk of loss (Friedenberg et al. 2007; Schmidt 2003; Johnson et al. 2009; Boyer 1972).

Within a warming climate, the concentration of atmospheric carbon dioxide is expected to increase. Runion et al. (2006) conducted an experiment that evaluated the effects of elevated atmospheric carbon dioxide on a longleaf pine forest, finding that longleaf pine positively responded in all measures of growth, including above and belowground biomass, height, and diameter. Furthermore, there was no increase in percent mortality, suggesting that longleaf pine has significant potential to be a carbon sink within the Southeast U.S. as atmospheric carbon dioxide increases (Runion et al. 2016). Additionally, a study by Prior et al. (1996) showed that that under higher concentrations of carbon dioxide, stand initiation in a typical longleaf pine forest ecosystem is not compromised, maintaining ecosystem processes

In the next century, as some regions of the U.S. are expected to experience more prolonged periods of drought, forest types specific to a region may change, due in part to stress-related mortality. Forest managers are seeking solutions to such potential changes in the form of increasing resistance and resilience or promoting the transition of forests. Resistance strategies may include thinning to reduce competition to increase the likelihood that a tree can withstand a disturbance. Resilience techniques could consist of promoting drought hardy genotypes, ensuring that the best-adapted trees remain on the landscape. Transition approaches aim to intentionally alter an ecosystem so that it is better adapted to thrive in a new environment (Nagel et al. 2017).

A dendrochronology study by Zahner (1989) showed that longleaf pine is an excellent candidate in terms of management for transition. Reports indicate that the Midwest and Northeast U.S. are expected to experience 10 to 15% less precipitation within the current century (National Climate Assessment 2017). In southern Alabama, Zahner (1989) found that radial growth of longleaf pine was not affected by drought. Additionally, Samuleson et al. (2012) found that longleaf pine has greater hydraulic efficiency, promoting a higher drought tolerance. If the Midwest and Northeast experience less precipitation, longleaf pine could prove to be a suitable target species for forest type transition in these regions. Overall, the versatility of longleaf pine to withstand expected drought conditions while also promoting forest functions could prove to be a valuable management option.

Sequestering Carbon at Higher Rates

Forest carbon pools are stored in five main areas: aboveground biomass; belowground biomass; dead wood; litter; and soil organic carbon (McKinley et al. 2011). Longleaf pine is the longest-living pine species in the Southeast U.S. and has an extremely low mortality rate, thus allowing it to sequester carbon in living biomass for up to 500 years (Diop 2009). Samuelson (2017) found that the belowground lateral root growth of longleaf pine had higher rates of carbon accumulation compared to other forest types. Birdsey et al. (2000) reported that among the various vegetative carbon pools, live biomass stored the highest amount of carbon. With the highest rates of carbon stored in above and belowground biomass, the most significant potential for a carbon sink solely falls to the longleaf pine. This potential exists even with decreased annual precipitation, as is predicted by National Climate Assessment models. Starr et al. (2016) found that even after 2.5 years of drought conditions, longleaf pine growth rates were not affected after precipitation returned to within the normal ranges. Tree form and wood structural strength were not compromised even when conditions limited growth and then favored release (Starr et al. 2016).

In addition to above and below ground biomass carbon storage, longleaf pine has exceptional potential to sequester carbon in wood products. Wood products account for the second most amount of carbon stored in the world, only behind biomass (Birdsey et al. 2000). Overall, longleaf pine has higher value and longer--lasting wood products than those derived from other southern pines, such as loblolly, slash and shortleaf pine (Kush et al. 2004). Additionally, longleaf pine wood, rates as straight-grained, extremely hard, strong, and durable (USAD, Wood Handbook 2010). According to Schmulsky and Jones (2011), some of the most important mechanical properties that determine wood structural performance are elastic properties (modulus of elasticity), compression strength parallel to grain, shear strength parallel to grain, and tension strength perpendicular to grain (Table 2). Longleaf pine has a higher density and increased resistance to bending, compression, and tension when compared to other southern pine species such as loblolly and slash pine. These properties enable the use of longleaf pine timber in numerous high-value wood products.

Approximately 80% of poles used for power lines and additional utility functions come from southern pine species (Platt 2012). Longleaf pine is the favored pole species due to its higher quality, general straightness and ability to produce more poles from a higher number of trees per acre, as is frequently the case in longleaf pine timber stands (Platt 2012). Longleaf pine is the preferred species in the use of support beams for a wide range of construction projects. It is also used in railroad crossties, large dimensional lumber, posts, joists, and piles (USDA, Wood Handbook 2010). Longleaf pine is easily glued and receives stain well making it an excellent flooring and decking option. (USDA Wood Handbook 2010).

Birdsey et al. (2000) listed four effective and cost-efficient methods to increase carbon sequestration: increased productivity of forested land; increased area of forested land; increased agroforestry; and increased wood products. These methods align with the restoration goals of organizations such as the Longleaf Pine Alliance, reinforcing research to increase carbon sequestration. Additionally, improved management of forested lands is positively attributed to more cubic and board feet per acre (Smith 2001). Therefore, a fully stocked stand can increase the overall productivity of timber, further increasing carbon storage within wood products and furthering the value of longleaf pine over other southern pine species (Smith 2001).

Table 2. Comparison of specific gravity, and different mechanical properties at 12% moisture content for three southern yellow pine species (USDA Wood Handbook 2010). Schmulsky and Jones (2011) list these properties as some of the most important when determining the strength and mechanics of wood.

Tree Species	Specific Gravity	Modulus of Elasticity (MPa)	Compression parallel to grain (kPa)	Shear parallel to grain (kPa)	Tension perpendicular to grain (kPa)
Longleaf Pine	.59	13,700	58,400	10,400	3,200
Loblolly Pine	.51	12,300	49,200	9,600	3,200
Slash Pine	.59	13,700	56,100	6,200	-

Restoring parts of the historical range, as well as improvements in longleaf pine forest management, can lead to increased carbon storage on a variety of scales. Increased acreage of longleaf pine forest alone holds significant potential to sequester atmospheric carbon dioxide. Also, longleaf pine stores large amounts of carbon in both living biomass and wood products. Paired with exceptional longevity and low mortality rate, longleaf pine could contribute to reduced atmospheric carbon and mitigation of the effects of climate change.

Persistence Against a Wide Range of Mortality--Inducing Disturbance

Southeastern pine forests face a wide variety of disturbances that include southern pine beetle, fusiform rust, wind, brown-spot needle blight, and wildfire (Figure 6) (Friedenberg et al. 2007; Schmidt 2003; Johnson et al. 2009; Boyer 1972). Longleaf pine shows significant resistance to each of these disturbances. A study conducted by Friedenberg et al. (2007) suggested loblolly pine sustained 3-18 times more infestation of southern pine beetles and 3-116 times more mortality from infestation than longleaf pine. Additionally, mature longleaf pine stands were found to be the most resistant to fusiform rust (Schmidt 2003). In highly infected loblolly pine stands, longleaf pine found within and among disease-ridden loblolly pine, showed no signs of infection (Schmidt 2003). A second pathogen common in the Southeast is brown-spot needle blight. Boyer (1972) found only a 10% infection rate of brown-spot needle blight in longleaf pine seedlings despite overall high infection rates within the study site. Longleaf pine seedlings are most susceptible to pathogen-induced mortality during the seedling stage. However, despite this susceptibility, longleaf pine still exhibited low rates of infection.

Overall, in terms of resistance to pests and pathogens, longleaf pine experiences significantly lower infestation, infection rates, and mortality.

The Southeast experiences high wind events in the form of seasonal hurricanes that can be extremely damaging to forests in the form of windfall. Johnson et al. (2009) found that after Hurricane Katrina, loblolly and slash pine experienced 26 and 15% mortality from windfall, respectively, whereas longleaf pine experienced a minimal mortality rate of 5%. Furthermore, Gresham et al. (1991), in a study that compared wind damage to different tree species after Hurricane Hugo, found that not only did longleaf pine have lower rates of damage than loblolly pine but also lower rates than eight other tree species (Gresham et al. 1991). The wind resistance of longleaf pine is attributed to the extensive resources contributed to root growth during the grass stage (Boyer 1990). This adaptive trait results in the somewhat slower early height growth when compared to loblolly and slash pine and has contributed to misconceptions that favored other southern pine species. However, longleaf pine reaches commercial heights only a few years after loblolly and slash pine. Overall, a trade-off exists between 7-8 years of additional growth needed by longleaf pine to reach commercial harvesting height and the risk of losing up of 26% of growing stock.

A common disturbance currently increasing in both frequency and intensity is wildfire. In 2018, 13,548 fires burned 267,768 acres of the southeastern United States (National Interagency Fire Center 2019). Longleaf pine forests used to burn frequently and have one of the shortest fire return intervals of all global ecosystems at every 1-2 years (Christensen 1981). High-frequency fires result in high canopy base heights, reduced ladder fuels, high torching indices, low canopy bulk densities, and low fuel loads that do not promote high severity fires. A mature longleaf pine forest is virtually immune to high severity, stand-replacing fire. This characteristic of longleaf pine ecosystems is critically important when viewed in the context of the wildland-urban interface (WUI).

The WUI, as defined by the United States Department of the Interior, is the "area where humans and their development meet or intermix with wildland fuel" (USDI and USDA 2001). Residential development into the WUI is becoming increasingly more common, more valuable, more attractive, and explains the continued growth seen today (Duryea and Vince 2005). Butte County in Northern California, situated directly within the WUI, experienced one of the deadliest and costly wildland fires in U.S. history (NIFC 2019). Known as the Camp Fire, this wildland fire killed 85 civilians, burned 153,336 acres and cost $16.5 billion in damages, not including fire-fighting costs (NIFC 2019). Although the Southeast is as not fire prone as the West, there is considerably more WUI (Vince et al. 2005, Stewart et al. 2005). Because longleaf pine promotes forest conditions that reduce high severity fires, these woodlands could serve as a buffer against the worst effects of catastrophic wildfires.

Promoting Diversity of Flora and Fauna

Longleaf pine forests harbor an incredible array of biodiversity. The number of species per hectare is ranked highest among North American temperate forests (Mitchell et al. 2006). Stein et al. (2000) found that more than one-quarter of all plant species that exist within the entirety of the U.S. and Canada are located in longleaf pine forests. In further detail, Sorrie et al. (2006), in their study of the vascular flora within a longleaf pine ecosystem in North Carolina, found 143 families, 490 genera, and 1,206 species, of which, 61 are rare and three that are federally endangered. Peet and Allard (1993) similarly documented 170 plant species in a 1000 square meter area of a North Carolina longleaf pine ecosystem.

Beyond an extensive flora, Landers et al. (2005) found that more than 30 federally endangered animal species depend on the longleaf pine ecosystem including the red-cockaded woodpecker (*Leuconotopicus borealis*), gopher tortoise (*Gopherus polyphemus*), and eastern indigo snake (*Drymarchon couperi*). Furthermore, mammals such as the red wolf (*Canis rufus*), mountain lion (*Puma concolor*), and bison (*Bison bison*) found in longleaf pine forests during European settlement have been completely extirpated, substantially altering the ecosystem (Engstrom 1993). As longleaf pine forests are further fragmented, more of these critical species are reduced in number (Brudvig et al. 2009, Harris and Silva-Lopez 1992, Lear et al. 2005). However, with proper management, these flora and fauna species can thrive.

Longleaf pine ecosystems are maintained by high frequency, low severity fires (Landers et al. 1995), which allows sunlight to penetrate the canopy, thus promoting a species-rich understory (Lear et al. 2005). Furthermore, more than one-third of bird species and two-thirds of mammal species found in a longleaf pine ecosystem forage on the flora found in the understory. The relationship of fire to flora and fauna of longleaf pine woodlands has led to the development of an ecosystem where some animal and plant species are found nowhere else in the world (Blaustein 2008)—a clear illustration of the relationships between fire, species richness, and species abundance in a longleaf pine ecosystem. Flora and fauna evolved alongside a dominant longleaf pine landscape with a frequent, low severity fire regime. Without intensive management and restoration of longleaf pine forest, some or all of these species could be lost forever.

Providing Ecosystem Services

As defined by Boyd and Banzhaf (2009), "ecosystem services are components of nature, directly enjoyed, consumed or used to yield human well-being." Based on this reference, every ecological consideration discussed within this review is an essential ecosystem service that holds considerable value. For instance, in relation to climate change and the onset of more severe natural disturbances, longleaf pine stands tolerated high winds from Hurricane Katrina, a Category 3 hurricane (Johnson et al. 2009). The wind firmness of the longleaf pine acted as a buffer to protect communities within Louisiana. Concerning carbon sequestration, longleaf pine can reach heights of more than 120 ft. and diameters approaching 36 in. and live for up to 500 years (Boyer 1990). Not including belowground biomass, this represents a substantial potential to sequester carbon, otherwise captured in the atmosphere. In addition to acting as a barrier to the increased destructiveness of natural disturbances, resistance to disturbances such as fire is a valuable ecosystem service. Last year alone, 14,236 acres of Georgia burned (NIFC 2019). Longleaf pine forests drive fire intensity down, reducing the risk of catastrophic loss and providing an invaluable service to those it protects. Beyond these ecosystem services, within biodiversity, longleaf pine provides intrinsic values, direct and indirect values, as well as monetary and biological resources (Nunes and van den Bergh 2001).

Ecosystem services also include critical processes such as water purification, drinking water recharge, flood control, soil conservation, pollination, wildlife, and aesthetics (Krieger 2001). Markets are beginning to emerge that would provide private landowners a revenue stream by providing these services through longleaf pine forests. Specifically, the federal Conservation Reserve Program (CRP) makes a yearly rental payment in exchange for planting species that improve environmental quality over agricultural productions (USDA Farm Service Agency 2019). Within the context of the major categories discussed in this review, longleaf pine forests enhance environmental conditions on a significant scale. Additionally, programs such as the Longleaf Stewardship Fund, funded by the Department of Defense, the U.S. Forest Service, the NRCS, the U.S. Fish and Wildlife Service, and private funding groups such as the Forestland Stewards Initiative, provide monetary incentives to restore, maintain, and enhance longleaf pine ecosystems (NFWF 2019). Additionally, the Environmental Quality Incentives Program (EQIP), and Wildlife Habitat Incentive Program (WHIP) all provide resources to establish, restore, and manage longleaf pine forests. Applicants can receive up to 90% of the costs associated with planting and managing longleaf pine. Once established, private landowners can reap the benefits of longleaf pine and could receive supplemental income in the form of the emerging revenue streams from provision of ecosystem services.

Outcomes of Longleaf Pine Ecosystem Management

Longleaf pine forests on Department of Defense (DoD) land located on Fort Bragg, North Carolina is an excellent example of longleaf pine ecosystem restoration. Not only is this an excellent example in terms of restoration and management, but Fort Bragg also conducts these activities in a dynamic and complex environment.

Fort Bragg is comprised of 161,000 acres of the North Carolina landscape~~.~~, approximately~~,~~ 120,000 of which are dominated by longleaf pine forests, resulting in one of its most extensive remaining contiguous ranges within the entire Southeast U.S. (Directorate of Public Works Fort Bragg, Endangered Species Branch 2018). In addition to the vast range of longleaf pine, Fort Bragg is considered to have the highest operational tempo of any military installation due to the Special Forces that reside and train on the base. The installation is home to seven major parachute drop zones, four artillery impact areas, 84 live fire ranges, 16 live fire maneuver areas, two airfields and the largest population of soldiers of any Army base in the world. Most recent reporting estimated that Fort Bragg supports 52,280 active duty soldiers, 12,624 Reserve Component and temporary duty soldiers, 8,757 civilian employees, 3,516 contractors, and 62,962 active duty family members (U.S. Military Installations 2019).

Fort Bragg is home to five federally endangered species that depend on the longleaf pine ecosystem: the American-chafseed (*Schwalbea americana)*, Michaux's sumac (*Rhus michauxii*), rough-leaved loosestrife (*Lysimachia asperulifolia*), the Saint Francis satyr (*Neonympha mitchellii*) (Directorate of Public Works Fort Bragg, Endangered Species Branch 2018), and perhaps the best known, the red-cockaded woodpecker (*Leuconotopicus borealis*). This species relies on mature longleaf pine to create cavity-nesting trees (Engstrom and Sanders 1997). Mature longleaf pine will not flourish on a fire-suppressed landscape (Landers et al. 1995). Before 1990, The U.S. Fish and Wildlife Service (FWS) issued a jeopardy decision on the critical habitat of the red-cockaded woodpecker on Department of Defense land in North Carolina (USFWS 2019). They found that conservation and restoration efforts for the Red-cockaded woodpecker were not adequate to support their rehabilitation and repopulation. To restore habitat for this woodpecker, over 1,818 acres of scrub oak were thinned, along with the implementation of prescribed fire across 117,433 acres. These efforts recreated 3,100 acres of red-cockaded woodpecker habitat that ultimately rescinded restrictions implemented by the FWS and increased populations of the American-chaffseed, Michaux's sumac, rough-leaved loosestrife, and the Saint Francis satyr (Directorate of Public Works Fort Bragg, Endangered Species Branch 2018).

Today, Fort Bragg has a developed natural resource conservation team that is focused on regional ecosystem management leading to a long-term balance between the military mission, environmental stewardship and the community. They have been recognized by the United Nations World Commission on the Environment and are now consistently modeled throughout the country. They have also developed partnerships with eight additional military installations within the Southeast, who also have extensive ranges of longleaf pine. Additionally, Fort Bragg is responsible for introducing the Private Lands Initiative brought about through management and restoration of longleaf pine. The success of managing this forest type while also increasing the habitat and biodiversity of federally endangered species on Fort Bragg provides strong evidence that further restoration is feasible across the Southeast.

Like the longleaf pine forest of Fort Bragg, North Carolina, the Red Hills Region found in Georgia, and Florida also has one of the largest remaining remnants of longleaf pine woodlands. This area of longleaf pine is intensively managed to increase or maintain the longleaf pine ecosystems. The Longleaf Alliance (2012) conducted a study of the water supply, groundwater recharge, gas and climate regulation, pollination, habitat conservation, and aesthetic value of these longleaf pine forests and valued those ecosystem services at $1.136 billion per year (The Longleaf Alliance 2012). This valuation encompasses 30,000 acres of longleaf pine. Extrapolating that value to the current range, planned restoration, and potential restoration conceivably yields extraordinary monetary value.

The successful outcomes of intensive longleaf pine management on Fort Bragg, North Carolina and the Red Hills Region of Georgia and Florida are a result of numerous actions. However, the basis for these actions is firmly rooted in the professional ethics of forest management.

Professional Ethics in the Management of Forested Land

As a member of the Society of American Foresters (SAF), I pledged to uphold the essential principles that are the cornerstones to managing forested land. Derived from the SAF Code of Ethics, these principles are:

- a responsibility to manage land for both current and future generations;
- practice forest management in accordance with landowner objectives and professional standards, and to advise landowners of the consequences of deviating from such standards;
- continually improve individual scientific knowledge and skills;
- use my knowledge and skills to help formulate sound forest policies and laws;
- communicate openly and honestly; and
- conduct myself in a civil and dignified manner (Eforester 2019).

These principles led me to conduct this review and framed its structure. First and foremost, the goal of forest management is to maintain the long-term capacity of the land. The staggering reduction of longleaf pine ecosystems in the Southeast threatens the existence of this forest type for future generations. Moreover, the rich and abundant flora and fauna of the longleaf pine ecosystem is susceptible to loss. For a forest type that once spanned across 92 million acres, the notion that it may not exist for future generations feels inconceivable. To prevent this loss and promote the longleaf pine ecosystem for generations to come requires multiple efforts, including informing landowner objectives.

The SAF calls upon foresters to respect landowner's rights. In addition, foresters are responsible to society to ensure landowner objectives are managed ethically. Therefore, as a professional forester, I have the responsibility to ensure landowners understand forest management within the scope of their objectives. Because of the complexity, long--term implications and responsibility to society, I also have an obligation to discuss the initial and cascading effects of those objectives. However, it is not my responsibility to advocate an agenda. Although this review focuses on longleaf pine, landowners in the Southeast may choose to manage their forest in favor of other species, including loblolly or slash pine. Regardless of the landowner's objective, my purpose as a professional forester is to provide open, honest, unbiased, and scientific information to promote the best forest management policies for both the landowner and society.

To perform this function properly, it is my responsibility to meet and exceed the third principle of the SAF: strive for scientific excellence. This includes personal skills, and the knowledge of continually improving methods, techniques, and approaches to solve forestry-related issues. In the context of this review, I meticulously evaluated the peer-reviewed scientific literature on longleaf pine and its relationship to climate change, carbon sequestration, disturbance resistance, biodiversity, and ecosystem services to prove the best science for landowners, society members, and forest policymakers. This goal supports the principles of helping to formulate sound forest policies as well as communicating openly and honestly.

A vital component of this review and a critical principle in the SAF Code of Ethics is to provide open, honest, accurate, and conflict-free information. These characteristics serve to prompt dialogue not only within the forestry community but also in society about longleaf pine ecosystem management. The implications inherent within this review among the scientific and public communities requires that my professional and civic conduct to be fair, respectful, and understanding of other viewpoints. As stated in the preamble in the SAF Code of Ethics "Service to society is the cornerstone of any profession." With these qualities in mind, I can provide competent service to society while striving to be a steward for our forests.

Overall, my ethics are ingrained in the mission to promote the sustainable management of forested lands within the guidelines and principles outlined by the Society of American Foresters. Whether through science, education or individual actions, my ethos is to cement professional excellence in the use of my technical knowledge and know-how to ensure society benefits from forests for all of time.

Conclusion

Climate change, the loss of forests, and the degradation of ecosystem processes are serious issues that require immediate attention. This review strives to provide a scientific background to support more informed conversation on the restoration of longleaf pine ecosystems. Additionally, this review identifies the values and benefits of longleaf pine restoration efforts to inform policy and management decisions related to forestry in the Southeast. To inform policies and decisions, this review investigated the relationship of longleaf pine forests to climate change, carbon sequestration, disturbance resistance, biodiversity, and ecosystem services. Within each of these categories, longleaf pine provides numerous advantages.

In relation to climate change, longleaf pine is resistant to many factors, including stress from prolonged drought and increased temperatures. Worst-case scenario models of temperature and precipitation indicate longleaf pine has the physiological capacity to withstand such stresses resulting in less climate-induced mortality. The same precipitation models suggest that regions neighboring the range of longleaf pine may experience lower precipitation, causing increased rates of mortality. In these cases, longleaf pine could provide forest managers with a viable management option in terms of managing for transition. In addition to surviving in a warmer and drier climate, longleaf pine exhibits traits to withstand the effects of more severe storms, such as windfall and flooding, expected to occur at higher intervals in a changing climate.

Carbon sequestration has emerged as a prominent solution to mitigate the effects of climate change by reducing atmospheric carbon dioxide. With longevity exceeding 450 years and significant accumulations of carbon in above and belowground biomass, longleaf pine can sequester large amounts of carbon. Beyond living biomass, the high wood quality of longleaf pine is commercially desired and lasts for long periods, further increasing its carbon sequestration potential. Additionally, low mortality rates from a wide range of disturbances add to the contributions longleaf pine can make towards increased carbon sequestration.

Within southern pines, fusiform rust and brown spot needle blight cause high rates of mortality. The evidence suggests that longleaf pine is highly resistant to infestation from insects, and infections from pathogens within each stage of its life cycle. In the context of fire as a disturbance, longleaf pine has a high resistance to, and dependence on fire. These factors create conditions that reduce the risk of high severity fires. Overall, the increased resistance to these disturbances enhances the ecological importance detailed in this review, furthering highlighting the importance and necessity of longleaf pine restoration. Furthermore, the ability of longleaf pine to survive these disturbances has resulted in a highly diverse and rich plant and animal community.

High levels of biodiversity found in longleaf pine forests rank above other temperate forests of North America and only falls behind biodiversity found in rain forests. Additionally, the management of longleaf pine forest with biodiversity as an objective has achieved substantial success and has the potential to serve as a model for forest restoration across the Southeast. The military base of Fort Bragg, North Carolina serves as a successful example of increased biodiversity through active forest management. Finally, the value of ecosystem services provided by longleaf pine forests is exceptionally high. Beyond climate change resistance, carbon sequestration, disturbance resistance, and biodiversity, longleaf pine forests purify and recharge water, protect against floods, limit soil erosion, and maintain watersheds.

The relationship of longleaf pine to some of the top environmental challenges of our century indicate that this ecosystem is essential to forest sustainability in the Southeast United States. The values, advantages, and benefits that longleaf pine provides, within these contexts, requires additional efforts to restore the current range and to improve natural resource management policies that favor the expansion and restoration of longleaf pine ecosystems.

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Figure 1. The typical structure, spatial arrangement, and understory of a mature longleaf pine forest

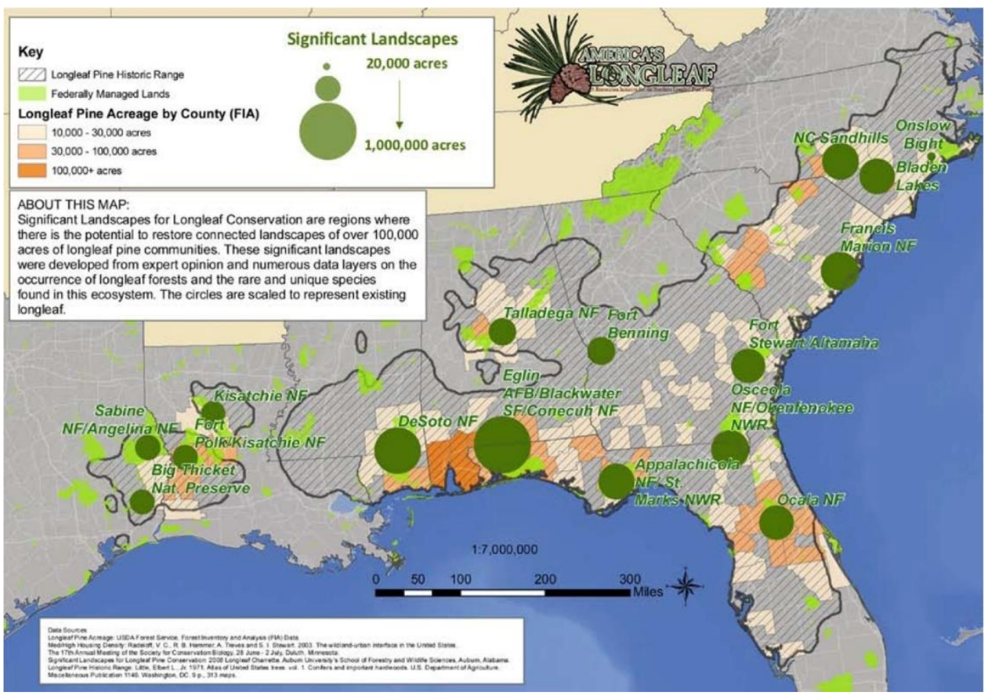

Figure 2. Historical range and current extent of longleaf pine (Longleaf Pine Alliance 2019).

Figure 3. The typical structure, spatial arrangement, and understory of a loblolly pine forest

Figure 4. The typical structure, spatial arrangement, and understory of a slash pine forest

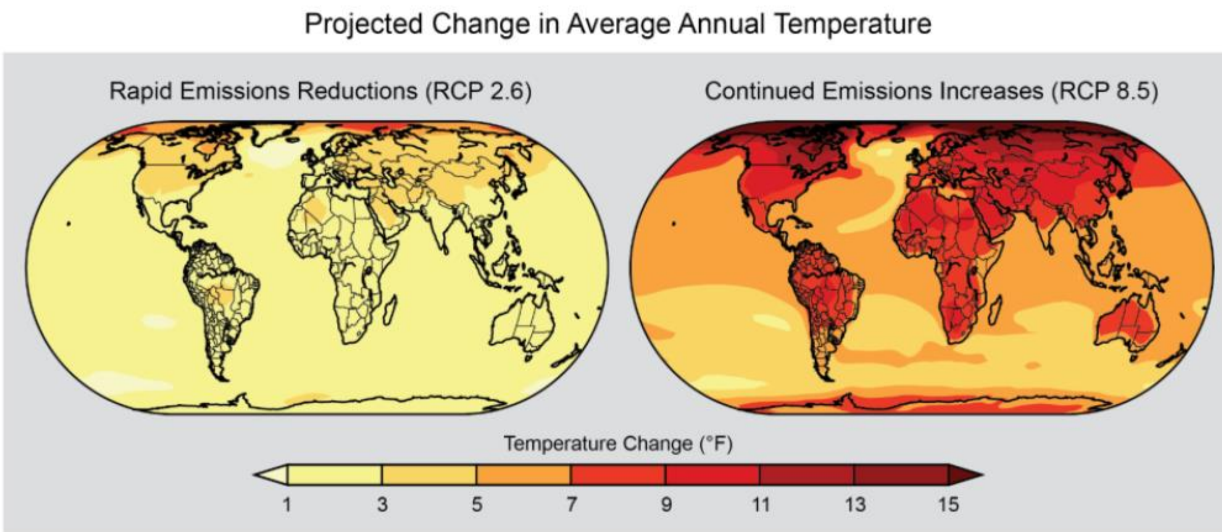

Figure 5. Projected change in average annual temperature over the period 2071-2099 under a low scenario that assumes rapid reductions in emissions and concentrations of heat-trapping gases (RCP 2.6), and a higher scenario that assumes continued increases emissions (RCP 8.5) (Figure source: NOAA NCDC / CISC-NC).

Figure 6. The primary disturbance types found within the Southeast A. Pitch tubes caused by the southern pine beetle. B. Fusiform rust infection on loblolly pine. C. Brown spot needle blight on longleaf pine. D. Wind damage in a loblolly pine forest. E. Fire within a longleaf pine ecosystem

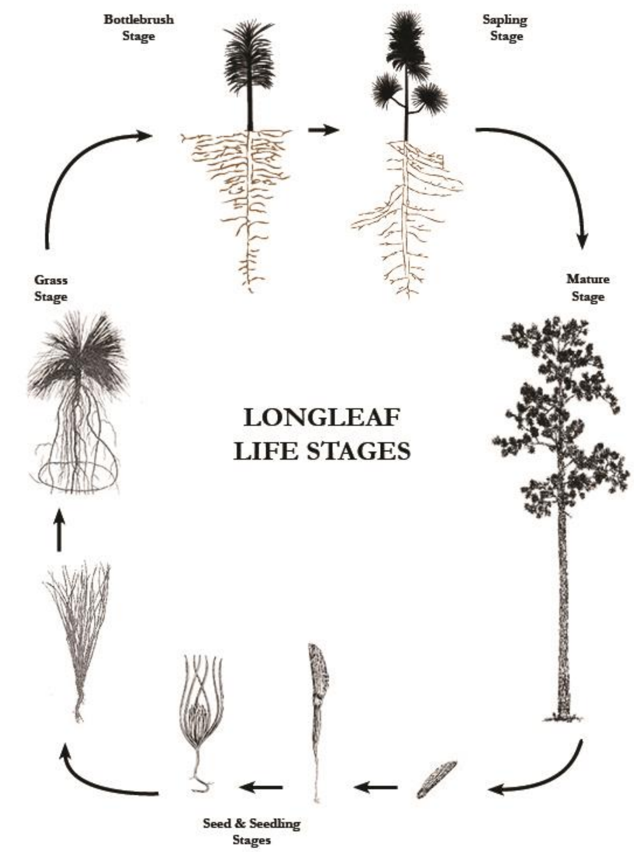

Figure 7. The life stages of longleaf pine (Longleaf Pine Alliance 2019)