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Overstory Species Composition, Structure, and Conservation Challenges of a Mature, Natural-Origin Pine Stand After Decades of Management

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Abstract - This study provides a preliminary assessment of 4 compartments on the Crossett Experimental Forest (CEF) being restored to old-growth-like conditions. After being partially cleared for agriculture or lumbered in the late 1910s, Compartments 1, 2, 11, and 12 were included in a combination of pulpwood-thinning and uneven-aged cutting-cycle studies for the next 50 y. Today, these compartments are overwhelmingly comprised of large *Pinus taeda* (Loblolly Pine) and *Pinus echinata* (Shortleaf Pine). A mixture of 22 other species comprise the remainder, primarily in small-diameter stems. Of the 139 ring-counted trees, similarly-sized Shortleaf Pines were significantly older than Loblolly Pines. Current, live-tree oven-dry biomass in Compartments 1, 2, 11, and 12 approaches 200 Mg/ha, or approximately twice that historically reported for old-growth pine. The effects of decades of conventional silviculture, the limited occurrence of fire, and a lack of pine (especially Shortleaf Pine) regeneration are conservation concerns related to this long-term study.

Introduction

Since the clearing of the virgin timber in the early 20th century, silvicultural practices have been the main factor in determining forest composition, structure, and dynamics across most of the southeastern US. With its suitable soils, abundant moisture, long growing season, and predominantly privately owned forests, it is not surprising that the southeastern US is now the largest timber-producing region in the world (larger than any other single nation), producing about 12% of the global supply of industrial roundwood and 63% of US timber-growing stock removals (FAO 2014, Oswalt et al. 2014). Much of this production was initiated after 1950 and has increased in recent decades following reduced harvest of old-growth conifers from the western US and the expansion of increasingly intensively managed southern *Pinus* (pine) plantations (Carter et al. 2015, Wear and Greis 2002).

Pine plantation cover in the southeastern US has grown from an estimated 750,000 ha in 1952 to almost 16 million ha in 2010 (~19% of all forests), with concurrent declines in natural-origin pine and oak–pine stands (Hartsell and Conner 2013). The Upper West Gulf Coastal Plain (UWGCP; Klepzig et al. [2014] labeled the UWGCP as their "Middle Gulf-West section") of southern Arkansas, northern Louisiana, and northeastern Texas has experienced this transformation to an even greater degree, with about 23% of the 8.5 million ha of forestland now

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in planted pine (Klepzig et al. 2014). Although the loss of natural-origin upland forests is expected to continue well into the future, natural pine-dominated forests are still forecast to cover much of the UWGCP (Klepzig et al. 2014), and they offer opportunities for certain ecosystem services otherwise unavailable from intensively managed, short-rotation *Pinus taeda* (Loblolly Pine) plantations (e.g., Bragg et al. 2014, 2015). Indeed, numerous public-land management agencies, non-governmental organizations, and some private landowners are actively seeking alternatives to southern pine-plantation silviculture that protect elements of mature forest systems with the promise of some timber returns to help cover management and restoration expenses (Guldin 2011).

However, those interested in a treatment regime that improves ecosystem services beyond timber production and restores certain conditions found in old-growth Loblolly and *Pinus echinata* (Shortleaf Pine) forests have few guiding principles available to direct their efforts. Designs for this type of alternative silviculture have precedent: researchers have been working on encouraging the development of old-growth-like characteristics in second-growth stands of other forest types, such as *Pinus palustris* (Longleaf Pine, Mitchell et al. 2006, Moser et al. 2002), western conifers (Baker et al. 2007, Lindh and Muir 2004), and northern hardwoods (Fassnacht et al. 2015). Fortunately, natural-origin Loblolly and Shortleaf Pine-dominated upland forests respond well to a range of silvicultural options (Guldin 2011, Schultz 1997), suggesting that a management strategy to enhance old-growth-like characteristics in this forest type is possible.

Restoration success depends on both initial stand conditions and how the second-growth Loblolly–Shortleaf Pine forest responds to the applied treatments. As suggested by recent reviews (e.g., Stanturf et al. 2014a, b), there are a number of guiding principles of silviculturally based ecosystem restoration that can help provide a treatment framework. Key to this framework are the development of fundamental knowledge of the system to be restored, articulation of the desired future outcomes, and the identification of the silvicultural treatments and natural processes available to achieve this outcome. The research presented here represents the first step of this process—the description of a mature, natural-origin pine-dominated stand in the UWGCP of southeastern Arkansas, including an assessment of past management practices and a number of likely conservation challenges that may affect restoration treatments. Full nomenclature, including authorities, for all species mentioned is provided in Table 1 and Appendix A.

Field-site Description

The work for this study was conducted in Compartments 1, 2, 11, and 12 of the Crossett Experimental Forest (CEF), located in southern Ashley County, AR (Fig. 1). The study area is part of a long-term research project to evaluate a range of silvicultural treatments designed to accelerate and enhance old-growth-like attributes in second-growth pine-dominated forests of the UWGCP. These northeastern-most compartments (centered at 33°2.65'N, 91°55.2'W) occupy 64.8 ha, or just under 10%, of the 678-ha CEF.

Geologically, this part of the UWGCP consists primarily of the late Quaternary Prairie Terrace complex, composed of alluvium from the Arkansas, Mississippi, and Ouachita rivers deposited ~110,000–210,000 years ago (Saucier 1974, Shen et al. 2012). These older terraces are capped across most of the region with late

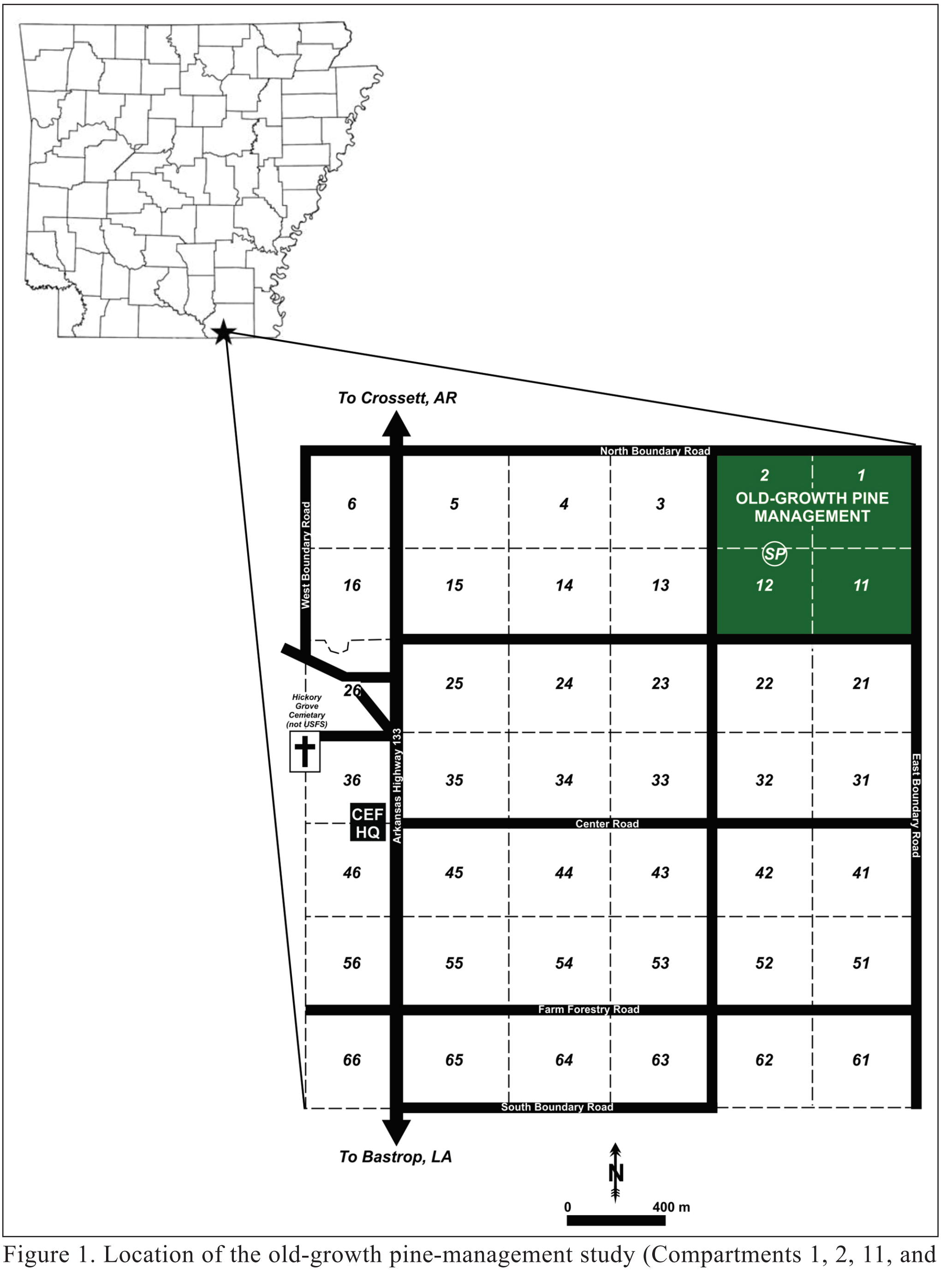

Figure 1. Location of the old-growth pine-management study (Compartments 1, 2, 11, and 12) on the Crossett Experimental Forest in southeastern Arkansas.

Pleistocene loess (Heinrich 2008, Rutledge et al. 1996, Shen et al. 2012). The landforms of the CEF consist primarily of gently rolling hills and relatively level flatwoods incised by meandering ephemeral stream channels. Compartments 1, 2, 11, and 12 gradually rise in elevation with increasing latitude; the lowest elevations are ~40 m ASL in the south, and the highest are in the north and east (to 47 m ASL). The somewhat poorly drained soils of the CEF formed primarily in the 0.5- to 1-m-thick loess that covers most of the area. The tops of the ridges are Bude silt loams, the side slopes consist primarily of Providence silt loams, and the immediate streamside areas (Holocene terraces) are Arklabutla silt loams (Gill et al. 1979). Low (typically, <1 m tall), circular (often 10–20 m wide), naturally formed "prairie" or "pimple" mounds are common across the CEF, including in the study compartments.

Climatically, the Crossett area is in the humid subtropical zone and receives on average 1445 mm of precipitation, primarily in the form of rain (1981–2010 climate norms; NOAA 2015). Precipitation tends to be fairly evenly distributed across the year, with somewhat more from December to February, and slightly less from August to September). Average January and July maximum temperatures are 12.4 °C and 33.2 °C, respectively, and average January and July minimum temperatures are -0.6 °C and 20.0 °C, respectively. Ashley County has a growing season of approximately 240 d per year (Cain and Shelton 2001).

Current forest composition on the CEF is predominantly Loblolly Pine, with lesser amounts of Shortleaf Pine, *Liquidambar styraciflua* (Sweetgum), *Quercus alba* (White Oak), *Quercus falcata* (Southern Red Oak), *Quercus nigra* (Water Oak), *Acer rubrum* (Red Maple), *Nyssa sylvatica* (Blackgum), *Ulmus alata* (Winged Elm), and numerous other tree species. Understory vegetation is similarly diverse, with many woody shrubs (e.g., *Callicarpa americana* [American Beautyberry], *Rhus glabra* [Smooth Sumac]), lianas (e.g., *Vitis rotundifolia* [Muscadine], *Gelsemium sempervirens* [Carolina Jessamine], *Toxicodendron radicans* [Poison Ivy]), briars (e.g., *Rubus* spp. [raspberries, blackberries], *Smilax* spp. [greenbriars]), forbs, graminoids, and ferns. A number of invasive plant species are also found on the CEF including *Ligustrum sinense* (Chinese Privet), *Lonicera japonica* (Japanese Honeysuckle), *Lygodium japonicum* (Japanese Climbing Fern), and *Triadica sebifera* (Chinese Tallow-tree).

Methods

Determining the management history of the study area

I conducted this research on a second-growth forest that arose following the cutting of the virgin pine between 1915 and 1920 (Darling and Bragg 2008, Reynolds 1980). The timber cut by the Crossett Lumber Company was a relatively even mixture of old-growth Loblolly and Shortleaf Pine, with a minor and varying hardwood component (Chapman 1913, Reynolds et al. 1984). Unfortunately, there are no detailed accounts of the study compartments, including their cutting history, prior to the establishment of the CEF. However, I consulted a number of historical records of the general area to provide an assessment of forest conditions prior to 1934.

After the CEF opened, this 64.8-ha block was managed using various silvicultural techniques, primarily a range of uneven-aged treatments. In the 1990s, Compartments 2 and 12 were designated as a part of an old-growth pine-management study, but no major management interventions were conducted. Compartment 1 was added to this research in 2005, followed in 2006 by Compartment 11. Over the past 15 years, management has focused on ensuring overstory consistency between the different compartments, with treatment decisions determined based on a long-term strategy of managing for old-growth-like conditions (Bragg 2004a). Since 2000, only 1 harvest, a thinning from below to 12–16 m^2/ha of basal area, has been conducted in the study compartments; several prescribed burns (in all compartments) and a limited amount of understory brush mowing (Compartment 12 only) have also been undertaken.

Plot establishment and field measurements

With CEF staff, I established permanent plots in 2014 to act as the standard inventory locations for this long-term study. Twelve circular, 0.05-ha (radius = 12.62 m) plots were systematically installed along each of 12 transects, with transects spaced 60 m apart. To ensure that sample plots would not overlap and good coverage of the stand was provided, none of the 144 overstory-sample plots were spaced closer than 60 m along each transect. Each plot was also located at least 48 m from any compartment border to minimize edge effects, and a metal barbed-wire spacer was inserted into the ground at plot center to permanently monument plot locations.

I identified to species all live trees >10 cm in diameter at breast height (DBH; 1.37 m above ground line) and recorded their diameter to the nearest 0.1 cm. I determined stand-level estimates of stem frequency and basal area by summing all individual live-tree records (1198 total) across all 144 plots standardized to a per hectare basis. This study sought to emphasize current mid- and overstory structure and composition; I did not evaluate regeneration (stems ≤ 10 cm) of any species. The understory in these compartments is predominantly mixed hardwoods, with very few pines. I also identified, counted, and measured the diameters of standing dead trees (snags) >10 cm DBH.

Pine age-structure for these compartments was estimated using a randomized subsample. I cored at breast height the sound (i.e., not hollow or decayed), live, overstory pine nearest to plot center (139 of 144 plots had usable overstory pines) regardless of species and counted the number of rings in the field. These ring counts are only approximations of age because I did not conduct cross-dating. The pines in the current study were cored at a different point along the bole and did not share the same stand-development history as the nearby Farm Forestry Forties described by Bragg and Guldin (2015); thus, I did not apply their the pine-age adjustment factor. Nevertheless, the age estimates for these specimens are still probably within 5 y of the true age. DBH/ring-count relationships were fit for Loblolly and Shortleaf Pine using ordinary least squares (OLS) linear regression and compared the differences between the slopes and intercepts of these species-based equations using a Student's *t*-test ($\alpha = 0.05$; Zar 1984).

Stand-level biomass calculations

For this paper, I determined all stand-level biomass values by calculating individual live-tree biomass, subsequently scaled to a per-hectare basis, using the model and coefficients of Chojnacky et al. (2014):

$$B_{AG} = (e^{b0 + b1 \ln[\mathrm{DBH}]}) / 1000 \quad [1]$$

where B_{AG} is total aboveground oven-dry biomass (in Mg) for all stems >10 cm DBH and b_0 and b_1 are species-based or species-group–based regression coefficients. Belowground oven-dry live-tree biomass (also in Mg) was adapted from the relationship developed by Enquist and Niklas (2002):

$$B_{BG} = (B_{AG} / 3.88)^{0.9803922} \quad [2]$$

I determined total oven-dry live-tree biomass by summing B_{AG} and B_{BG}. To supplement data from an existing review of the literature (Bragg 2012b), I undertook a new biomass analysis using cordwood data from a historical inventory report (Cruikshank and Wheeler 1937) for uncut old-growth forests across the UWGCP. This analysis assumed that 1 cord of pine yielded 2.55 m^3 of green wood (470 kg/m^3 dry wt), and 1 cord of hardwood yielded 2.27 m^3 of green wood (570 kg/m^3 dry wt) (conversion ratios adapted from Fonseca [2005]). I calculated belowground biomass using equation 2. The cordwood volumes did not include branch and foliar biomass; thus I added a fixed adjustment of 25% to the aboveground biomass calculation because separate analyses (data not shown) using several different approaches to component ratios (e.g., Gonzalez-Benecke et al. 2014, Jenkins et al. 2003) have suggested that branches and foliage contribute between 20% and 30% of total aboveground biomass, depending on tree size.

Results

Historical review

This part of Ashley County has been utilized by humans for millennia, primarily as a source of game and botanical resources. Archeological evidence of prehistoric Native American use of the lands that would eventually become the CEF dates to at least 10,000 y ago, with periodic occupation and utilization fluctuating during the intervening years. At first European contact (circa 1542), the settlements and farms of the agriculturally oriented Mississippian culture were concentrated along the floodplains of the major waterways rather than upland sites (Gibson 1983, Jeter and Early 1999). By the time of the 1803 Louisiana Purchase, Quapaw Indians had wrested control of this region from the Tunican and Koroa tribes, and it was the Quapaw who ceded the land to the US government in an 1818 treaty (Sabo 1992). Although it was probably not farmed, much of the pine-dominated upland in the UWGCP experienced fires deliberately set by Native Americans to improve hunting and foraging conditions. Centuries of frequent fire helped establish and maintain pine dominance in an area that would otherwise have succeed to hardwood forests, and it is likely that this pyrogenic regime was a factor in the historical prominence of Shortleaf Pine across much of the UWGCP (Bragg 2002, 2008).

The interior uplands of Ashley County remained largely unsettled by Euroamericans until the mid-1800s; an 1842 plat map of the area showed only a single road passing through the lands that became the CEF, and no settlers are documented (Bragg 2012a). Between 1850 and 1860, Euroamerican settlement rapidly expanded across the area (Bragg 2004c). Although the first formal land patents for the eventual CEF property were not filed until 1861 (Bragg 2012a), other documentary evidence indicates that settlers had started clearing some of the virgin timber for crops by 1853. For example, Russell R. Reynolds described an old-field stand of pine in Compartment 1 (Fig. 2) located at one of the earliest permanent photographic points on the CEF. In his captions written on these photographs, Reynolds provided the following narrative: "About 1860, this road passed through a rich farming section. The fields have since seeded into Shortleaf and Loblolly Pine and the road has been abandoned." Locally, most of the upland farms that developed during the latter half of the 1800s had failed by the early 1900s (Bragg 2012a, Darling and Bragg 2008). The Crossett Lumber Company acquired most of the still-timbered lands between 1900 and 1920 prior to cutting them with crews from their Hickory Grove Lumber Camp (Darling and Bragg 2008).

Figure 2. Historical road passing through former farmlands (originally cleared before the Civil War), now old-field Loblolly and Shortleaf Pine, in Compartment 1 of the Crossett Experimental Forest, AR. Photograph #352495 from the US Forest Service archives.

Reynolds (1959) described most of the forests on the CEF when it opened in 1934 as burned-over, populated with numerous, low-quality hardwoods, and with insufficient quantities of the larger pines needed to viably manage them using the conventional approaches available at the time. In 1937, a 100% inventory (by 2.54-cm size classes) of pines (Loblolly and Shortleaf Pines), Southern Red Oak, White Oak, and other hardwoods, was completed on the CEF (Reynolds 1955). According to a map developed from this inventory (Fig. 3), Compartments 1, 2, 11, and 12 were primarily natural-origin pine stands in "light condition" or "heavy condition". The map identified more limited areas in the study compartments as old-field stands, ~43 y old, with a small amount of open land on the extreme eastern edge (Figs. 2, 3). Between 1937 and the early 1950s, the old-field

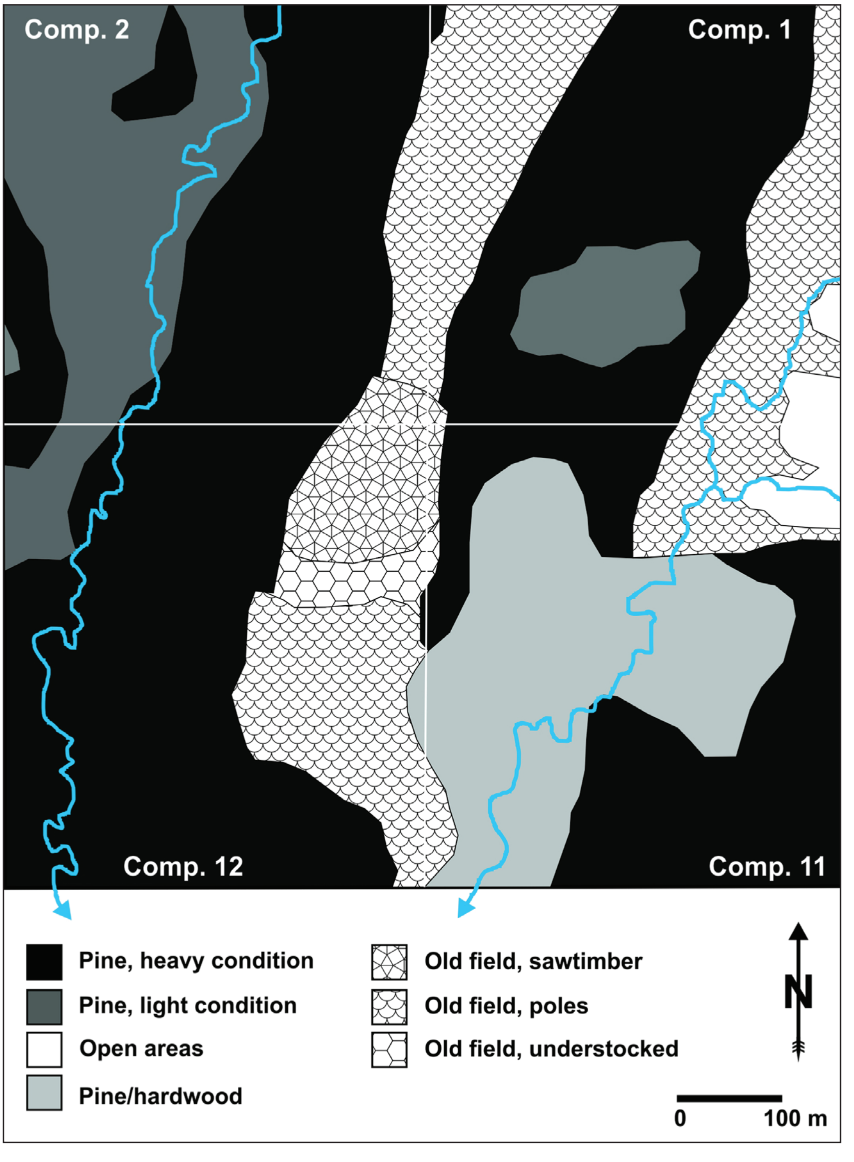

Figure 3. Crossett Experimental Forest cover type/condition classes as originally mapped in the late 1930s (adapted from Wahlenberg 1941). Cross-hatched and open areas in this map reflect the areas cleared for row crops; livestock probably also grazed throughout the study compartments until establishment of the experimental forest in 1934.

portion in the center of the study compartments was part of a pulpwood-thinning project (Guttenberg 1954; Reynolds 1937, 1980). This thinning study had a number of treatments that reduced the overstory significantly from the dense original old-field stand (Fig. 4a), some of which were substantial enough to permit the recruitment of pine seedlings (Fig. 4b).

With the exception of the old-field study blocks, Compartments 1, 2, 11, and 12 were included in a series of large-scale experiments on uneven-aged southern pine silviculture. Eventually, the pulpwood-thinning study area was incorporated into the uneven-aged research. To address questions regarding the implementation of uneven-aged silviculture in southern pines, a cutting-cycle–length study was developed in 1937. Compartments 1 and 11 were placed on a 9-y cutting cycle, Compartment 2 was on a 3-y cycle, and Compartment 12 was on a 6-y cycle (Reynolds 1955); these harvest-return intervals were maintained until about 1970 (Cain and Shelton 2001, Reynolds 1969). When the CEF reopened after being closed from 1974 to 1979, most of Compartments 1, 2, and 12 were transferred into the experimental forest's operational management areas, and Compartment 11 was

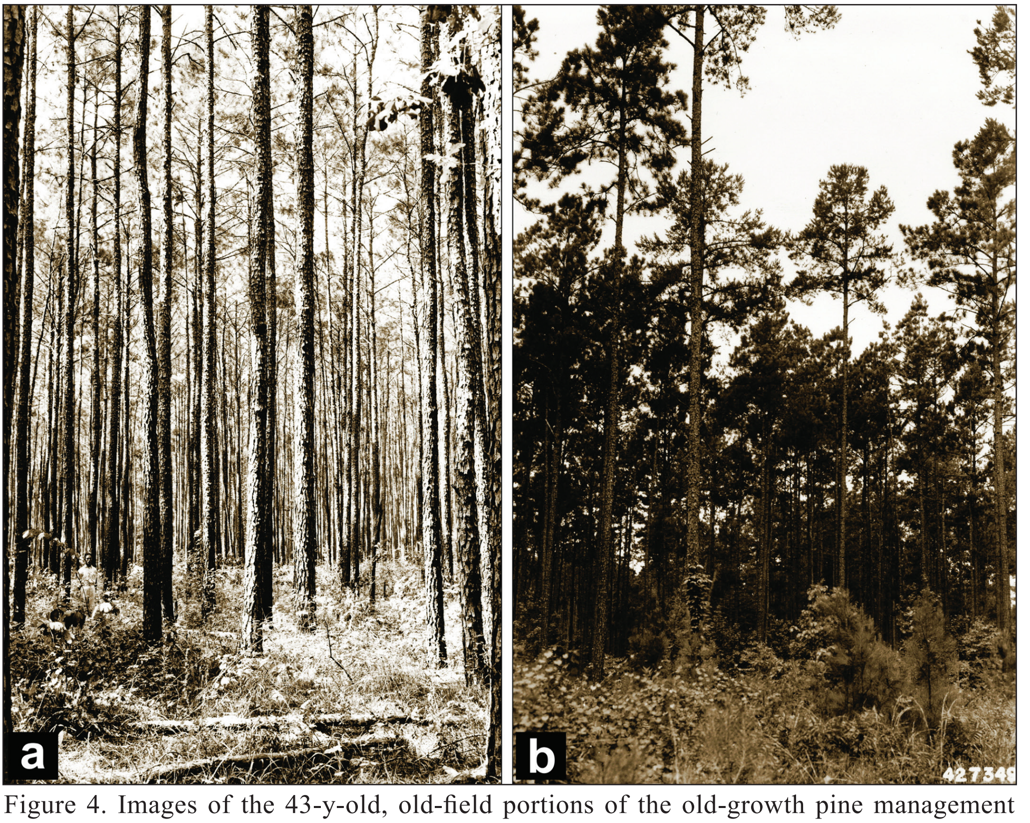

Figure 4. Images of the 43-y-old, old-field portions of the old-growth pine management study on the Crossett Experimental Forest, AR, taken in 1936 (a), immediately prior to the 1937 thinning, and then 6 years after treatment (b) showing the released pine overstory and a new cohort of pine seedlings emerging from the undergrowth. Overstory trees in (a) that are still surviving are ~120 y old today; new seedlings in (b) are now nearly 80 y old. Photographs #352494 and #427349 from the US Forest Service archives.

assigned to a study evaluating the influence of stand basal-area and different burning regimes on uneven-aged stand structure (Baker and Bishop 1986, Cain 1993).

Current overstory species composition

The 2014 live-tree inventory identified 24 native tree species on the permanent sample plots (Table 1). Loblolly Pine was the overwhelmingly dominant species, composing 42% of the 166.4 live stems >10 cm DBH per ha in the study area. More significantly, Loblolly Pine represented 73% of live-overstory basal area. Shortleaf Pine accounted for <5% of live stems, had numerous large individuals, and therefore, also disproportionately contributed to stand basal area (8% of the total). A handful of hardwoods, including Sweetgum (11% of live stems), Winged Elm (8%), White Oak (7%), Red Maple (6%), Southern Red Oak (6%), and Water Oak (6%), each made up >5% of overstory stems counted, but most of these trees were small in stature and when combined, accounted for only 16% of stand basal area (Table 1). The remaining 16 species represented only a small fraction of the stand (<10% of stems and 2% of basal area), and a number of them had only a single specimen.

Table 1. Species abundance and stand density of live trees (stems >10 cm DBH) in Compartments 1, 2, 11, and 12 on the Crossett Experimental Forest, AR, in 2014. Species nomenclature from Gentry et al. (2013).

		Abundance		Basal area	
Common name	Scientific name	Count (stems/ha)	Fraction (%)	Density (m^2/ha)	Fraction (%)
Loblolly Pine	*Pinus taeda* L.	69.72	41.90	14.451	73.05
Shortleaf Pine	*Pinus echinata* Mill.	7.50	4.51	1.612	8.15
Sweetgum	*Liquidambar styraciflua* L.	17.78	10.68	0.863	4.36
Southern Red Oak	*Quercus falcata* Michx.	9.86	5.93	0.598	3.02
White Oak	*Quercus alba* L.	12.36	7.43	0.547	2.76
Water Oak	*Quercus nigra* L.	9.58	5.76	0.543	2.75
Winged Elm	*Ulmus alata* Michx.	12.78	7.68	0.357	1.81
Red Maple	*Acer rubrum* L. var. *rubrum*	10.56	6.34	0.353	1.79
Black Cherry	*Prunus serotina* Ehrh.	0.97	0.58	0.057	0.29
Sassafras	*Sassafras albidum* (Nutt.) Nees	2.78	1.67	0.053	0.27
Flowering Dogwood	*Cornus florida* L.	3.19	1.92	0.050	0.25
Green Ash	*Fraxinus pennsylvanica* Marshall	0.56	0.33	0.050	0.25
Blackgum	*Nyssa sylvatica* Marshall	1.81	1.09	0.050	0.25
Post Oak	*Quercus stellata* Wangenh.	0.97	0.58	0.039	0.20
Cherrybark Oak	*Quercus pagoda* Raf.	0.14	0.08	0.038	0.19
Mockernut Hickory	*Carya alba* (L.) Nutt. ex Elliott	1.25	0.75	0.035	0.18
Eastern Hophornbeam	*Ostrya virginiana* (Mill.) K.Koch	1.94	1.17	0.031	0.16
Red Mulberry	*Morus rubra* L.	0.42	0.25	0.019	0.10
American Holly	*Ilex opaca* Ait.	1.53	0.92	0.017	0.09
Willow Oak	*Quercus phellos* L.	0.14	0.08	0.007	0.04
Black Hickory	*Carya texana* Buckley	0.14	0.08	0.005	0.02
Slippery Elm	*Ulmus rubra* Muhl.	0.14	0.08	0.003	0.02
Black Locust	*Robinia pseudoacacia* L.	0.14	0.08	0.002	0.01
Eastern Redcedar	*Juniperus virginiana* L.	0.14	0.08	0.001	0.01
	Totals:	166.40	100.00	19.781	100.00

Tree-diameter and basal-area distributions

Table 2 provides the minimum, maximum, and average DBH by species for the study compartments. *Quercus pagoda* (Cherrybark Oak) had the highest average DBH (58.7 cm), although this species was represented by only a single overstory tree. Of the most common taxa, Shortleaf Pine had the highest average DBH (50.3 cm), followed by Loblolly Pine (48.5 cm). Most hardwoods were small in diameter, averaging 10–30 cm DBH. Loblolly Pine (85.6 cm), Water Oak (80.5 cm), and Shortleaf Pine (80.0 cm) were the only species whose maximum DBH exceeded 70 cm, a threshold sometimes used to help define types of old-growth in the eastern US (e.g., Brown et al. 1997).

As noted earlier, Loblolly and Shortleaf Pine contributed >81% of the 19.8 m^2/ha of live-overstory basal area in the study area (Table 1). However, their contribution to basal area was not evenly distributed. Figure 5 provides the basal-area contributions by diameter classes for the 6 most-dominant species (Loblolly Pine, Shortleaf Pine, Sweetgum, Southern Red Oak, White Oak, and Water Oak) plus a group that includes all of the remaining taxa. Although Loblolly Pine clearly dominates total stand basal area, it has only a minor presence in the understory (trees <10

Table 2. DBH distribution of live trees >10 cm DBH in Compartments 1, 2, 11, and 12 on the Crossett Experimental Forest, AR, in 2014. For species with only 1 observation, only the average DBH is given.

Common name	*n*	Minimum (cm)	Maximum (cm)	Average (cm)	Standard deviation (cm)
Loblolly Pine	502	10.4	85.6	48.5	16.84
Shortleaf Pine	54	19.1	80.0	50.3	14.42
Sweetgum	128	10.2	61.5	22.5	10.61
Southern Red Oak	71	10.2	53.8	25.5	11.17
White Oak	89	10.2	57.9	21.1	10.87
Water Oak	69	10.2	80.5	23.3	13.53
Winged Elm	92	10.2	37.1	18.1	5.30
Red Maple	76	10.2	42.9	19.1	7.98
Black Cherry	7	15.0	45.2	25.5	10.30
Sassafras	20	10.4	22.4	15.2	3.69
Flowering Dogwood	23	10.2	20.3	13.8	3.10
Green Ash	4	11.2	45.5	30.4	16.90
Blackgum	13	10.2	34.3	17.7	6.33
Post Oak	7	15.2	27.7	22.1	5.03
Cherrybark Oak	1	-	-	58.7	-
Mockernut Hickory	9	10.4	29.2	17.8	6.46
Eastern Hophornbeam	14	11.4	19.6	14.1	2.74
Red Mulberry	3	16.5	33.3	23.1	8.94
American Holly	11	10.2	14.5	11.9	1.58
Willow Oak	1	-	-	26.2	-
Black Hickory	1	-	-	20.8	-
Slippery Elm	1	-	-	17.5	-
Black Locust	1	-	-	15.0	-
Eastern Redcedar	1	-	-	10.4	-

cm DBH) and midstory (10–35 cm DBH) and shares dominance with a number of hardwoods to about 44 cm DBH. Shortleaf Pine is uncommon in size classes <40 cm DBH and only erratically present in the largest-diameter classes. The understory of this stand is overwhelmingly comprised of hardwood species; only an occasional oak or Sweetgum exceeded 50 cm DBH (Fig. 5).

Live biomass

Consistent with the basal-area results, Loblolly Pine and Shortleaf Pine contributed the vast majority of the 199.1 Mg/ha of total oven-dry live-tree biomass in the study compartments, 73% and 8%, respectively (Table 3). Even though most hardwoods have higher wood specific gravity than pines, a difference reflected in the predictive models used in this paper (Chojnacky et al. 2014), the pines were so dominant in the largest tree-size classes, that their somewhat lower specific gravity had little influence on total biomass contributions.

Age structure

Of the 139 pines cored for age estimates, 18 were Shortleaf Pine (just under 13% of all pines), or slightly more than the ~10% of the Shortleaf Pine stem counts compared to the overall pine sample. Although I made no attempt to ensure the randomized sample came from across the full size- (and age-) distributions, the absence of young Shortleaf Pine (the youngest sampled had 49 rings) compared to the presence of multiple young Loblolly Pine (the youngest had only 11 rings) indicates

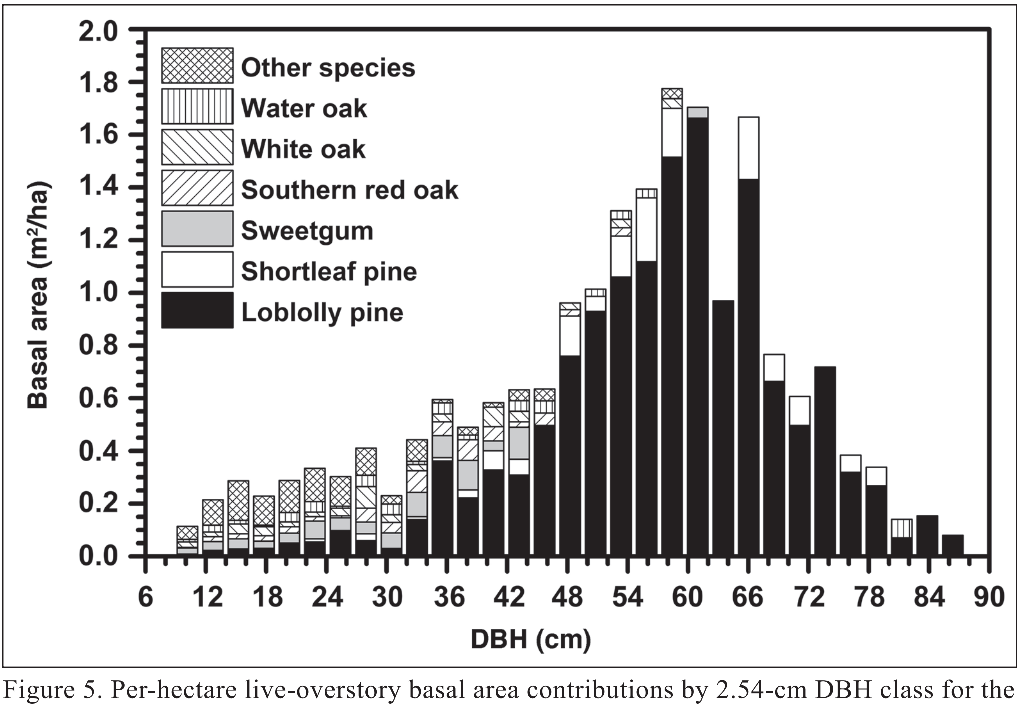

Figure 5. Per-hectare live-overstory basal area contributions by 2.54-cm DBH class for the most dominant taxa in Compartments 1, 2, 11, and 12 on the Crossett Experimental Forest, AR, sampled in 2014.

that Shortleaf Pine has not dependably regenerated in the study compartments for decades. Both Loblolly Pine and Shortleaf Pine were well represented in trees estimated to be 50 y old or older, with a particular concentration of pines between 50 and 70 y (Fig. 6). The oldest cored pine was a Shortleaf Pine that had 129 rings; the oldest cored Loblolly Pine had 121 rings. On average, Shortleaf Pines had 86.5 rings (standard deviation = 22.5 rings), and Loblolly Pine had 65.8 rings (standard deviation = 19.3 rings). The randomized sample did not purposefully seek out the oldest living specimens; thus, it is possible that even older pines remain in these study compartments.

OLS regressions fit to DBH and ring count produced similarly trending but statistically different lines (Shortleaf Pine ring count = 32.0746 + [0.9563 × DBH], adjusted R^2 = 0.3257, RMSE = 18.51; Loblolly Pine ring count = 19.7166 + [0.8592 × DBH], adjusted R^2 = 0.4743, RMSE = 14.01; Fig. 6). Even though both species had considerable amounts of variability around these trend lines, the age/

Table 3. Calculated oven-dry biomass of live trees >10 cm DBH by species in Compartments 1, 2, 11, and 12 on the Crossett Experimental Forest, AR, in 2014. Total biomass = aboveground + belowground.

Common name	Aboveground[A] (Mg/ha)	Belowground[B] (Mg/ha)	Total (Mg/ha)
Loblolly Pine	119.512	25.642	145.154
Shortleaf Pine	13.270	2.848	16.118
Sweetgum	7.504	1.645	9.149
Southern Red Oak	5.432	1.187	6.619
White Oak	4.783	1.047	5.830
Water Oak	5.375	1.164	6.539
Winged Elm	2.421	0.542	2.963
Red Maple	2.002	0.447	2.449
Black Cherry	0.499	0.109	0.608
Sassafras	0.315	0.071	0.386
Flowering Dogwood	0.276	0.063	0.339
Green Ash	0.509	0.110	0.619
Blackgum	0.346	0.077	0.423
Post Oak	0.284	0.063	0.347
Cherrybark Oak	0.481	0.102	0.583
Mockernut Hickory	0.240	0.054	0.294
Eastern Hophornbeam	0.173	0.039	0.212
Red Mulberry	0.154	0.034	0.188
American Holly	0.084	0.019	0.103
Willow Oak	0.058	0.013	0.071
Black Hickory	0.032	0.007	0.039
Slippery Elm	0.020	0.005	0.025
Black Locust	0.014	0.003	0.017
Eastern Redcedar	0.003	0.001	0.004
Totals:	163.8	35.3	199.1

[A]After Chojnacky et al. (2014).
[B]After Enquist and Niklas (2002).

diameter slopes were different between Loblolly Pine and Shortleaf Pine ($t = 4.238$, $P < 0.001$). According to these regressions, a 50-cm DBH Shortleaf Pine would be 17 y older on average than a similarly sized Loblolly Pine (80 y old compared to 63 y; $t = 4.298$, $P < 0.001$).

Snag composition and abundance

Only 18 snags occurred within the 144 study plots, and no new species were added to the overstory species list. The standing-dead trees included Loblolly Pine (5 snags); Shortleaf Pine, Red Maple, Southern Red Oak, and Winged Elm (2 snags each); and Flowering Dogwood, Green Ash, Sweetgum, Water Oak, and Sassafras (1 snag each). Most of the hardwood snags were small (10–25 cm DBH), while most of the pine snags were >50 cm DBH. Snag density was so low in this stand (2.5 snags/ha in 2014) that I undertook no further analysis of this stand component.

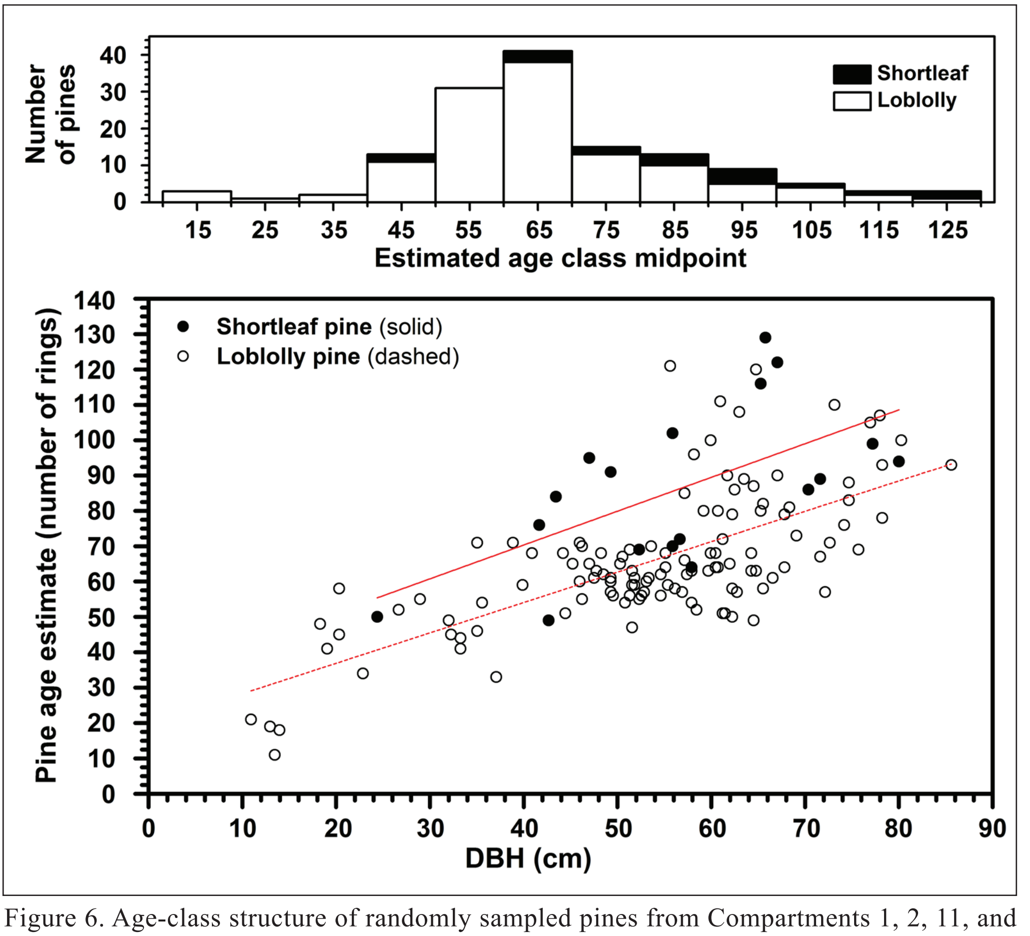

Figure 6. Age-class structure of randomly sampled pines from Compartments 1, 2, 11, and 12 on the Crossett Experimental Forest, AR, collected in 2014 (top histogram shows the sample distribution). Solid line is for the ordinary least squares (OLS) linear regression through the Shortleaf Pine; the dashed line represents the Loblolly Pine samples.

Discussion

Similarity of study compartments to old-growth, past and present

Virtually no functional examples of open, pine-dominated old-growth forests remain across the UWGCP to serve as a basis of comparison with the study compartments. Available reference conditions from historical sources (e.g., Bragg 2002) suggest that Compartments 1, 2, 11, and 12 have a number of attributes consistent with past examples of old-growth pine forests. In addition to a substantial Shortleaf Pine component, the study compartments are dominated by large-diameter pines in many age classes, with only a scattering of smaller hardwoods. At just under 20 m^2/ha of live-overstory basal area, the study compartments are at the upper end of the stand-density ranges reported in historical records for old-growth pine stands from the UWGCP (Table 4). Unlike historical old-growth, which usually had many pines from 150 to 300 years of age (Bragg 2002, 2010; Chapman 1913), lumbering followed by decades of uneven-aged silviculture seem to have capped the maximum pine age at ~130 years in the study compartments, with most (72%) overstory pines between 50 and 90 years old (Fig. 6).

In addition to the relatively high basal area and a scarcity of old pines, the biomass range of these compartments (nearly 200 Mg/ha) exceeds the biomass range historically reported for old-growth pine forests in the UWGCP (Bragg 2012b; see also Table 4). This distinction is important because some researchers have theorized that both high basal area and aboveground live-tree biomass can serve as indicators of certain types of old-growth, particularly when concentrated in large individual trees (Brown et al. 1997, Held and Winstead 1975). For example, Brown et al. (1997) used a collection of known old-growth hardwood-dominated forests from the eastern US, with aboveground biomass between 220 Mg/ha and 260 Mg/ha and 30% of all stems in trees >70 cm DBH, to identify potential old-growth stands from large-scale inventory data. While these criteria may be acceptable for mesic hardwood-dominated old-growth forests, they overstate the stand density and biomass for fire-prone, pine-dominated systems in the UWGCP. Table 4 clearly shows that in historical pine-dominated old-growth stands from this region, basal area was generally 10 m^2/ha to 20 m^2/ha and tree biomass was 100 Mg/ha to 150 Mg/ha, or approximately one-half of that reported for contemporary examples of mature, unmanaged, pine-dominated forests in southeastern Arkansas, including a few remaining unrestored examples of old-growth.

The biomass estimates I derived from inventories conducted in the mid-1930s of remaining old-growth stands within the UWGCP (summarized in Cruikshank and Wheeler [1937]; reference 6 in Table 4) are the most-comparable target for the biomass management goal of the current study compartments. Although most of the virgin pine-dominated UWGCP forests had been cut by the 1930s, Cruikshank and Wheeler's (1937) old-growth inventories covered hundreds of thousands of hectares, and likely represent a reasonable estimate of the range of stand biomass (104 Mg/ha to 163 Mg/ha in live trees, mostly from an overstory dominated by large pines) under most circumstances in this fire-prone region. Unfortunately,

Table 4. Comparison of certain stand attributes of Compartments 1, 2, 11, and 12 on the Crossett Experimental Forest, AR, with selected historical and contemporary examples of old-growth and mature second-growth pine-dominated forests across the Upper West Gulf Coastal Plain.

Source [A]	Region and state [B]	Min DBH (cm)	Total biomass (Mg/ha)	% pine biomass	Trees per ha (tph)	% pine tph	Basal area (m^2/ha)	% pine basal area	Notes
Historical sources									
1	SE AR	36.8	102.6	47.1	67.7	54.6	12.1	57.9	Old-growth, pine ridge type
1	SE AR	34.5	109.0	49.5	75.4	54.3	13.0	60.0	Old-growth, pine flat type
2	E TX	2.5	170.6	51.7	519.4	28.2	22.9	57.3	Old-growth, poorly drained thicket
3	SE AR	30.5	107.2	100.0	50.0	100.0	13.8	100.0	Old-growth, pines only
4	SE AR	5.1	128.8	100.0	222.5	100.0	18.9	100.0	Old-growth, pines only
5	E TX	10.2	54.0	100.0	168.3	100.0	8.9	100.0	Old-growth, pines only
6	NE TX	12.7	130.0	91.9	n/a	n/a	n/a	n/a	Uncut old-growth Shortleaf–Loblolly
6	NE TX	12.7	104.5	53.8	n/a	n/a	n/a	n/a	Uncut old-growth Shortleaf–Loblolly–hardwoods
6	N LA	12.7	145.1	89.0	n/a	n/a	n/a	n/a	Uncut old-growth Shortleaf–Loblolly
6	N LA	12.7	127.4	47.8	n/a	n/a	n/a	n/a	Uncut old-growth Shortleaf–Loblolly–hardwoods
6	SW AR	12.7	163.2	84.4	n/a	n/a	n/a	n/a	Uncut old-growth Shortleaf–Loblolly
6	SW AR	12.7	131.9	54.4	n/a	n/a	n/a	n/a	Uncut old-growth Shortleaf–Loblolly–hardwoods
7	SE AR	8.9	233.5	64.1	390.4	41.1	32	69.8	Old-field–second-growth pine–hardwood stand
Contemporary sources									
8	SE AR	8.9	284.6	21.7	429.9	4.3	31.4	22.7	Bottomland hardwood–Loblolly Pine old-growth
9	SE AR	9.1	224.8	48.2	349.2	16.2	28.2	51.9	Unmanaged pine–hardwood growth (LWDF)
10	SE AR	9.1	259.4	61.3	506.5	22.8	34.5	63.5	Old-field–second-growth pine–hardwood stand
11	CEF AR	9.1	310.0	47.7	454.7	13.9	36.9	52.7	Reynolds Research Natural Area; pine–hardwood
12	SE AR	9.1	317.3	37.4	333.9	16.3	37.1	52.2	Mature pine–hardwood, old-growth cull remnants
13	CEF AR	9.1	101.8	97.8	253.5	91.7	15.9	97.3	Average of Good and Poor Farm Forestry Forties
14	CEF AR	9.9	199.1	72.9	166.4	46.4	19.8	81.2	Compartments 1, 2, 11, 12

[A]Size, oven-dry biomass, trees per hectare, and basal area derived from the following sources: 1 = Olmsted (1902), 2 = Zon (1905), 3 = Chapman (1913), 4 = Forbes and Stuart (1930), 5 = Garver and Miller (1933), 6 = Cruikshank and Wheeler (1937), 7 = Bragg (2004b), 8 = Heitzman et al. (2004), 9 = Bragg (2006), 10 = Bragg and Heitzman (2009), 11 = Bragg and Shelton (2011), 12 = Bragg (2013), 13 = Bragg and Guldin (2015), 14 = current study.
[B]Region and state abbreviations: AR = Arkansas, LA = Louisiana; TX = Texas, E = eastern, NE = northeastern, N = northern, SW = southwestern, SE = southeastern, CEF = Crossett Experimental Forest.

these inventories lack the species and tree-size detail needed to provide the required context; other sources (including some found in Table 4) are required to help set specific compositional and structural objectives.

The impacts of long-term management on stand development

The study compartments had been maintained at their 3-, 6-, or 9-year uneven-aged cutting cycles for at least 29 years; this regimen had a decided influence on current age-class structure. Of the 139 overstory pines aged during this study, 28.1% originated prior to the establishment of the cutting-cycle study in 1937, 64.7% during the years of the study (1937–1969), and only 7.2% since 1970 (Fig. 6). This skewed, broadly modal multi-aged distribution differs notably from that observed in the nearby Farm Forestry Forties (Bragg and Guldin 2015), and is considered silviculturally "unbalanced". The failure to achieve significant pine regeneration over the last 45 years is largely due to decreased overstory regulation (D.C. Bragg, pers. observ.). Lack of management activities in the CEF during the 1970s profoundly impacted uneven-aged stand structure, with increased pine-overstory basal area and cover by shade-tolerant hardwoods in the understory (Cain and Shelton 2001). Harvests conducted since 1980 have focused on thinning the overstory of the study compartments from below. Not surprisingly, the combination of a relatively continuous overstory, coupled with a dense, hardwood-dominated understory has greatly limited pine regeneration. Furthermore, it appears that the periodic prescribed fires conducted in recent years have also removed some of the younger, less fire-tolerant Loblolly Pine without improving establishment conditions sufficient to promote the recruitment of new Shortleaf Pine.

Perhaps more surprising than the influence of past cutting cycles is the persistence of the oldest pines in this long-managed stand. Even after nearly 80 years of rigorous management based on cutting cycle and periodic thinning, about 12% of the overstory pines may have originated prior to the late-1910s lumbering of the virgin timber—including a number that germinated prior to 1900. Years ago, Reynolds (1969:2) noted some of these old trees in his descriptions of the initial stand conditions when the compartments were included in the uneven-aged-stand study: "Except for a few acres of abandoned fields, the land has always been in forest … in 1937, none of the stands had been previously managed. The pines consisted of grown-up residuals (stems <31 cm DBH) from the virgin forest scattered among second-growth trees that had seeded in after the virgin timber had been cut." Undoubtedly, many of the pines that had established before 1937 have been harvested, and mortality will continue to take others, but it is apparent from this study and others (Bragg and Guldin 2015) that uneven-aged silvicultural practices in Loblolly Pine and Shortleaf Pine forests can retain some of the oldest size classes.

Shortleaf Pine has long been known to be less productive than Loblolly Pine on most sites (Mattoon 1915, Mohr and Roth 1897). For example, several studies of soils and site index across southeastern Arkansas and northeastern Louisiana (Turner 1936, Zahner 1958) found that Loblolly Pine produced larger trees than Shortleaf Pine at the same base ages. This pattern also appears in the age structure of the study compartments, with Shortleaf Pines significantly older on average than

Loblolly Pines of comparable diameter (Fig. 6). This slower growth, though not inherently problematic, suggests that Shortleaf Pine could have been selected against by foresters who marked timber for harvest (Bragg 2016). This practice likely occurred on the CEF, which did not traditionally manage for one pine species over another for most of its history. Reynolds (1951) reported that the implementation of uneven-aged silviculture on the CEF appeared to gradually favor Loblolly Pine over Shortleaf Pine—a tacit recognition that marking preferences and the suppression of fire were affecting forest development.

Conservation challenges and their management implications

There are many challenges to the conservation of the diverse and dynamic natural-origin pine-dominated forests of the UWGCP, not the least of which is the widespread expansion of short-rotation, intensively managed Loblolly Pine monocultures. As a direct consequence of this conversion, one of the primary conservation concerns is the rapid decline of Shortleaf Pine (Bragg 2016, Moser et al. 2007, Oswalt 2012), due in part to increased coverage of Loblolly Pine plantations. However, Shortleaf Pine is also disappearing from many otherwise intact natural-origin forests. Presumably, biased silvicultural selection favoring Loblolly Pine, and the absence of frequent fire that helped to maintain the historically prominent UWGCP Shortleaf Pine component, have been the primary causes of the decline in natural-origin stands (Bragg 2016).

Although Compartments 1, 2, 11, and 12 have more Shortleaf Pine today than most of the UWGCP, there is some evidence for a pronounced decline within this study area. Professor H.H. Chapman and Yale forestry students helped to inventory some of the properties of the Crossett Lumber Company in this part of Ashley County, and he stated Shortleaf Pine and Loblolly Pine were found "… in an almost equal mixture …" in the virgin timber, with more Shortleaf Pine on the drier sites (Chapman 1913:4). Reynolds et al. (1984) reported a somewhat lower fraction of Shortleaf Pine (25%, compared to 50% for Loblolly Pine and 25% for hardwoods) in the virgin forests of the Crossett area. The second-growth stands that arose following the original agricultural clearing and lumbering at the turn of the 20th century also had a significant Shortleaf Pine component—many reports list Shortleaf Pine as 30–40% of the saw-timber volume (Turner 1936, USDA Forest Service 1933, Wackerman 1936). More locally, Guttenberg (1954) noted that the old-field stands of the pulpwood-thinning study in Compartments 1, 2, 11, and 12 were about 80% Loblolly Pine and 20% Shortleaf Pine prior to their cutting in 1937.

A 2000 inventory conducted in Compartments 2 and 12 (then the only compartments in this study) noted about 26% of the pine basal area was Shortleaf Pine (Bragg 2004a). A later (2007) 100% inventory of Compartment 12 found just over 15% of the pine overstory basal area was Shortleaf Pine (D.C.. Bragg, unpubl. data); Compartment 2 is slightly higher in elevation and more Shortleaf Pine-dominated than Compartment 12. Shortleaf Pine currently accounts for ~10% of the pine overstory basal area in all 4 compartments (Table 1). Restoring the study compartments to the 25–50% Shortleaf Pine overstory composition once common to the uplands of the UWGCP (Bragg 2002, 2016; Chapman 1913; Reynolds 1959; Reynolds et al. 1984) represents a major conservation challenge, especially given recent research suggesting that many putative Shortleaf Pine seedlings are actually Shortleaf Pine–Loblolly Pine hybrids (Stewart et al. 2012). Fire appears to be a crucial environmental factor in maintaining the genetic identity of both Shortleaf Pine and Loblolly Pine. Burning tends to only top-kill young Shortleaf Pine, which can resprout, while it kills both Loblolly Pine and Shortleaf Pine–Loblolly Pine hybrid seedlings (Stewart et al. 2015, Tauer et al. 2012, Will et al. 2013). Because there are as yet no mechanical or chemical treatments that can cost-effectively emulate this selection process, the use of frequent fire to bolster the abundance of Shortleaf Pine appears to be a potentially useful management tool.

A related conservation issue is the failure of recent management efforts to recruit sufficient pine seedlings of either species to help ensure that these compartments remain pine-dominated. Although not specifically inventoried for this paper, I observed only limited pine regeneration (stems ≤10 cm DBH) across most of the compartments. Decades of experience in uneven-aged southern pine silviculture at the CEF have provided a reliable blueprint for achieving good Loblolly Pine recruitment—the evidence is less convincing that this system is effective for reproducing Shortleaf Pine in quantity. Although fire appears to be vital to retaining significant proportions of Shortleaf Pine, it has long been considered antithetical to uneven-aged southern pine silviculture because it kills too many pine seedlings to ensure proper stocking, especially if stands are burned frequently enough to control non-pine competing vegetation (e.g., Baker et al. 1996, Guldin 2011). Research on the CEF has shown that hardwood, shrub, vine, and briar competitors are insufficiently controlled by infrequent dormant-season fires or mechanical releases (Cain 1993, Cain and Shelton 2002). Hence, a blended approach to pine regeneration may be required, with locally intense treatments (including some herbicides or mechanical removals) to control non-pine vegetation and permit pine establishment immediately after an overstory harvest, coupled with a fire of sufficient intensity shortly thereafter to help reduce the number of Loblolly Pine and Shortleaf-Loblolly hybrid seedlings while simultaneously stimulating Shortleaf Pine to resprout. Once sufficient pine regeneration has been accumulated, additional burning treatments of understory woody vegetation could be implemented to help encourage the development of a forb- and graminoid-dominated understory.

Conclusions

Managing mature second-growth forests for old-growth-like conditions presents distinct challenges, and is made even more difficult when initial conditions are unknown. However, this study was initiated in a stand with a reasonably well-documented history. The baseline data presented in this paper will help guide the long-term restoration of these study compartments to develop old-growth-like characteristics by providing both starting conditions and benchmarks for evaluating success. For instance, a survey of pine age-classes found that a small portion of the overstory dates back to before the original "big cut", suggesting that the biological legacy of the virgin forest has not vanished even after decades of silviculture at these sites. The overstory of this Loblolly Pine-dominated stand is decidedly uneven-aged, due largely to decades of selective cutting in the middle of the 20th century. However, limited pine regeneration following more-recent lighter harvests and periodic prescribed fires suggests that additional treatments will be needed to maintain dominance of pine in the overstory and the presence of Shortleaf Pine, which has continued to decline in prominence.

The long management history of Compartments 1, 2, 11, and 12 on the CEF has had both obvious and subtle influences on the present-day forest that affect future restoration efforts. As an example, even though the pine overstory represents a single layer of dominant and codominant trees and is thus reminiscent of an even-aged stand, this simplicity is not reflected in the pine age-structure of the study compartments. Silvicultural practices from years ago continue to influence this stand. Decades of selective harvesting and the absence of prescribed fire during this critical period (1940–1970) both contributed to the decline of Shortleaf Pine and provided better establishment conditions for Loblolly Pine. The failure to reverse this trend has significant implications for the long-term viability of the overall restoration strategy for these stands, and suggests further interventions are required to ensure a continued Shortleaf Pine presence. The resulting evenly distributed, well-stocked overstory is not conducive to regeneration of either Shortleaf Pine or Loblolly Pine, an aspect that will need to be remedied in order to maintain pine dominance.

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Appendix A. Scientific names with authorities and common names of other species named in this paper (nomenclature from Gentry et al. 2013).

Scientific name	Common name
Pinus palustris Mill.	Longleaf Pine
Callicarpa americana L.	American Beautyberry
Rhus glabra L.	Smooth Sumac
Vitis rotundifolia Michx.	Muscadine
Gelsemium sempervirens (L.) J.St.-Hil.	Carolina Jessamine
Toxicodendron radicans (L.) Kuntze	Poison Ivy
Rubus L.	Blackberry
Smilax L.	Greenbriar
Ligustrum sinense Lour.	Chinese Privet
Lonicera japonica Thunb. ex Murray	Japanese Honeysuckle
Lygodium japonicum (Thunb. ex Murray) Sw.	Japanese Climbing Fern
Triadica sebifera (L.) Small	Chinese Tallow-tree