Lessons from 72 years of monitoring a once-cut pine-hardwood stand on the Crossett Experimental Forest, Arkansas, U.S.A.

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ABSTRACT

The Crossett Experimental Forest was established in 1934 to provide landowners in the Upper West Gulf Coastal Plain with reliable, science-based advice on how to manage their loblolly (*Pinus taeda*) and shortleaf (*Pinus echinata*) pine-dominated forests. A key component of this program was the establishment of an unmanaged control, currently known as the Russell R. Reynolds Research Natural Area (RRNA). Originally intended to show how the lack of regulation reduced sawtimber production compared to more intensively managed stands, the once-cut RRNA is now recognized as an increasingly scarce example of an undisturbed, mature pine-hardwood stand. This, in turn, has led to studies on forest succession, coarse woody debris, old-growth stand structure conditions, and biomass accumulation patterns. Long-term (72 years, to date) research has shown, as an example, that the RRNA has sustained >33 m^2 of basal area and over 240 Mg of aboveground live tree biomass per hectare for decades, values that are near the upper end of temperate forest ecosystems (outside of rainforests). These high levels are made possible by the abundance of large pines; however, pine mortality and natural successional patterns in this undisturbed stand will likely result in declining biomass in the near future. Additional work is possible regarding endangered species habitat and paleoclimate change, and there is potential for studies on invasive species effects on mature, unmanaged forests. Monitoring will continue indefinitely on the RRNA.

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1. Introduction

One of the most important contributions to forestry by the United States (U.S.) government are experimental forests (EFs). From the 1908 establishment of the first U.S. Department of Agriculture Forest Service (USFS) experimental forest in Fort Valley, Arizona, to the 2009 creation of the Héen Latinee Experimental Forest in Alaska, the lasting and often large-scale nature of the research and demonstration projects at 81 sites across the country represents an unparalleled manifestation of the vision of Raphael Zon, who sought to establish the scientific foundation for the forest management practices being implemented by the fledgling federal agency (Young, 2008). This foresight, embodied locally by scores of scientists, technicians, administrators, and other support staff, has not only solidified the science-based reputation of National Forest management, but has provided for an unprecedented set of opportunities to continue this effort.

EFs are usually created to address a set of predetermined questions, with research programs based on these topics maintained (in some cases) for many decades. However, the framework in which EFs are designed is flexible enough to permit both the adaptation of existing studies for new questions as well as the establishment of fresh research directions based on emerging issues. For instance, EFs now are a critical part of the global change research strategy of the USFS (Solomon et al., 2009). In this frontier, scientists are adapting long-term records from EFs to better understand carbon dynamics under different management regimes across a range of scales. As an example, the data from conventional growth and yield studies can be recast in terms of carbon sequestration to help landowners and policymakers produce solutions towards optimizing the management of U.S. forestlands (e.g., Canadell and Raupach, 2008).

The 680-ha Crossett Experimental Forest (CEF), located 7 km south of the city of Crossett (Ashley County) in extreme southeastern Arkansas (Fig. 1), provides a classic example of how the past work of early USFS scientists can serve us now and in the future. The CEF is one of the oldest experimental forests in the southeastern U.S., and contains a number of research and demonstration areas that have been continuously maintained for >70 years. One of these study areas, the 32.4-ha once-cut Russell R. Reynolds Research Natural Area (RRNA), is an example of mature unmanaged pine-hardwood forests formerly common to
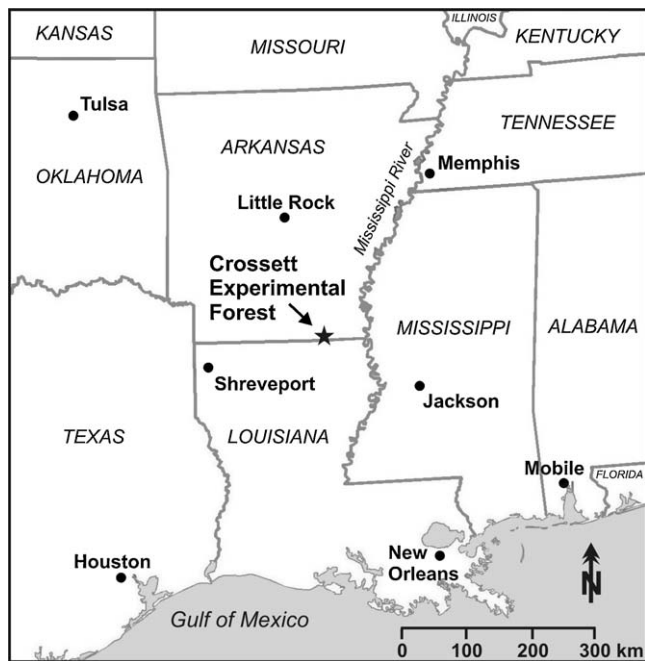
Fig. 1. Location of the Crossett Experimental Forest (latitude 32°2′North, longitude 91°57′West) relative to the geography of the southeastern United States.

the Upper West Gulf Coastal Plain (UWGCP). This paper describes the primary lessons learned from 72 years of observing the RRNA, and places this work in context of possible venues of future research.

2. Establishment history

2.1. A brief human history of the Crossett area

At the Hernando de Soto expedition of the early 1540s, this portion of southeastern Arkansas was dominated by Native Americans of the Tunican and Koroa cultures (Hoffman, 1993; Jeter and Early, 1999; Sabo, 1992). Archeological and paleoclimatic records suggest that massive Indian population decline(s) followed the initial Spanish explorations, likely caused by a combination of disease, prolonged drought, warfare, and related social upheaval (Young and Hoffman, 1993; Stahle et al., 2007). However, we have virtually no written record of this period—after first contact, there was no documented interaction between Europeans and Native Americans until French explorers and missionaries returned to the area during the late 17th century. By this time, the Quapaw Indians had taken control of the now sparsely populated region, and they remained until treaties signed between 1818 and 1833 moved them further south and west (Sabo, 1992). During the 18th and 19th centuries, other tribes from east of the Mississippi River canvassed the region for hunting and foraging grounds and to escape Euroamerican persecution. Few of these groups had any kind of permanence, and virtually all had moved (or been pushed) to Indian Territory by 1836, when Arkansas became a state. Undoubtedly, Native Americans played a key role in the development of the vegetation patterns of the Crossett region, as historical records note their use of fire and land clearing (Key, 2000; Berry et al., 2006).

The earliest regional Euroamerican settlement was built in 1686 by the French at Arkansas Post 122 km to the north of the CEF, followed by a mid-18th century French community at Longview along the Saline River (about 38 km to the north) and a late 18th century Spanish post at Fort Miro (now the city of Monroe, Louisiana, approximately 40 km to the south). Besides these

outposts, there were almost no permanent Euroamerican settlers in this region prior to the 1804–1805 Ouachita River expedition of William Dunbar and George Hunter (Etheridge, 1957; Berry et al., 2006). Southeastern Arkansas became part of the U.S. following the 1803 Louisiana Purchase, but remained largely unknown until the first General Land Office (GLO) public land surveyors traversed the area after 1814. The earliest boundary line surveys of Ashley County were done in 1818, but these make no mention of settlement. Interior land surveys during the mid- to late-1820s reported a few settlers and their scattered homes, improvements, and trails (Etheridge, 1957; Bragg, 2004d). In the 1840s, more organized development appeared in other parts of Ashley County, and by 1860, much of the landscape was occupied with farms and even plantations (Etheridge, 1957).

The first decades of regional settlement were dominated by relatively small-scale agricultural efforts, with timber cut primarily to clear farms and for local consumption of wood in homes, stores, fences, and other parts of the infrastructure (Curry, 1960). The GLO surveyors noted some lumbering along the Ouachita River just west of what would become the city of Crossett in the late 1820s, with baldcypress (*Taxodium distichum*) and pine (probably loblolly, *Pinus taeda*) being cut and rafted to mills in Louisiana (Curry, 1960; Bragg, 2004d). Commercial-scale exploitation of the timber in southern Arkansas did not occur until after extensive railroad penetration by the late 1800s (Curry, 1960). The Crossett Lumber Company began large-scale forest acquisitions and lumbering just before the turn of the 20th century, joining other smaller operators such as the Gulledge Brothers Lumber Company (Darling and Bragg, 2008). The area that would eventually become the Crossett Experimental Forest was logged of its virgin forest between 1915 and 1920 (Darling and Bragg, 2008).

2.2. Establishment of the Crossett Experimental Forest

Lumbering in southern Arkansas was often not as environmentally devastating as in other parts of the South. Because of a lack of floatable streams, loggers used oxen, mules, and horses to haul the felled logs from the woods to temporary railroads (tramlines) built every few hundred meters. Only the biggest and the best trees were harvested during this period, with any small or defective trees left behind. In many places, this cutting strategy completely cleared the timber, but in other locations a substantial residual stand remained (Williams, 1925; Hall, 1945). Company staff soon noticed the considerable growth rates of many of these residual pines, and took some of the first tentative steps towards the possibility of future harvests from cutover stands. As early as 1909, the Crossett Lumber Company instituted a 36-cm minimum diameter limit for their pine stands (Williams, 1925). Yale University Professor H.H. Chapman further encouraged the protection of regenerating pine forests from fire and other threats (Chapman, 1913; Hall, 1945; Reynolds, 1980; Bragg, 2005; Darling and Bragg, 2008) and helped lead the Crossett Lumber Company towards the scientific management of its cutover timberlands.

By the 1920s, the Crossett Lumber Company had committed to using good forestry practices to supplement its virgin pine lumbering operation (Reynolds, 1980; Darling and Bragg, 2008). However, silvicultural knowledge during this time was limited. To help support their efforts, the Crossett Lumber Company negotiated an agreement with the USFS's Southern Forest Experiment Station to establish a research station for developing effective management practices for loblolly and shortleaf (*Pinus echinata*) pine-dominated forests (Reynolds, 1980). Boundaries for the newly christened CEF were laid out in late 1933 on cutover company lands, and the facility began regular operations in 1934 under the supervision of Russell R. Reynolds. During the first couple of years, the 680-ha CEF was subdivided into 42
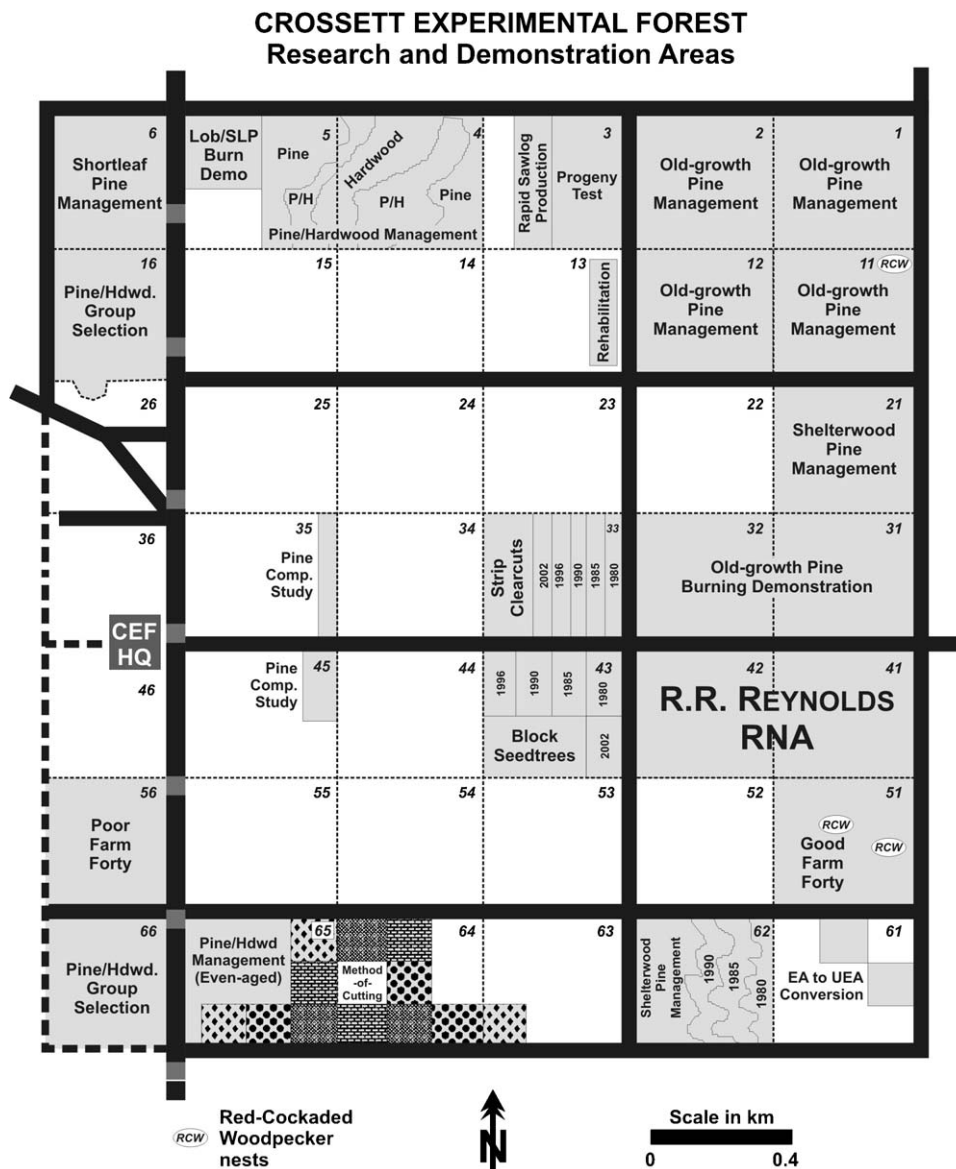
CROSSETT EXPERIMENTAL FOREST
Research and Demonstration Areas

Fig. 2. Location of the Reynolds Research Natural Area in the Crossett Experimental Forest.

management compartments, and firebreaks and a road network were built between these ∼16-ha compartments. After the infrastructure was completed, Reynolds began work on identifying the research and demonstration projects.

2.3. Reservation of the unmanaged natural area

Although the first large-scale studies on the CEF were installed after 1936, the decision to reserve an unmanaged "check" block to the north of the 16.2-ha uneven-aged demonstration compartment known as the Good Forty (Fig. 2) was made in 1935 (Reynolds, 1980). In 1937, Reynolds protected Compartments 41 and 42 (32.4 ha) from harvesting to demonstrate to foresters and landowners the negative consequences of passively managing their woodlots. The transition from unmanaged stand to a formal Research Natural Area was only recently made official (USFS, 2005). However, with the exception of decades of fire exclusion and some limited (<0.5 ha) salvage along the edge of the stand following an outbreak of southern pine beetle (*Dendroctonus frontalis*) in the early 1970s, this stand has been allowed to develop without intervention for >70 years (Fig. 3).

The establishment documentation for the RRNA codifies the no-intervention management approach indefinitely into the future, allowing for the continued study of this particular parcel well beyond its commercial rotation age. Note that passive management in this stand specifically establishes fire exclusion as a goal; this is more consistent with contemporary silvicultural practices at the CEF, whereas ecosystem restoration approaches would emphasize the return of presettlement burning regimes. This is important, because during the last few decades, research has shifted away from comparing the productivity of what is now known as the RRNA with other CEF silvicultural studies into analyses of long-term changes in composition, structure, and functionality. Hence, although this stand is generally recognized as an increasingly rare example of mature, unmanaged pine-dominated forest, its developmental trajectory is not comparable to that of the virgin forest.

2.4. Inventory designs and implementation

There have been a number of inventories taken of the RRNA (not all of which are discussed in this paper). From its establishment in

Fig. 3. The Reynolds Research Natural Area in 1959, approximately 4 decades after virgin timber of this stand was cutover. Photo from the USFS archives at the Crossett Experimental Forest.

1937 until the late 1980s, a 100% census was made of every live tree >9.0 cm in diameter at breast height (DBH) in the 32.4-ha RRNA. Fewer staff and resources by the early 1990s led to a switch to plot-based sampling of this stand. Since 1991, overstory inventories of the RRNA have been conducted on 21 regularly distributed 0.1012-ha square plots. Within each overstory plot, five 0.00081-ha circular woody understory subplots are located, one near the plot center and the rest near the corners of the overstory plot.

Other ecological inventories of the RRNA have varied in their implementation. For instance, different measures of dead wood have been collected over the past 20 years. During the mid-1990s, a snag-only inventory was conducted (Cain and Shelton, 1996). Later that decade, Zhang (2000) used a planar intersection method in 20 of the 21 established overstory plots to estimate coarse woody debris (CWD) loads. Most recently, an area-based CWD inventory

was taken of the 21 overstory plots (D.C. Bragg, unpublished data). Other information has been collected opportunistically—as an example, limited soil and litter data were collected following various small-scale mortality events that have occurred in recent decades (M.G. Shelton, unpublished data).

3. Lessons from early long-term studies

The earliest research that included the RRNA concentrated on two subject areas: contrasts with managed stand productivity and changes in stand composition and structure. Both of these emphases were possible because of the frequent (every 5–10 years) overstory inventories. The contrasting productivity aspect of the RRNA was intended since the establishment of the reserve. However, the detailed study of stand dynamics was a later idea that arose from the growing interest in alternative strategies for southern pine stands and the increasing scarcity of unmanaged upland pine forests.

3.1. Managed versus unmanaged woodlot productivity studies

Over the years, the pine sawtimber standing crop of the RRNA almost always exceeded that of the managed stands, especially those treated for uneven-aged stand structure, but the average pine sawtimber growth was substantially lower than in the managed compartments. For example, Baker and Bishop (1986) summarized 46 years of growth and yield data from the RRNA and an adjacent managed compartment. They reported that annual pine total merchantable growth in the unmanaged RRNA rarely exceeded 4.0 m^3/ha, while the managed compartment grew between 3.4 and 10.4 m^3/ha every year during this same period (Table 1).

Reynolds appears to have been so impressed with this difference that after the first major report on the productivity of selectively managed pine stands on the CEF (Reynolds, 1959), he did not report on unmanaged stand production in subsequent updates to this long-term study (e.g., Reynolds, 1969; Reynolds et al., 1984). Of course, Reynolds recognized that individual pines within the RRNA did not quit growing—the fact that total pine basal area remained relatively constant over the decades even as pine stocking declined due to continued mortality and the lack of new recruitment (Fig. 4) indicates that individual growth has offset losses.

3.2. Unmanaged stand development studies

Since the mid-1980s, researchers have reported on various aspects of the maturation of the forest on the RRNA (e.g., Guldin

Table 1
Comparison of growth and yield using the Reynolds Research Natural Area (RNA) as the unmanaged control for an adjacent managed compartment on the Crossett Experimental Forest (adapted from Baker and Bishop, 1986).

Year	Reynolds RNA				Adjacent compartment	
	Standing volume (m³/ha)[a]		Annual growth (m³/ha)[a]		Standing volume (m³/ha)[a]	Annual growth (m³/ha)[a]
	Pine	Hardwood	Pine	Hardwood	Pine only[b]	
1937	102.7	46.5	–	–	36.4	–
1942	123.4	45.4	4.1	−0.2	53.6	3.4
1946	135.1	43.0	2.9	−0.6	75.4	4.8
1952	162.3	52.6	4.5	1.6	92.9	4.1
1957	173.2	47.6	2.2	−1.0	135.4	10.4
1963	183.5	50.0	1.7	0.5	165.6	10.3
1973	202.9	59.1	2.0	0.9	222.2	7.6
1983	207.2	66.8	0.4	0.8	234.4	4.1

[a] These were initially reported in Baker and Bishop (1986) as total merchantable volume in cubic feet per acre. We multiplied these volumes by 0.069978 to convert them to metric units (cubic meters per hectare).
[b] No hardwoods were measured in this compartment because there were so few.
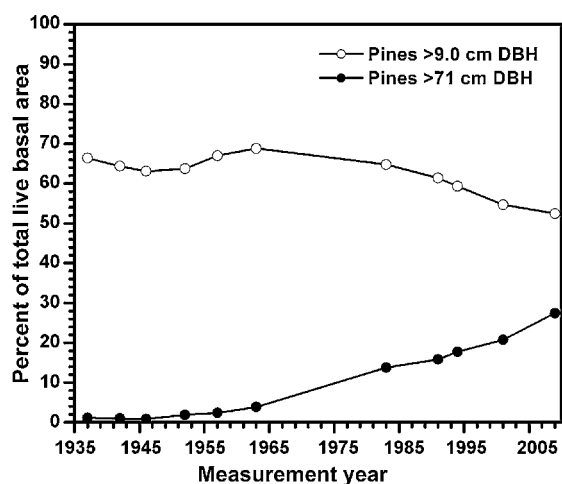
Fig. 4. Basal area for pines >9.0 cm DBH and pines >71 cm DBH as a percent of total live merchantable basal area (all trees >9.0 cm DBH) on the Reynolds RNA.

and Baker, 1985; Cain and Shelton, 1994, 1995, 1996, 2001; Shelton and Cain, 1999; Zhang, 2000; Bragg, 2004b), often using the long-term data on overstory tree species abundance. During the past 72 years, the RRNA has witnessed the gradual ebbing of the dominance of the pines. Shortleaf, in particular, has declined steeply—since 1991, it has dropped from 24 to 7 stems/ha in 2009 with a corresponding basal area loss of 57% (Table 2). Loblolly pine also lost 16 stems/ha between 1991 and 2009, although the strong growth of the surviving loblolly pine limited its basal area decline to 0.5%. Through mortality and ingrowth into large size classes, small diameter pines are an increasingly rare feature of the RRNA—pines >71 cm DBH now constitute 28% of total stand basal area, even as the overall basal area proportion of the tree component (those >9.0 cm DBH) had declined from 69% near its peak to 52% in 2009 (Fig. 4).

Stocking patterns (in terms of stems/ha) have shown an even more dramatic shift than basal area. During the first decade of its

existence, the RRNA was clearly dominated by pine in all size categories (Fig. 5). By the early 1950s, however, the smallest pines had either died or been recruited into the now closed overstory, and over the next couple of decades a broadly unimodal size class distribution arose (Fig. 5). Oaks (*Quercus* spp.) share a similar (if somewhat lagged) abundance history, with the smallest size classes dropping out of the stand during the 1990s. Pines and oaks are being gradually replaced by increasingly shade-tolerant hardwood species such as red maple (*Acer rubrum*), ash (*Fraxinus* spp.), American holly (*Ilex opaca*), blackgum (*Nyssa sylvatica*), eastern hophornbeam (*Ostrya virginiana*), and elms (*Ulmus* spp.), especially during the last 2 decades (Table 2).

The successional transition from pine-dominated stands to increasingly shade-tolerant hardwoods in the southeastern U.S. has long been documented (e.g., Billings, 1938; Quarterman and Keever, 1962; Halls and Homesley, 1966; Nicholson and Monk, 1975; Switzer et al., 1979), and these results are consistent with observations on other protected, pine-dominated old-growth stands in the southeastern U.S. (e.g., Gliztenstein et al., 1986; Fail, 1991; Heitzman et al., 2004; Masters et al., 2007). In fact, Quarterman and Keever (1962: 182) stated that "[n]o serious ecologist entertains the concept of a pine climax in the [southern] Coastal Plain." Yet, early observers of these forests in the early 1900s noted an overwhelming dominance of pine with a variety of ages on mesic sites, sometimes with too few hardwoods to warrant mention (e.g., Chapman, 1913; Hall, 1945; Reynolds, 1980; Bragg, 2008). This suggests that historically, a disturbance-mediated subclimax pine forest was present, with frequent surface fires (4–6-year return interval in this region; Frost, 1998) likely perpetuating the dominance of the more fire-tolerant pines prior to effective wildfire control in the 1930s (e.g., Garren, 1943; Quarterman and Keever, 1962). Historically, large-scale catastrophic wind events were also thought to help sustain pine-dominated forests in the Arkansas Gulf Coastal Plain (Turner, 1935), perhaps in conjunction with fires that consumed the blown-down timber.

Some have postulated that for a variety of reasons, the under-representation of canopy tree reproduction in the understory could

Table 2
Comparison of live tree density and basal area of the Reynolds Research Natural Area in 1991 and 2009, for stems >9.0 cm DBH.

Common name	Species name	Density (stems/ha)		Percent change since	Basal area (m²/ha)		Percent change since
		1991	2009	1991	1991	2009	1991
Shortleaf pine	*Pinus echinata*	24.47	7.06	−71.15	3.80	1.65	−56.64
Loblolly pine	*Pinus taeda*	71.54	56.01	−21.71	17.91	17.83	−0.49
Red maple	*Acer rubrum*	10.83	12.71	17.39	0.14	0.21	52.55
Hickory spp.	*Carya* spp.	1.41	0.94	−33.36	0.08	0.05	−32.47
Mockernut hickory	*Carya tomentosa*	1.88	1.88	0.00	0.11	0.13	17.27
Flowering dogwood	*Cornus florida*	25.89	6.12	−76.36	0.24	0.07	−71.01
White ash	*Fraxinus americana*	3.30	4.71	42.85	0.12	0.22	81.82
Green ash	*Fraxinus pennsylvanica*	7.53	12.24	62.49	0.14	0.30	119.85
American holly	*Ilex opaca*	14.59	36.24	148.40	0.14	0.47	229.58
Sweetgum	*Liquidambar styraciflua*	104.96	108.72	3.59	2.14	3.52	64.64
Red mulberry	*Morus rubra*	0.94	0.00	−100.00	0.02	0.00	−100.00
Blackgum	*Nyssa sylvatica*	31.06	40.48	30.30	0.52	0.88	69.04
Eastern hophornbeam	*Ostrya virginiana*	37.18	58.36	56.96	0.39	0.69	76.02
Black cherry	*Prunus serotina*	0.00	1.41	n/a[a]	0.00	0.02	n/a[a]
White oak	*Quercus alba*	41.42	32.48	−21.59	5.21	6.16	18.27
Southern red oak	*Quercus falcata*	84.25	7.06	−91.62	2.74	1.42	−48.16
Cherrybark oak	*Quercus pagoda*	8.47	5.65	−33.33	0.62	0.79	28.73
Water oak	*Quercus nigra*	10.83	6.12	−43.47	0.74	0.78	6.26
Willow oak	*Quercus phellos*	0.94	0.47	−49.95	0.07	0.04	−50.00
Post oak	*Quercus stellata*	10.83	6.12	−43.47	1.14	0.86	−24.93
Sassafras	*Sassafras albidum*	3.30	1.88	−42.85	0.05	0.04	−21.57
Winged elm	*Ulmus alata*	28.24	43.30	53.33	0.44	0.75	71.72
American elm	*Ulmus americana*	1.88	2.82	49.97	0.02	0.05	177.78
Slippery elm	*Ulmus rubra*	1.41	1.41	0.00	0.02	0.03	38.89
Horse-sugar	*Symplocos tinctoria*	0.47	0.47	0.00	0.00	0.01	66.67
Totals		527.61	454.66		36.77	36.93	

[a] Lack of black cherry on the remeasurement plots in 1991 makes it impossible to calculate change in 2009.
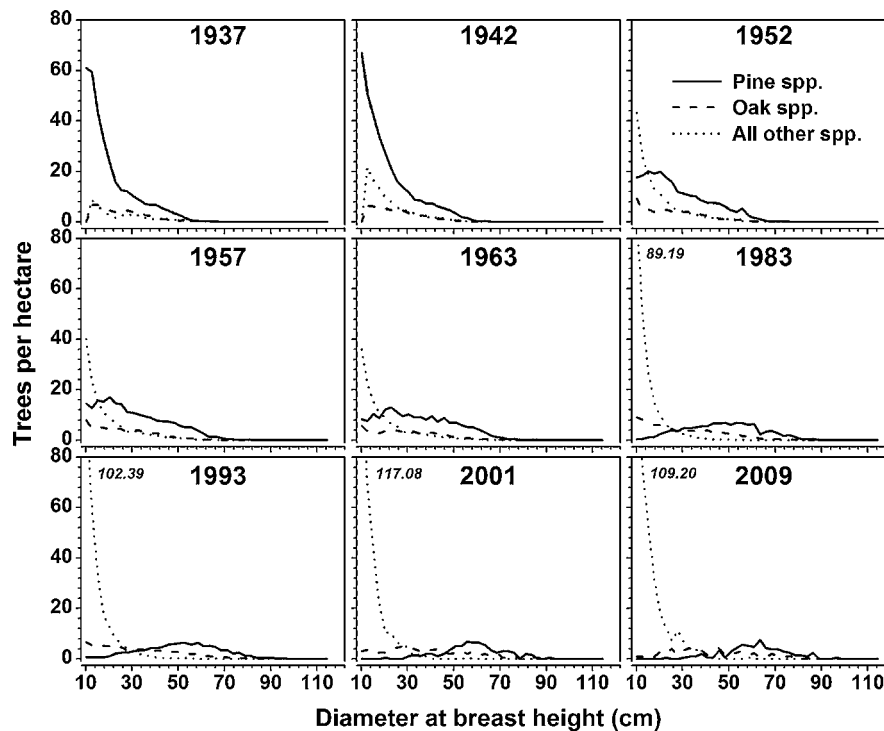
Fig. 5. Shifts in tree species group abundance on the Reynolds Research Natural Area from the 1937 100% inventory through the 2009 field sample. The italicized numbers in the upper left corners of the graphs from 1983–2009 are the number of stems in the smallest DBH class otherwise truncated by the scale.

affect the long-term stability of cutover forests and suggest the likely climax species (e.g., Harcombe and Marks, 1978). Despite the documented high seed production of the pine overstory of the RRNA (Cain and Shelton, 2001), the decades-long absence of pine regeneration (except for new germinants) suggests the current stand is transitional, with increasingly shade-tolerant species likely to replace pine in the overstory barring truly catastrophic disturbance (Cain and Shelton, 1995). The unmanaged RRNA can serve as a standard upon which to compare other stands that receive more frequent pine-killing disturbances and are thus thought to have their successional conversion to hardwood accelerated (e.g., Blair and Brunett, 1976).

Others have suggested different means to evaluate successional status using more quantitative measures of stand development. For instance, Held and Winstead (1975) hypothesized that mesic climax forests have ≥ 30 m^2/ha of basal area in trees ≥ 10 cm DBH. However, their index does not reflect the size-density capacity of early successional stands in this region—multiple examples of mature, unmanaged pine-dominated once-cut forest with ≥ 30 m^2/

ha of basal area have been documented (e.g., Bragg, 2004a; Liechty and Guldin, 2009; Bragg and Heitzman, 2009), including the RRNA, which has exceeded 34 m^2/ha for most of the last 30 years (Table 3).

4. Addressing today's issues

4.1. Biomass patterns

Biomass has become an increasingly important measure of ecosystems in the southeastern U.S., especially with regard to carbon (C) sequestration, C credits, and bioenergy potential (Han et al., 2007). To date, much of this interest has focused on rapidly growing fiber plantations (e.g., Baral and Guha, 2004; Williams and Gresham, 2006), and far less attention has been paid to stands of natural origin, especially unmanaged ones. This is important, as there is some debate over the ability of older, unmanaged forests to store more atmospheric CO_2 than younger, more intensively managed stands (e.g., Harmon et al., 1990; Carey et al., 2001;

Table 3
Basal area by species group and year for all live stems >9.0 cm DBH on the Reynolds Research Natural Area.

Year	Pine[a] basal area (m^2/ha)	Oak[a] basal area (m^2/ha)	Other hardwoods[a] basal area (m^2/ha)	Total basal area (m^2/ha)	Basal area in pines >71 cm DBH (m^2/ha)
1937	13.03	3.99	2.60	19.61	0.22
1942	15.18	3.79	4.61	23.58	0.24
1946	15.73	3.80	5.40	24.92	0.21
1952	17.44	4.42	5.51	27.37	0.51
1957	18.54	4.37	4.75	27.66	0.65
1963	20.50	4.57	4.71	29.77	1.14
1983	21.81	7.78	4.07	33.67	4.63
1991	22.63	10.12	4.12	36.87	5.84
1994	21.59	10.29	4.51	36.39	6.46
2001	18.84	10.22	5.40	34.46	7.14
2009	19.53	10.04	7.65	37.22	10.22

[a] Pine (*Pinus* spp.), oaks (*Quercus* spp.), other hardwoods (all other taxa); see Table 2 for details.

Table 4
Aboveground biomass by species group and year for all live stems >9.0 cm DBH on the Reynolds Research Natural Area.

Year	Pine[a] biomass (Mg/ha)	Oak[a] biomass (Mg/ha)	Other hardwoods[a] biomass (Mg/ha)	Total biomass (Mg/ha)	Biomass, in stems >71 cm DBH (Mg/ha)	Percent, total biomass	
						Stems >71 cm DBH	Pines only
1937	58.11	32.71	15.52	106.34	2.34	2.20	54.65
1942	69.02	30.43	25.90	125.36	2.29	1.83	55.06
1946	74.27	30.58	29.68	134.52	1.95	1.45	55.21
1952	86.91	36.30	30.53	153.74	4.17	2.71	56.53
1957	95.11	36.07	26.45	157.63	5.08	3.22	60.34
1963	108.96	38.75	26.43	174.14	8.57	4.92	62.57
1983	126.39	68.09	18.73	213.21	33.14	15.54	59.28
1991	133.12	91.79	17.49	242.40	42.40	17.49	54.92
1994	128.68	94.42	19.23	242.33	47.85	19.75	53.10
2001	114.96	96.26	23.81	235.03	54.27	23.09	48.91
2009	121.78	98.30	34.61	254.69	81.89	32.15	47.81

[a] See the footnote a in Table 3 for the species included in these groups.
[b]Biomass values predicted from equations and coefficients provided in Jenkins et al. (2003). There may be subtle differences between this table and other estimates of biomass in this paper due to rounding errors and more refined use of the Jenkins et al. (2003) coefficients with the more detail species groups.

Johnsen et al., 2001; Lippke et al., 2005; Perez-Garcia et al., 2005; Wilson, 2006; Luyssaert et al., 2008; Keith et al., 2009). The RRNA provides a unique opportunity to add to the baseline information on biomass in part because of the increasing scarcity of mature, unmanaged, pine-dominated stands in the southeastern U.S. (Wear and Greis, 2002) and because of the long history of detailed measurements of this stand.

4.1.1. Biomass and forest development

Biomass patterns in the RRNA reflect the initial lumbering and 15–20 years of post-logging development prior to reservation of this stand. Unlike many old-field, nearly pure pine stands that arose following lumbering and agricultural use, the RRNA started out with a considerable amount of hardwoods. During the first few decades of observation (Table 4), the proportion of pine biomass increased gradually from 55% and peaked in the 1963 inventory at 63%. Since then, a slow decline in pine biomass dominance has ensued, with the pines falling below 50% of total aboveground live biomass in the late 1990s. This transition occurred somewhat earlier (at ~80 years post-logging) than the 100–150 years expected by Switzer et al. (1979) for old-field pine stands, but this outcome is not surprising given the abundance of hardwoods early in the stand's history and because some of the pines in the current stand actually date back to before the lumbering in the late 1910s (Shelton and Cain, 1999).

The RRNA rapidly increased in total aboveground live biomass from 1937 until 1991, when it first peaked at 242 Mg/ha. For most of the next decade, this stand fluctuated between 235 and 242 Mg/ha, but the most recent inventory shows that the RRNA has reached a new high of 255 Mg/ha, with both pines and hardwoods contributing to this increase. Pine biomass is still somewhat lower in 2009 compared to its maximum in 1991 (122 Mg/ha vs. 133 Mg/ha), largely due to considerable shortleaf pine mortality during the last 20 years (Fig. 6). However, pine biomass will not likely gain significantly during future decades due to the failure of shortleaf or loblolly to regenerate in the shaded understory.

Large-scale inventories (e.g., the USFS's Forest Inventory and Analysis (FIA) program) have made it possible to assess the development stage of forested ecosystems over wide regions. This has led to the creation of stand development metrics based on these inventories, with the goal of evaluating the maturation of region-wide forest cover as a proxy for other ecosystem attributes such as C sequestration or rates of old-growth renewal. For example, Brown et al. (1997) described two parameters, aboveground biomass density (AGBD) and the percent of AGBD in stems >70 cm DBH, for known old-growth hardwood tracts in the eastern U.S. They then suggested that old-growth hardwood forests could be identified as stands with at least 220 Mg/ha in AGBD, with ≥20%

of that in trees ≥70 cm DBH (sawtimber-sized managed stands from their FIA sample reached a maximum AGBD of 175–185 Mg/ha, with 8–10% in large trees) (Brown et al., 1997).

If we assume that Brown et al.'s technique reasonably approximates old-growth structure, it should be possible to determine when any given stand transitions between mature and old-growth status. The 1983 inventory of the RRNA showed the stand had reached 213 Mg/ha, of which 15.5% was in trees >71 cm DBH, both measures slightly below the thresholds of Brown et al. (1997). The 220 Mg/ha AGBD threshold was crossed between the 1983 and 1991 inventories, and the 20% of AGBD in large trees threshold was probably exceeded by the mid 1990s (Table 4). Given that the second-growth RRNA established following the original cutting of the virgin timber (and is not composed of old-growth culls, as suggested by the very limited quantity of biomass in large trees during the first decades of this stand (Tables 3 and 4)), it would seem that the 220 Mg/ha and 20% of AGBD thresholds are too low to define old-growth in this forest condition—a partially disturbed stand with fast growing species on a good site (site index of 26–29 m at 50 years).

4.1.2. Aboveground live tree biomass

The long-term inventories of the RRNA provide the opportunity to study biomass accumulation over the developmental sequence of this stand, and provide a benchmark for evaluating the potential of southern pine-dominated stands for C storage. Total aboveground live biomass has more than doubled since the initial 1937 inventory of 106 Mg/ha to an all-time high of 255 Mg/ha in 2009 (Table 4). Pine aboveground live biomass increased from 58 Mg/ha
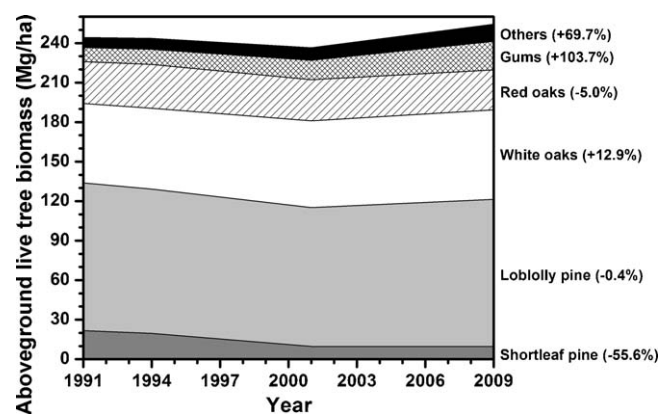
Fig. 6. Aboveground live tree biomass by species or species groups in the Reynolds Research Natural Area from 1991 through 2009. Percentages are in terms of biomass change relative to the quantity observed in 1991.

to a peak of 133 Mg/ha by the early 1990s before a modest decline to 122 Mg/ha by 2009 (a decrease largely due to the mortality of shortleaf pine during the last decade). After only modest increases during the first 3 decades of observation, oaks rapidly added biomass between the early 1960s and the early 1990s before slowing again during the last decade. Other (non-oak) hardwoods fluctuated between 15 and 30 Mg/ha until the early 1960s, with a steady increase since the early 1990s, coinciding with the slight decline in pines.

Using regional FIA data, Delcourt et al. (1981) estimated that the forests of southern Arkansas and northern Louisiana averaged between 50 and 75 Mg/ha of aboveground live tree biomass. Others have placed aboveground live biomass density for managed forests in the southeastern U.S. at noticeably higher levels (up to 193 Mg/ha), depending on stand developmental stage and site quality (e.g., Birdsey, 1992; Schroeder et al., 1997). The retention of >200 Mg/ha of aboveground live biomass for >25 years in the RRNA (Table 4) suggests that unmanaged stands of natural origin pine-hardwood can develop and sustain significant standing crops of trees for long time periods.

4.1.3. Coarse woody debris

Limited study of dead wood has been made in the RRNA during the last 2 decades. Using an area-based census, the first approximation of coarse woody debris (CWD) in the RRNA concentrated on standing dead trees and reported between 8 and 56 pine and 6 and 11 hardwood snags ≥9 cm DBH per hectare (Cain and Shelton, 1996). Most of the pine snags were created by beetle outbreaks aggravated by injury from an ice storm in 1994, while hardwood mortality seemed to be more sporadic in its occurrence.

A considerably more comprehensive assessment of dead wood in the RRNA was conducted by Zhang (2000). Using a planar intersection method, Zhang (2000) noted that the 25–66 snags per hectare in the RRNA far exceeded the 7 snags per hectare in the adjacent Good Forty uneven-aged demonstration. Combined pine and hardwood snag volumes ranged from 30.9 m^3/ha in areas with low damage from the beetles and the 1994 ice storm to 140.3 m^3/ha in high damage locations, with pines comprising 80–95% of the snag volumes. Downed dead wood varied from 64.7 to 169.7 m^3/ha in the RRNA (vs. 33.6 m^3/ha in the Good Forty), of which 60–85% was identified as pine. Oven-dry biomass of downed wood (snags not included) in the RRNA ranged from 30.4 to 75.7 Mg/ha (55–85% of which was pine), compared to 15.6 Mg/ha in the Good Forty.

A lack of continuity and completeness make it is difficult to use existing data on CWD from the RRNA to understand long-term dead wood dynamics. However, it is apparent that unmanaged mature pine-dominated stands produce considerably more CWD than managed stands (see also Bragg and Heitzman, 2009). This is not surprising, given that regulated uneven-aged forests are often less susceptible to beetle outbreaks due to the vigor and relatively low density of the overstory pines (Ku et al., 1980), periodic harvests remove vulnerable trees, and salvage of dead timber sometimes occurs. It also seems plausible that CWD loads may be noticeably higher at the end of the pine dominance period than in the later hardwood-dominated phases of succession due to the much greater size of the pines and their tendency to die en masse over relatively short periods of time.

4.2. Non-commodity stand attributes

During the 1930s, many experimental forests were established to demonstrate silvicultural practices for the predominant timber species of that region. In the case of the CEF, research focused on loblolly and shortleaf pine, with only limited interest in any other species (the CEF lacks the hydrological features needed to properly study watersheds, so this was never a part of its mission). However, over time questions related to non-timber attributes became significant issues for the USFS to address, including topics such as threatened and endangered species, climate change, air quality, and land use history. In particular, conditions on the RRNA are conducive toward addressing three of these: red-cockaded woodpecker (Picoides borealis) habitat, a paleoclimate proxy found in natural soil mounds, and stand attributes related to old-growth. The first two topics represent potential field research, while the third is an adaptation of existing studies for a new silvicultural direction.

4.2.1. Red-cockaded woodpecker habitat

The red-cockaded woodpecker (RCW) is a federally endangered species dependent on open, mature southern pine forests across the southeastern U.S. The RCW is unique in that it requires live pine trees to nest in, and in particular seeks out relatively old, large pines with red-heart (Phellinus pini) infections in which to excavate their cavities (Conner and O'Halloran, 1987; Masters et al., 1989). Old-growth pine forests of this region had been prime habitat for the RCW—frequent fires maintained open stands dominated by fire-resistant mature pines, many of which had extensive red-heart infections. Historic lumbering, turpentine extraction, and land clearing removed most of the preferred habitat, causing RCW populations to decrease sharply during the 20th century. This decline was further aggravated by the widespread expansion of short-rotation loblolly pine plantations, few of which ever develop suitable nesting habitat for the RCW.

The large, mature, red-heart-infected loblolly and shortleaf pines that dominate the RRNA would therefore seem to offer a good opportunity for RCW nest cluster(s). However, RCWs have been missing from the RRNA for decades. The dense hardwood understory and midstory that developed following the lumbering, coupled with decades of fire exclusion, have produced a stand that is unsuitable for RCW nesting, regardless of the favorable condition of the overstory pine.

The failure to produce suitable habitat suggests a different approach for reserve management if pine timber is to be set-aside for RCW management. Untouched reserves alone cannot affect one key RCW habitat feature—the development of red heart in mature pine is largely a time-dependent function, with rapidly increasing frequency and extent in pines >80 years old (Conner et al., 2004). Rather, efforts need to be made to ensure the stand remains open, with only a sparse tree-dominated midstory and (preferably) grassy understory. Historically, this would have been achieved with frequent, low-intensity surface fires that encouraged grass and other herbaceous plants and greatly reduced most woody shrubs and tree regeneration. Given the growing difficulty of using prescribed fire in settled landscapes, forest managers are increasingly using combinations of fire, mechanical, and chemical means to regulate understory vegetation patterns (Brose and Wade, 2002; Boerner et al., 2008). Unmanaged set-asides such as the RRNA that do not address this critical RCW habitat feature will lose whatever acceptable habitat they may have—a result seen at much larger scales in other places where habitat protection strategies have witnessed continued losses of RCWs (e.g., Saenz et al., 2001; Masters et al., 2007).

4.2.2. Prairie mounds and paleohistory

Low, circular mounds of natural origin can be found across much of Arkansas, Louisiana, Missouri, Oklahoma, and Texas. The mechanism responsible for their formation has long been debated, with many different theories proposed (e.g., Veatch, 1906; Knechtel, 1952; Melton, 1954; Allgood and Gray, 1974; Carty et al., 1988; Cox and Scheffer, 1991; Horwath and Johnson, 2006). Most recently, research supports the theory that these "prairie"

mounds are paleorelict nebkhas (also called "coppice mounds") formed when isolated patches of vegetation captured wind-blown soil particles during extended periods of prehistoric drought (Seifert et al., 2009). Optically stimulated luminescence (OSL) dates from these features increased with depth along the vertical profile, and when coupled with the shape and the soil particle size patterns across the axes of the mounds strongly suggest an aeolian origin (Seifert et al., 2009). However, further testing and a more extensive sample of these mounds is needed before a wind-based theory of prairie mound origin is universally accepted. Note that other main alternative hypothesis for prairie mound formation, construction by fossorial rodents (Cox and Scheffer, 1991; Horwath and Johnson, 2006), also implies that areas with prairie mounds were once much drier than current conditions, likewise suggesting major climatic differences.

The prairie mounds found in the RRNA appear to follow the patterns of those reported in Seifert et al. (2009). Conventional forest management practices for establishing new pine plantations in the uplands of this region include ripping of the subsoil and bedding of the surface to break up preexisting roots and to improve soil drainage. These site preparation techniques are highly disruptive to the mounds, and the mixing of soils from these treatments greatly lessens the likelihood of accurate age determination using OSL. Because the RRNA is permanently reserved from timber harvesting and site preparation impacts, the prairie mounds preserved on this site will be available for future geomorphological research on their origins without concern for their destruction or contamination.

4.2.3. Reference conditions for old-growth restoration

Public land managers, non-governmental organizations, and some private landowners are increasingly interested in restoring portions of their ownership to old-growth-like conditions. To best manage for this strategy, a set of reference conditions should be established to define silvicultural objectives and set benchmarks for success. Defining these reference conditions is a difficult task since historical records are notoriously unreliable or unavailable and we lack representative examples of functional old-growth pine-dominated ecosystems in this part of the southern U.S. (Bragg, 2002, 2004c,e). However, approximations of reference conditions can be derived from other sources such as GLO public land surveys, early explorer and settler accounts, old trade and scientific journals, government reports, and contemporary studies of remnant old timber (e.g., Egan and Howell, 2001; Bragg, 2002, 2004e, 2008).

Even though it is not old-growth, certain attributes of the RRNA lend themselves to the description of the presettlement forests, even if the example is contrary to expectations. Most historical photographs and written descriptions of the virgin pine forests of southern Arkansas suggest open stands dominated by large pines with little to no hardwood visible and few (if any) lianas reaching into the canopy (Zon, 1905; Chapman, 1913; Reynolds, 1980; Bragg, 2002, 2004b, 2008). However, mature, unmanaged pine-dominated stands in this region (including the RRNA) now contain dense under- and midstories of hardwood, with significant quantities of woody vines forming parts of the midstory and canopy leaf area (Bragg, 2004b; Heitzman et al., 2004; Bragg and Heitzman, 2009). Yet, it is almost certain that a gradient of stand conditions existed across the UWGCP during historic times— Olmsted (1902) and Morbeck (1915) reported between 35 and 40% hardwood in some of the virgin stands they visited, and there were hardwood-dominated presettlement forests with a minor and varying pine component across the region, especially in areas more sheltered from fire (e.g., bottomlands). This suggests that the RRNA has value as an example of one of these protected mesic sites while simultaneously representing the antithesis of the more xeric, fire-prone landscapes in the UWGCP.
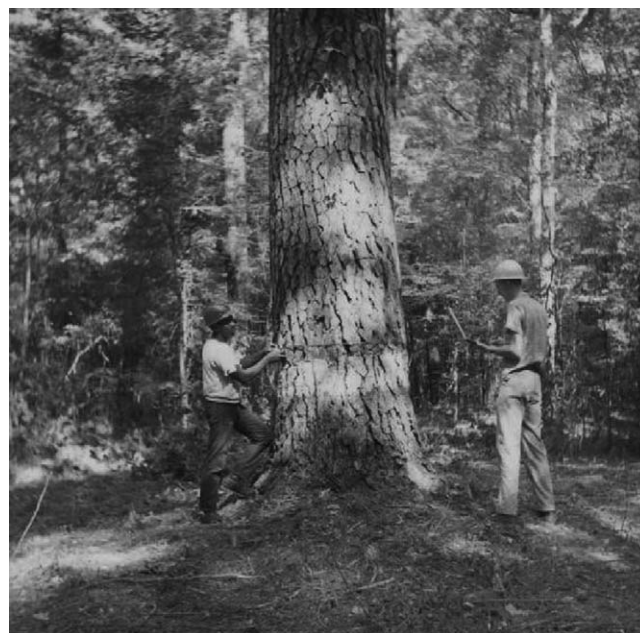

Fig. 7. A large loblolly pine that emerged following the harvesting of the virgin timber from the area that would become the Reynolds Research Natural Area. Photo from the USFS archives at the Crossett Experimental Forest.

Another of the lessons learned from the RRNA is that it does not take centuries to produce very large pine trees. Historical records indicate that loblolly and shortleaf pine in southern Arkansas and northern Louisiana took between 150 and 300 years to produce specimens that exceeded 100 cm in DBH and 40 m tall (e.g., Mohr, 1897; Chapman, 1913, 1942; Reynolds, 1980; Bragg, 2002, 2004c). The RRNA produces pines of this scale in 120 years or less. A loblolly pine (now dead) from the RRNA that reached 118 cm in diameter and just under 40 m tall was undoubtedly one of the relatively small trees left in the cutover stand when the area was logged in the late 1910s (Fig. 7). Even trees established post-lumbering have grown quickly to large size—numerous examples of 70+ cm DBH pines can be found on the remains of a temporary logging rail line built approximately 90 years ago. Current RRNA inventory records show that even at this age, many of these large pines can grow ≥0.3 cm annually (Table 5). This rate of growth is substantially greater than that reported for the virgin pine forests of this region (e.g., Chapman, 1912, 1913; Davis, 1931) and comes without silvicultural crown release, as has been suggested as a tool for developing old-growth-like characteristics in managed stands (e.g., Singer and Lorimer, 1997).

5. Addressing future issues

By definition, the future is far less certain than the past. However, we can say reliably that the silvicultural direction given in the establishment documentation of the RRNA will ensure that

Table 5
Annualized statistics on pine increment in the Reynolds Research Natural Area from the most recent decade of growth (2000–2009).

Species	n	Annual diameter growth, in cm			
		Average	Standard deviation	Minimum	Maximum
Shortleaf pine	15	0.24	0.17	−0.08[a]	0.51
Loblolly pine	119	0.33	0.17	−0.08	0.73

[a] Negative diameter growth is largely a function of bark loss.

this stand remains unmanaged and protected from fire into the foreseeable future (Cain et al., n.d.; USFS, 2005). Therefore, barring some severe and unpreventable perturbation, forest succession will continue and increasingly shade-tolerant hardwood species will replace the large pines, oaks, and gums that currently occupy dominant and codominant canopy positions (Cain and Shelton, 1996; Shelton and Cain, 1999).

On mesic sites, neither loblolly nor shortleaf pine tends to be long-lived, with very few trees surviving past 300 years of age. Under a closed canopy with limited gap formation and poor conditions for pine germination, it seems likely that the pine-dominated overstory of the RRNA may persist for only a few more decades. While this stand developmental trajectory is expected, we can only infer the actual species composition at various points in the stand's future—there is virtually no published data on unmanaged upland hardwood-dominated old-growth from this region. One particularly interesting avenue for future research is whether any pine will persist under the conditions that will be maintained for the RRNA. The disappearance of pine from this relatively small parcel, however, is not likely to preclude the possibility of reestablishment via seed rain from adjacent pine stands.

5.1. Forest succession under climate change

Will environmental conditions remain suitable for pine regeneration in the UWGCP? Long-term climate change predictions suggest that southeastern Arkansas will become increasingly warmer and wetter (Iverson et al., 2008). Large-scale inventories may be showing some signs of species migration (e.g., Woodall et al., 2009), and biogeographic models have predicted widespread shifts in species abundance as a function of climate change (e.g., Iverson and Prasad, 1998; Iverson et al., 2008).

While the RRNA is too small to dependably measure species migration, the ability to retain a constant management environment for an indeterminate period into the future should allow for some detection of change. For example, certain magnolia species (e.g., Magnolia grandiflora and Magnolia virginiana) are currently found south of the RRNA and are generally considered to be climate-limited in their distribution. If the UWGCP warms and stays relatively moist, it seems likely that these magnolias will extend their range, and one might expect to see the shade-tolerant M. grandiflora invade the understory of the RRNA at some point in the future (there are many M. grandiflora seed sources in the yards of local residences).

5.2. Unmanaged stand response to invasive species

There are other scenarios in which future successional trajectories may be influenced by exogenous events rather than differential species response to stand conditions. For instance, the spread of exotic pests or diseases could significantly alter long-term stand development patterns. The emerald ash borer (Agrilus planipennis), as an example, is eventually expected to spread across the range of Fraxinus in North America, and threatens the survival of all known ash in this region (Poland and McCullough, 2006). Flowering dogwood (Cornus florida) and sassafras (Sassafras albidum) are likewise threatened across much of their range (including the UWGCP) by the exotic diseases dogwood anthracnose (Discula destructiva) and laurel wilt (Raffaelea lauricola), respectively (Holzmueller et al., 2006; Fraedrich et al., 2008). Though none of these trees are locally commercial species, nor do they dominate the RRNA, their potential loss from the ecosystem could have substantial long-term impacts on stand development and would represent the loss of hallmark taxa in the pine-hardwood forests of this region.

Our ability to track the long-term abundance of invasive species in a controlled environment with few major disturbances is invaluable for understanding their ecological role and the functionality of natural forests. Are unmanaged forests inherently more resistant to exotic species, or are they susceptible to invasion by certain non-native species adapted to closed forest conditions? After all, Shelton and Cain (1999) noted the RRNA lacked shade-tolerant, late successional species with overstory potential, suggesting that this niche was open for exploitation. Could the widespread disappearance of some native species (due to natural successional tendencies, climate change, or exotic pests/pathogens) facilitate the establishment of non-native plants (e.g., Chinese tallow-tree (Triadica sebifera)) that could further displace native trees and alter succession even more?

6. Conclusions

The primary lesson learned from >70 years of experience in long-term research and demonstration projects on the CEF is the value of programmatic continuity while retaining adaptability—the evolution of natural sciences means that it is virtually impossible to know what data will be considered useful decades in the future. The maintenance of existing lines of research also helps to ensure that systems that we think we understand do not suddenly show behavior for which we cannot account. If properly implemented and monitored, departures from expectations in these long-term studies should be embraced as opportunities to better refine our conceptual models or perhaps modify data collection techniques.

Seventy-two years of observations of the RRNA have produced many valuable insights. During the earliest years, studies that used inventory information from the RRNA to contrast productivity with managed stands provided convincing evidence of the commercial gains possible under proper silvicultural regulation. Furthermore, decades of observations on stand dynamics confirmed most aspects of the hypothesized development of cutover pine timberlands in this portion of the southeastern U.S., including the gradual replacement of pine by increasingly shade-tolerant hardwood species in the absence of significant disturbance. More recent work has documented dead wood production in unmanaged stands, which can provide important insights into C sequestration patterns in undisturbed forests when coupled to newer studies evaluating the biomass accumulation in the RRNA. The long-term unmanaged nature of the RRNA also provides reference conditions that can be used to better understand pine-dominated ecosystems in this region, whether related to endangered species with exacting habitat requirements (e.g., RCWs), possible relics of past climates (prairie mounds), or stand conditions that can be encouraged to add old-growth-like features to managed landscapes.

Future research and demonstration projects on the RRNA will continue to focus on the long-term observations of the past—the ability to detect departures from expectations hinges upon a reliable record of information. Scientists can also adapt past measurements to reflect and evaluate new emphases—the trade-offs between optimum stocking for sawtimber production versus maximizing C storage, for example. The growing rarity of mature, unmanaged forests in the southeastern U.S. accentuates the value of the data from the RRNA, and new studies following completely original lines of investigation are almost certain. All of these are possible even as the RRNA gradually loses the primary features for which it was originally reserved—the loblolly and shortleaf pines.

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