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Developing contemporary and historical live tree biomass estimates for old pine-hardwood stands of the Midsouth, USA

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ABSTRACT

Calculating stand biomass potential is an increasingly important aspect of silviculture, particularly when attempting to restore forest ecosystems or determining additionality in sequestered carbon. However, the lumbering of the original forests of the Midsouth region of the United States of America, coupled with the accelerating conversion of unmanaged natural-origin stands to loblolly pine (*Pinus taeda* L.) plantations, make quantifying historic biomass difficult. If carefully done, it is possible to estimate presettlement biomass from past references and modern-day old pine-hardwood remnants. Pine sawtimber-only volume estimates from old reports indicated low biomass in the virgin pine-dominated forests of the Midsouth, from as little as 10–14 Mg/ha up to 72 Mg/ha. Given the incompleteness of these lumber yield-only data, a set of more detailed stand table-based historic descriptions were then coupled in this study with modern allometric equations to produce more complete estimates of biomass. These suggested that presettlement pine-hardwood stands of this region averaged ~112 Mg/ha in total (above- and below-ground) live tree biomass (range = 54–171 Mg/ha; $n = 6$ stands). Contemporary old forests are considerably better stocked, with an estimated 224–318 Mg/ha ($n = 6$ stands). Individual loblolly pines from the historic period reached 183 cm in diameter and may have had as much as 32 Mg of biomass, though specimens <6 Mg were considerably more common. Large individual tree values but low stand levels imply disturbance (especially fire) regulated total tree biomass in historic forests of the Midsouth. These results further indicate that extensive restoration of modern unmanaged forests to past stand structures will likely decrease regional biomass.

1. Introduction

The study of forest biomass accumulation in the southeastern United States of America (USA) has largely focused on the description of loblolly pine (*Pinus taeda* L.) stands, particularly the more intensively managed plantations (e.g., Hinesley, 1978; Pehl et al., 1984; Adegbidi et al., 2002; Miller et al., 2006; Subedi et al., 2012). Because of how well loblolly pine responds to cultural treatments, it has become the overwhelmingly preferred plantation species in the southern USA and even other parts of the world (Schultz, 1999; Borders and Bailey, 2001; Jokela et al., 2004; Allen et al., 2005). This is not surprising, given the documented productivity of southern pine forests and the willingness of many property owners in this region to engage in intensive management (e.g., Jokela et al., 2004; Munsell and Fox, 2010; Joshi and Mehmood, 2011). Pine plantations now constitute at least 19% of the forest cover in the southeastern USA (27% in the Gulf Coastal Plain), or 15.8 million ha—in contrast, pine-dominated stands of natural origin have declined from over 29 million ha in 1950 to about 13 million ha in 2010 (Wear and Greis, 2011).

The realization of this potential has come with some serious environmental consequences. Since large areas of native vegetation have been converted to loblolly pine plantations, there have been numerous impacts to a range of ecosystem services. By their nature, intensively managed plantations have significantly fewer species, are younger, and generally less structurally complex than the naturally regenerated forests they replaced. The silvicultural treatments needed to maximize productivity of loblolly pine plantations also involve the use of petrochemical-based fertilizers and herbicides and can further affect soil conditions by altering drainage patterns, encouraging erosion, and accelerating the decomposition of organic matter (Jokela et al., 2004; Munsell and Fox, 2010). However, the trade-offs in biomass accumulation/carbon (C) sequestration related to forest type change are less clear, even with increasing inquiry and synthesis on forest C dynamics (e.g., Malmsheimer et al., 2011).

Researchers lack critical information on biomass patterns in even the otherwise well-studied southern pine ecoregion partly because of the rapid conversion of natural-origin stands to loblolly pine plantations. Certain management objectives, such as restoring degraded ecosystems or sequestering additional atmospheric carbon dioxide, are predicated on the notion that original forest

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conditions can be used to define baseline targets. For example, it is widely thought that old forests (defined in this paper as intact old-growth or unmanaged, mature second-growth stands) in North America contain significantly higher quantities of biomass because of greater arboreal diversity, larger trees, more complex stand structure, and higher stand density than second-growth (e.g., Jones, 1945; Harmon et al., 1990; Bauhus et al., 2009; Rhemtulla et al., 2009; Bradford and Kastendick, 2010; Van Deusen, 2010; Malmsheimer et al., 2011). Unfortunately, today unaffected old-growth forests are rare in eastern North America, and there is some question as to how representative these remnants are of past conditions (e.g., Bragg and Shelton, 2011).

Determining the biomass of any modern forest is a relatively easy task, but deducing the biomass of historic stands is considerably more difficult, as only rarely do we have any kind of reliable data on them. A few descriptions of "trophy" stands of virgin timber published decades ago remain, such as a number of reports on sawtimber-only yield from groves of eastern white pine (*Pinus strobus* L.) in the northeastern USA. These stands[1] include a small (0.8 ha) parcel in New Hampshire that contained an estimated 376 Mg/ha of oven-dry biomass (Baldwin, 1951) and a series of tracts <1 ha in size from Pennsylvania with 196–220 Mg/ha (Keffer, 1897; Mlodziansky, 1898). These biomass levels are appreciably greater than the averages given for larger virgin stands of eastern white pine during that period, such as the 72–160 Mg/ha found in groves in Michigan and Pennsylvania (Chaffee, 1924; Wackerman, 1924), and much greater than the retrospective estimates (1.0–2.2 Mg/ha) of sparsely stocked eastern white pine across large portions of Maine (Wilson, 2005; Lorimer, 2008).

The tendency to overestimate stand attributes because of biased sample selection and small observation extent has been documented (e.g., McCune and Menges, 1986) and supports a reevaluation of the biomass in virgin forests. After all, many historic forests appear to have been less well stocked than contemporary examples (e.g., Bruner, 1930; Nowacki and Abrams, 2008; Bragg and Shelton, 2011). In particular, some (if not most) of the pine and oak forests of eastern North America were fire-dependent ecosystems that developed prior to the implementation of effective fire control in the 1930s (Chapman, 1942; Quarterman and Keever, 1962; Crow, 1978; Nowacki and Abrams, 2008). Frequent surface burns promoted open forests that often transitioned into woodland, savanna, or even grassland. During the early years of North American forestry, even though some researchers recognized the healthy role fire played in many ecosystems (e.g., Garren, 1943; Bruce, 1947; Chapman, 1952), conventional silvicultural wisdom supported the suppression of all fires to increase the stocking of pine-dominated stands and lessen the degree of scorch-induced bole degradation. Over time, these fire-sheltered stands matured without the periodic loss of overstory pines and developed dense understories of hardwood species (Nowacki and Abrams, 2008; Bragg and Shelton, 2011).

Now, as researchers investigate the potential of temperate forests to accumulate biomass (e.g., Brown and Schroeder, 1999; Jenkins et al., 2001; Luyssaert et al., 2011; Woodall et al., 2011; Aspinwall et al., 2012), they must ascertain what condition best represents baseline storage for pine-dominated forests—modern-day unmanaged stands or those from the historic literature. Such a determination could help direct both restoration efforts as well as greenhouse gas mitigation policies, especially on publicly-controlled lands. This paper represents a first approximation of the range of biomass totals that can be expected from the arboreal component of old pine-dominated ecosystems in the Midsouth region of the USA, and places it the context of current management efforts.

2. Materials and methods

2.1. Study region and data sources

For this paper, the Midsouth covers approximately 20 million ha (Fig. 1) and includes parts of five states—southern Arkansas, northern Louisiana, western Mississippi, southeastern Oklahoma, and eastern Texas. This largely rural area encompasses part of the Gulf Coastal Plain, a gently rolling physiographic province consisting of a patchwork of different marine, alluvial, and loess-derived parent materials of varying ages. Today, upland forests are pine-dominated and have been repeatedly logged—prior to extensive Euroamerican settlement in the late 1800s, these uplands were sparsely occupied and largely open (little understory), dominated by pines and various hardwood admixtures (Bragg, 2008). The rolling uplands of the Midsouth are also dissected by a number of major floodplains, including those of the Mississippi, Red, and Ouachita rivers, which have mostly been converted to agriculture over the last 200 years.

Detailed descriptions of the live tree component of modern-day mature, unmanaged, pine-dominated stands in the Midsouth have been recently published, and will serve as the data source for contemporary examples of this forest type (Table 1). These stands were chosen for their lack of harvesting and dominance of large loblolly (*Pinus taeda* L.) and shortleaf (*Pinus echinata* Mill.) pine. All of these stands also possess a significant hardwood component, most of which has accumulated over the last 70+ years as effective fire suppression and changes in litter quantity have contributed to the "mesophication" of forests across eastern North America

Fig. 1. Map of the Midsouth region of the USA, with the primary area of interested indicated by the dashed oval. Most of this area is forested, with the exception of the lands bordering the major riverways.

[1] All eastern white pine values were converted for this paper from board foot lumber yield (1 board foot per acre = 0.00933 m^3/ha) and then to biomass quantities (Mg) per hectare, assuming 1 m^3 of oven-dried eastern white pine weighed 0.35 Mg (Miles and Smith, 2009). Lumber yield includes only bole wood (no bark, branches, leaves, roots, reproductive structures) for trees big enough to produce sawtimber, which itself varies based on merchantability standards (often, minimum log diameters of 25–40 cm).

Table 1
Descriptions of old southern pine-dominated forests (both modern and historic) used in this study, including predicted sawtimber yield and derived biomass.

Source	Location	Site and/or sampled forest description	Site area (ha)	Sawtimber only	
				Lumber yield (bd ft/ac)[a]	Oven-dry biomass (Mg/ha)
MODERN (both old-growth and unmanaged second-growth)					
Bragg (2004a)	Ashley County, Arkansas (AR)	Old-field pine-hardwood	3.2	14,450	69.0
Heitzman et al. (2004)	Calhoun County, AR	Bottomland pine-hardwood	16.2	7,991	38.2
Bragg (2006)	Ashley County, AR	Pine-hardwood flat	6.0	12,556	60.0
Bragg and Heitzman (2009)	Monticello, AR	Old-field pine-hardwood	22.5	17,096	81.6
Bragg and Shelton (2011)	Crossett, AR	Once-cut pine-hardwood	32.4	17,642	84.2
Bragg (unpublished data)	Drew County, AR	Pine-hardwood terrace	1.2	13,869	66.2
HISTORIC (virgin timber)					
Olmsted (1902)	Pine Bluff, AR	Pine ridge	613.5	4,825	23.0
		Pine flat	92.7	5,404	25.8
Zon (1905)	Eastern Texas	Poorly drained thicket	2.0	8,357	40.0
Chapman (1913)	Ashley County, AR	Only pines > 30 cm DBH	16.2	12,185	58.2
Forbes and Stuart (1930)	Southern AR	Pines only	242.8	12,329	58.8
Garver and Miller (1933)	West-central AR	Pines only	21.8	4,039	19.2

[a] Pine-only sawtimber lumber yield (board feet/acre) using the Doyle log rule (minimum DBH = 24.4 cm) calculated from Farrar et al. (1984). Converting from lumber yield to biomass assumes 7.5 board feet = 1 ft3, 35.31 ft^3 = 1 m^3, and 1 m^3 of oven-dry loblolly or shortleaf pine biomass weighs 0.512 Mg.

(Nowacki and Abrams, 2008). One of these contemporary stands was actually inventoried during the 1930s (Bragg, 2004a), but given that this stand apparently arose in an abandoned agricultural clearing and had been sheltered from fire over the years, it was more consistent with current examples of old forest. Otherwise, these modern stands are recently sampled (within the last 10 years) unmanaged old-growth and mature second-growth.

Finding reliable and adequately quantifiable descriptions of virgin forests is considerably more difficult, as they obviously can no longer be directly measured. Rather, historic records must be used. First, I examined coarse-resolution documentation that only provided sawtimber volume estimates as an initial approximation. While suggestive, this information was incomplete and necessitated a search for reports on historic forests of the Midsouth with more detailed stand table information (usually, counts of trees by stocking, size, and/or species). I located five publications that described six different stands with the desired kind of data. Note that these accounts are not representative of all possible stand conditions from the Midsouth and none of them were true inventories–two stands from Olmsted (1902) were cruised to develop a management plan for a private landowner; Zon's (1905) work concentrated on the use of loblolly pine for railroad crossties; Chapman (1913) examined the possibilities of pine-dominated virgin forests for a second cut; and Forbes and Stuart (1930) and Garver and Miller (1933) both reviewed different silvicultural practices in pine-dominated forests. These data were also inconsistent in detail—three of these papers (Chapman, 1913; Forbes and Stuart, 1930; Garver and Miller, 1933) provided information on pines only. Olmsted (1902) and Chapman (1913) reported only sawtimber-sized trees (those >30-cm DBH) while the other papers included stems as small as 2.5–10 cm DBH (e.g., Zon, 1905; Forbes and Stuart, 1930; Garver and Miller, 1933). However, the dominance of large pine and paucity of hardwoods in many Midsouth virgin forests (e.g., Bragg, 2002) suggest that these incomplete records should not have a major impact on stand-level biomass estimates.

2.2. Analytical approach

For contemporary forests, determining biomass is straightforward—the stand is inventoried for both its live and dead components across all size classes, and allometric relationships or measurements are then used to estimate this quantity (e.g., Johnsen et al., 2004; Birdsey et al., 2006; Malmsheimer et al., 2009). While this quantifies the most obvious elements (live and dead trees), it does not account for the other system components that store C, including non-arboreal biota, the organic fraction of the forest floor, and the soil. These pools are considerably more difficult to measure, although the means in which to do so are being developed (Johnsen et al., 2004). Furthermore, some researchers also include the biomass exported off-site as persistent consumer goods (e.g., boards, paper, panels), "stored" in landfills, or substituted for fossil C-based products or energy sources in their C inventories (e.g., Perez-Garcia et al., 2005; Malmsheimer et al., 2009). This analysis does not incorporate any of these pools and fluxes, but rather concentrates on live tree biomass.

2.2.1. Converting from sawtimber-only volume to aboveground biomass

Most historic data on the old forests of the Midsouth is limited to lumber yield (boards only, e.g., Harvey, 1883; Mohr, 1897; Anonymous, 1904; Record, 1907; Morbeck, 1915), and many of these considered only pines >30 cm DBH. To convert from lumber yield to biomass, I followed the assumption of Jones (1945) that there were 7.5 board feet per cubic foot of wood in the virgin timber.[2] Since there are 35.31 ft^3 in 1 m^3 and 2.47 acres in 1 hectare, 1 board foot/ac = 0.00933 m^3/ha (or 1 m^3/ha = 107.2 board feet/ac). Another commonly used measure of roundwood, cords per acre, will be assumed equivalent to 1 cord/ac = 80 ft^3/ac = 5.6 m^3/ha. These conversions are made with the recognition that the exact translations between English and metric biomass or timber volume units are not fixed, but depend on the size of the stems being considered, the quantity of void space in aggregate units of volume measure (e.g., cords), and which log scaling rule is employed (Spelter, 2003; Fonseca, 2005).

The sawtimber-only volume estimates from the stand table data set were derived in a different fashion. Although lumber yields were provided by the authors in most of the stand table

[2] This seemingly inconsistent conversion reflects the difference between standing lumber volume estimates and actual cubic volume, in part due to losses in processing, inaccuracies in log scaling, and shrinkage due to drying (Jones, 1945; Spelter, 2003; Fonseca, 2005).

publications used in this study, I chose to use the same equation for all estimates to ensure that the same log measurement rule was followed. Thus, estimates of pine sawtimber volume were calculated from Farrar et al. (1984), who developed the following model for uneven-aged stands of loblolly and shortleaf pine on average sites in the western Gulf Coastal Plain:

$$V_D = 170.10568 - 37.68584\text{DBH} + 2.34851\text{DBH}^2 \quad (1)$$

where V_D is in board feet (Doyle Log rule) and *DBH* is diameter at breast height (in inches). All sawtimber volumes were transformed into metric volume units using the procedures described in the previous paragraph. Converting wood volume to the biomass required one additional step. One cubic meter of green (100% moisture content) loblolly or shortleaf pine wood weighs approximately 1,024 kg—when this volume is oven-dried, its weight is halved to 512 kg/m^3 (Patterson et al., 2004).

2.2.2. Calculating stand table aboveground biomass

Compared to the references that included only lumber yield, both diameter and species were known for the historic stand table data and the modern-day old stands. This allowed for direct calculation of oven-dry biomass from the US. National Biomass Estimators, which were developed from "pseudodata" taken from multiple biomass equations for tree species groups organized on factors such as phylogeny, adequacy of the original data sources, and similarity of wood specific gravity (Jenkins et al., 2003). The following model was then fit to the data for each group:

$$\text{AG}_{\text{bio}} = (e^{b_0 + b_1 \ln DBH})/1000 \quad (2)$$

where AG_{bio} = total oven-dry aboveground biomass (in Mg), DBH is in cm (either for individuals or using the midpoint of a diameter class), and b_0 and b_1 are taxonomic group-specific coefficients (Table 2).

2.2.3. Determining belowground biomass

Belowground oven-dry live tree biomass (BG_{bio}) was calculated from the relationship between the aboveground and belowground fractions described by Enquist and Niklas (2002):

$$\text{BG}_{\text{bio}} = (\text{AG}_{\text{bio}}/3.88)^{0.9803922} \quad (3)$$

Both above- and belowground live tree estimates were combined to produce total live tree oven-dry biomass. This value was then summed for each stand table to produce stand-level biomass. Statistical comparisons on the quantity of biomass between the historical and modern examples of old forests were made with a two-sample *t*-test (α = 0.05) assuming unequal variances.

3. Results and discussion

When the more detailed stand table records were analyzed for their sawtimber-only biomass totals (Table 1), historic examples of old forests produced between 19 and 59 Mg/ha, while the modern-day stands had a statistically greater 38–84 Mg/ha (paired *t*-test, t = 2.206, p = 0.0292). These values are both substantially lower than the total live tree (as opposed to lumber yield only) biomass predicted for the stand table data. This sample of historic pine-dominated old forests in the Midsouth ranged between 54 and 171 Mg/ha in total live tree biomass, averaging approximately 112 Mg/ha (Table 3). Modern examples of pine-dominated old forest varied between 224 and 318 Mg/ha, with an average of just under 272 Mg/ha (Fig. 2). The mean biomass between the stand tables from these periods was statistically different (paired *t*-test, t = 6.515, p < 0.0001).

3.1. Comparison of sawtimber-only and total tree biomass

Regional-scale historic estimates of lumber yield suggest low stand biomass. For instance, Harvey (1883) estimated there were approximately 51,800 km^2 of pine-dominated forestlands in Arkansas that averaged between 10 and 12 Mg/ha of pine biomass (sawtimber only). Across the same area, Mohr (1897) placed loblolly and shortleaf sawtimber-only yield (combined, at about an even mixture) at 18–24 Mg/ha, and Record (1907) provided a range of 14–46 Mg/ha in sawtimber for virgin pine-dominated forests. Other records corroborate these levels—Figs. 3 and 4 provide photographic examples of virgin pine stands from southern Arkansas with sawtimber-only biomass estimates of between 32 and 72 Mg/ha.

Not all historic estimates were this low—when converted to biomass, a map of estimated cordwood volumes for Arkansas and eastern Oklahoma showed many locations at 144–182 Mg/ha (depending on the proportion of pine to hardwood), with relatively few places as low as 12–32 Mg/ha (Sargent, 1884). This quantity of biomass is considerably closer to those derived from more statistically reliable estimates based on the first large-scale inventories for the Midsouth. Systematically implemented, these surveys by the U.S. Forest Service in the late 1930s included limited data on remnant virgin forests. For instance, Cruikshank (1937) estimated just under 32,000 ha of uncut old-growth remained in pine and pine-hardwood cover types in southwestern Arkansas. In the pine type, Cruikshank (1937) gave an average net yield of 168 m^3/ha of merchantable pine and 29 m^3/ha of merchantable hardwood, while the pine-hardwood cover type had an average net yield of 87 m^3/ha of merchantable pine and 68 m^3/ha of merchantable

Table 2
National Biomass Estimator parameters for the major Midsouth USA species groups used in this study (equation 2), adapted from Jenkins et al. (2003).

Jenkins et al. species group	Common name (scientific name)	b_0	b_1
Pine	Loblolly pine (*Pinus taeda* L.)	−2.5356	2.4349
	Shortleaf pine (*Pinus echinata* Mill.)		
Baldcypress	Baldcypress (*Taxodium distichum* (L.) Rich.)	−2.0336	2.2592
Juniper	Eastern redcedar (*Juniperus virginiana* L.)	−0.7152	1.7029
Cottonwood/willow	Eastern cottonwood (*Populus deltoides* Bartr.)	−2.2094	2.3867
	Black willow (*Salix nigra* Marsh.)		
Oak/hickory	White oak (*Quercus alba* L.)	−2.0127	2.4342
	Post oak (*Quercus stellata* Wang.)		
	Spanish or red oak (*Quercus falcata* Michx. and/or *Q. pagoda* Raf.)		
	Black oak (*Quercus velutina* Lam.)		
	Water oak (*Quercus nigra* L.)		
Soft maple	Red maple (*Acer rubrum* L.)	−1.9123	2.3651
Mixed hardwood	Sweetgum or red gum (*Liquidambar styraciflua* L.)	−2.4800	2.4835
	Black gum (*Nyssa sylvatica* Marsh.)		
	Other unlabeled hardwood species		

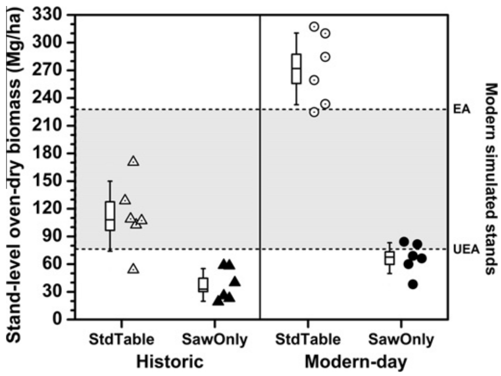

Fig. 2. Comparison of estimated oven-dry biomass (Mg/ha) from stand tables (StdTable, open symbols) and pine sawtimber-only (SawOnly, filled symbols) in pine-dominated old forests from historic (triangles) and modern (circles) times in the Midsouth, USA. Bars next to data represent (from center) the mean, ±1 standard error, and ±1 standard deviation. Shaded area is the simulated range for modern-day managed uneven-aged (UEA) and even-aged (EA, which includes both a plantation and a seed tree origin stand); data from Bragg and Guldin (2010).

hardwoods. Using prior assumptions, this translates into 86 Mg/ha in pines and 18 Mg/ha of hardwoods for the pine old-growth and 88 Mg/ha (44 of pine and 44 of hardwoods) for the pine-hardwood virgin forest.

Coupled with the predictions of the stand table data for historic old forests, it is obvious that pine lumber yield-only estimates of tree volume fail to fully document arboreal biomass. Part of this is due to an incomplete accounting of total tree biomass when only sawtimber is given—the topwood, branches, bark, foliage, etc. absent from these tallies can make up 30–40% (or more) of aboveground biomass of standing trees (Hinesley, 1978; Jenkins et al., 2003). However, even if this is included, with an average biomass of almost 272 Mg/ha modern-day old forests are still significantly better stocked than their historic analogs (Fig. 2). Contemporary old stands also have substantially greater biomass than current managed stands (Fig. 2), which are actually more comparable in biomass to historic old forests. For instance, using data from the US Forest Service's Forest Inventory and Analysis (FIA) program, Delcourt et al. (1981) mapped the aboveground live tree biomass of commercial forests (no agricultural lands were included) from eastern Texas to Virginia and Florida. Most of the managed pine forests of the Midsouth had 30–60 Mg/ha in aboveground biomass, and if an additional 25% for the belowground component is factored in, the region averaged approximately 38 to 76 Mg/ha in total tree biomass.

The findings of Delcourt et al. (1981) were further supported by a simulation exercise that estimated long-term biomass stocks in managed pine-dominated stands of the Midsouth. Bragg and Guldin (2010) projected naturally regenerated loblolly and shortleaf pine stands (both even- and uneven-aged) and a loblolly pine plantation over a 100-year management period. In this study, the live tree biomass in a simulated uneven-aged stand varied only slightly over time, from 74 to 96 Mg/ha (average = 87, standard deviation (SD) = 6.0 Mg/ha), while the even-aged stands varied considerably, from 0 (immediately post-harvest) to 230 Mg/ha (average = 96.8–125.0, SD = 53.4–64.6 Mg/ha) (Bragg and Guldin, 2010). When compared to the estimates from this study (shaded area in Fig. 2), it is clear that the range of biomass (minimum uneven-aged to maximum even-aged values) overlaps the historic virgin forest but only reaches the lower end of contemporary old forests.

3.2. Stand dynamics suggested from biomass totals

Even if the tree-only biomass in historic pine-dominated forests in the Midsouth is underestimated by 40%, they still would only approach the lower levels of modern old stands. This difference is largely attributable to changes in fire regime. Early observers of old pine-dominated forests in the Midsouth reported that many stands had 30–50% less stocking than would have been possible if fire was excluded (Bruner, 1930; Forbes and Stuart, 1930). With an estimated historic fire return interval of 4–10 years across most of the upland ecosystems of this region (Chapman, 1942; Frost, 1998), frequent surface fires limited pine and hardwood regeneration and thus help to reduce average stand stocking. Burning also helped exclude more fire-sensitive hardwoods, which further decreased total stand biomass since hardwood specific gravity is significantly higher than pine (Lamlom and Savidge, 2003). A greater proportion of pine in the overstory produces lower biomass on a given parcel of land, assuming the volume of wood remains fixed.

There are other possible ways fire may have affected reported sawtimber quantities. As an example, fire-damaged trees had a much higher rate of cull from decayed wood, pitch streaks, or hollow stems in the virgin forests of the Midsouth (Peters, 1906;

Table 3
Comparison of various measures of the pine components of old, pine-dominated stands from the Midsouth, USA.

Source	Minimum DBH (cm)	Total tree biomass All species (Mg/ha)	*Pinus* (%)	Number of trees All species (stems/ha)	*Pinus* (%)	Basal area All species (m^2/ha)	*Pinus* (%)
MODERN (both old-growth and unmanaged second-growth, all tree species)							
Bragg (2004a)	8.9	233.5	64.1	390.4	41.1	32.0	69.8
Heitzman et al. (2004)	8.9	284.6	21.7	429.9	4.3	31.4	22.7
Bragg (2006)	9.1	224.8	48.2	349.2	16.2	28.2	51.9
Bragg and Heitzman (2009)	9.1	259.4	61.3	506.5	22.8	34.5	63.5
Bragg and Shelton (2011)	9.1	310.0	47.7	454.7	13.9	36.9	52.7
Bragg (unpublished data)	9.1	317.3	37.4	333.9	16.3	37.1	52.2
HISTORIC (virgin timber, all tree species)							
Olmsted (1902) ridge:	36.8[a]	102.6	47.1	67.7	54.6	12.1	57.9
flat:	34.5[a]	109.0	49.5	75.4	54.3	13.0	60.0
Zon (1905)	2.5	170.6	51.7	519.4	28.2	22.9	57.3
HISTORIC (virgin timber, pines only)							
Chapman (1913)	30.5[a]	107.2	n/a[b]	50.0	n/a	13.8	n/a
Forbes and Stuart (1930)	5.1	128.8	n/a	222.5	n/a	18.9	n/a
Garver and Miller (1933)	10.2	54.0	n/a	168.3	n/a	8.9	n/a

[a] Original source included only sawtimber-sized trees.
[b] Not applicable (n/a)—original source included only pines (hardwoods were likely present, just not tallied).

Fig. 3. Example of a low density virgin pine-dominated stand from the Midsouth, USA, ca. 1934. Caption on photograph states that this stand averaged about 7,000 board feet (Doyle log rule) per acre, or 33.2 Mg/ha of biomass, mostly in pines >75 cm DBH. Photograph by R.R. Reynolds from the US Forest Service archives at Crossett, Arkansas.

Davis, 1931; Garver and Miller, 1933; Hepting and Chapman, 1938). While these bole defects may not have drastically affected individual pine biomass, it is possible that these cull trees may not have been tallied in the historic cruises and thus decreased the overall number of trees reported. However, given the absence of information on cruising techniques, it is impossible to determine if the standing timber volumes given in the old reports and trade journals (e.g., Harvey, 1883; Mohr, 1897; Anonymous, 1904; Record, 1907) represent gross or net yield, so the true impact of cull on the estimation of historic biomass will probably never be known.

In a recent study considering land use, disturbance, and biomass storage, Luyssaert et al. (2011) proposed the use of a land use disturbance intensity index (LUDI) based on a ‘‘relatively unmanaged/pristine’’ stand condition linking tree size (DBH) and the self-thinning relationship. Obviously, this design presumes that a stand is adequately stocked such that resource limitations due to competition define tree diameter over time. However, the LUDI approach is sensitive to the circumstances experienced in many historical forests where an exogenous disturbance factor (in this case, fire) was a density-limiting factor. This is particularly true if the same factor also helped to constrain tree size—frequent scorch injury of trees reduces their growth and thus can limit their girth relative to the availability of site resources. This relationship does not invalidate any of the concepts incorporated within an index such as LUDI, but underscores the need to clearly define the nature of the ‘‘pristine’’ stand(s) that set the acceptable bounds of biomass.

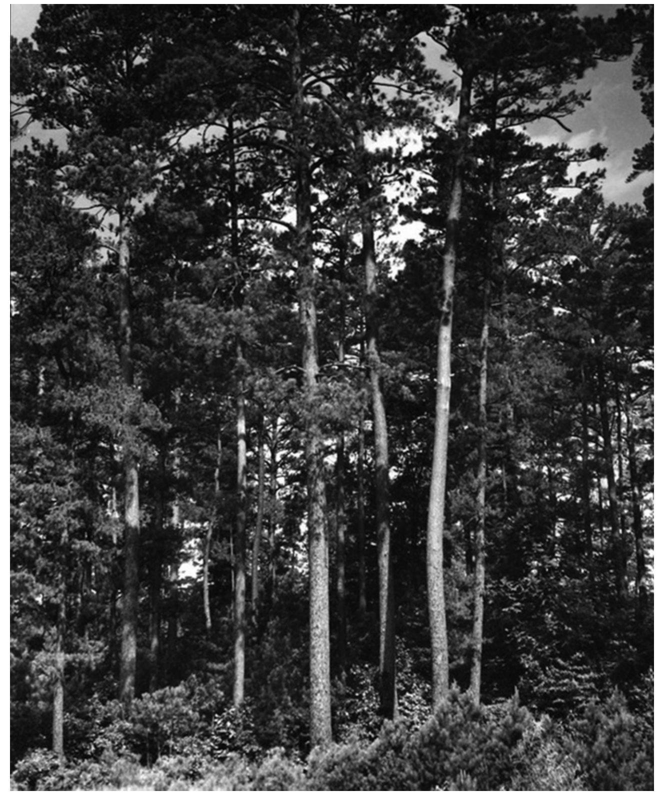

Fig. 4. Example of a better stocked virgin pine-dominated stand from the Midsouth, USA, ca. 1935. Caption on photograph states that this stand averaged just over 15,000 board feet (Doyle log rule) per acre, or about 72 Mg/ha of biomass, in trees up to 135 cm DBH. Photograph by R.R. Reynolds from the US Forest Service archives at Crossett, Arkansas.

3.3. Individual tree biomass

Even though it seems likely that stand-level live biomass in historic old forests of the Midsouth was significantly lower than in modern examples, individual tree contributions were almost certainly greater. Today, few pines approach the size they did in the past. For example, a recent analysis of the thousands of shortleaf and loblolly pines in the Midsouth using FIA plots provided maximum diameters of 80 cm and 137 cm for shortleaf and loblolly pine, respectively (Oswalt et al., 2010). However, specimens of either pine species between 100 and 120 cm DBH were common in the historical literature, and some loblolly exceeded 150 cm

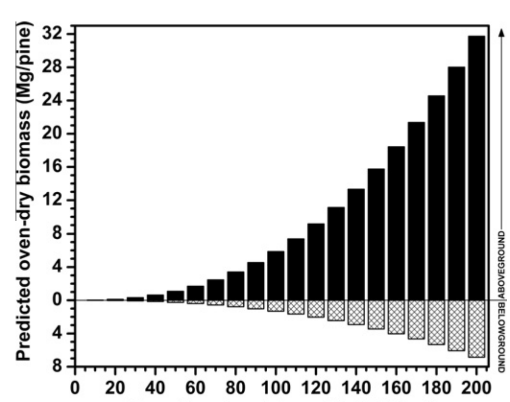

Fig. 5. Predicted individual pine oven-dry biomass (Mg) for loblolly or shortleaf pine.

DBH (Bragg, 2002, 2003, 2004b). Fig. 5 presents the estimated biomass of an individual pine tree as a function of DBH using the Jenkins et al. (2003) equation. The largest pine (probably a loblolly) from reviews of the historical literature and a public land survey records in the Midsouth region had a diameter of 182.3 cm (Bragg, 2002, 2003), which is predicted to yield 32 Mg using the National Biomass Estimators.

Note that in the past, the largest specimens in the Midsouth tended to be individual pines growing in small stream bottoms, not in dense stands in the uplands. The data from this paper and other reviews (e.g., Bragg, 2002) of historical sources on the lumber yield of pine-dominated old forests provided a range of 16–38 Mg/ha (all species included, but mostly pine), with some stands between 52 and 76 Mg/ha. Hence, even if maximum sawtimber biomass approached 6 Mg per individual, only a few big trees per unit area would produce these stand-level totals. This observation is once again consistent with many historical photographs from the Midsouth (e.g., Fig. 3).

3.4. Appropriateness of studied stands and allometric models

Some questions remain regarding the comparisons in this paper. These issues are not a matter of the appropriateness of the assumptions in the individual predictions, but rather a consequence of uncertainty in how well they reflect historic forests. As an example, the representativeness of the old stands compared in this study is unknown. The low stand densities suggested by this work are supported by a number of old photographs of the pine-dominated forests of the Midsouth showing stands of open timber (e.g., Fig. 3) with large, widely space pines and few (if any) hardwoods. However, it is uncertain if these vintage photographs are characteristic of "average" stand conditions found in primeval forests. Many of these images were taken for promotional purposes, so it is not surprising that they are dominated by "trophy" individuals (Bragg, 2004b). Likewise, modern-day old pine-dominated remnants represent a tiny fraction of this condition still found in the Midsouth, and thus may not reflect an average for this cover type.

Another concern lies in the appropriateness of the National Biomass Estimators to estimate biomass for past forests. There are some discrepancies between biomass derived from the original documents and those predicted with these estimators. For instance, Chapman (1942, p. 13) stated that individual loblolly pines from the virgin timber on upland sites in the Midsouth reached a maximum diameter of 91 to 102 cm DBH and up to 3,000–4,000 board feet (5.6–7.6 Mg per tree, sawtimber only). A different publication from this time period (Mesavage and Girard (1946), using their Table 79 for the Doyle log rule and a form class of 84 for old-growth trees) gives the maximum gross lumber yield of southern pines in this diameter range as 2,833–3,694 board feet, or 5.4–7.2 Mg per tree. Both of these estimates are notably greater than the 4.6 and 6.2 Mg predicted by Jenkins et al. (2003) for pines of 91 and 102 cm DBH, respectively, especially since the Jenkins et al. (2003) values are for whole trees, not just the sawtimber. There are several possible explanations for these discrepancies. First, for whatever reason, the board foot volume estimates given by different sources (in this case, Chapman versus Mesavage and Girard) for trees of identical diameters varied, and thus may have some error or did not use the same volume estimation techniques. Second, it is likely that the lumber volume conversion process outlined in Section 2.2. may contain inaccuracies, especially given the uncertainty of the board foot to cubic volume assumptions. Finally, on average the wood of virgin pines was denser than that of second-growth (Anonymous, 1936; Paul and Smith, 1956) and therefore Jenkins et al.'s (2003) biomass equations may be inadequate to describe historic tree properties.

4. The nexus of biomass estimates and restoration/ sequestration objectives

Unlike much of eastern North America, the piney woods of the Midsouth were historically more fire-prone and only briefly farmed (if at all), and have long been protected from fire and allowed to densely reforest. Arguably, this was a positive consequence of the implementation of sustainable forestry, but in recent years interest has grown in the restoration of presettlement stand conditions, particularly on public lands. However, this objective is at odds with another new goal for pine-dominated stands of the southeastern USA—C sequestration. Returning modern second-growth pine-hardwood forests (especially in unmanaged stands) to an approximation of presettlement stand structures will likely reduce total C storage because they tend to have significantly lower live tree stocking, particularly of high C density hardwoods. An example of the change in biomass following restoration was recently documented in southern Arkansas, with the post-treatment old pine-dominated stand retaining only 58% of the preharvest biomass in the live tree component (Bragg, 2010).

Rarely is biomass quantity an issue for small-scale restoration efforts. However, landscape restorations designed to replicate historic old-growth conditions may have significant impacts. For instance, the Ouachita National Forest in west-central Arkansas and southeastern Oklahoma has initiated efforts to restore over 100,000 ha of mature, second-growth shortleaf pine-mixed hardwood forest to a more open pine-bluestem (*Andropogon* spp.) woodland (Hedrick et al., 2007). While this effort has been highly beneficial for a number of threatened plant and animal species, the removal of most midstory hardwoods and the reduction of overstory shortleaf pine basal area by approximately 40% has appreciably lowered the live tree biomass over a very large area. The loss of some biomass should not dissuade land managers from restoring primeval forest-like characteristics to the Midsouth, as C sequestration is only one of numerous ecosystem services of forested lands (Ryan et al., 2010). While it will likely decrease net biomass if started from unmanaged stands, most restoration efforts are designed to benefit other components (e.g., migratory songbirds). If the restoration process includes burning to help manage live vegetation, some of the C lost from standing live trees may be transferred into the dead wood pools or recalcitrant charcoal in the soil, as would have occurred in the past.

The ability to estimate presettlement biomass totals can also be used to shape large-scale sequestration strategies. A few continental- or regional-scale estimates of biomass (e.g., Birdsey et al., 2006) are available for past forests of the USA, based largely on timber harvest records (e.g., Kellogg, 1909; Greeley, 1925; Reynolds, 1935) and early forest inventories (Rhemtulla et al., 2009), but these are very coarse in resolution and low in accuracy. Rhemtulla et al. (2009) used mid-19th Century public land survey notes, a 1930s-vintage land economic inventory, and US Forest Service inventory data from 2000–2004 to estimate long-term change in tree-based C storage for the state of Wisconsin. At this scale, their results suggested that even though modern-day forests have recovered significant quantities of C, widespread agricultural conversion of formerly forested lands still allows considerable potential for additional sequestration (Rhemtulla et al., 2009).

The results of this study suggest that if historic stand structures are used as the basis for determining baseline biomass totals, the amount of C stored in live timber lost to widespread deforestation may have been at least partially offset by increased stand density, especially if lower C density conifers are replaced with hardwoods and a minimal level of harvesting occurs. Extensive timber management does reduce the regional quantity of biomass found (see Delcourt et al. (1981) and Brown et al. (1999) for examples of contemporary large-scale biomass estimates). Yet even these noticeably reduced values are in the range of that witnessed in historic old pine-hardwood forests (50–150 Mg/ha of oven-dried live tree biomass), implying that at least regionally, C storage has probably not declined significantly in the southeastern USA from what it would have been prior to widespread Euroamerican settlement. Thus, an argument for additionality could be made in the case of modern stands kept near the full stocking of unmanaged, naturally regenerated second-growth if the biomass of presettlement stand structure is the accepted baseline.

5. Conclusions

Decades before interest in bioenergy and C storage arose, naturally regenerated southern pine-dominated forests began to decline in prominence as they were gradually replaced by plantations, trends that shows little sign of abating (e.g., Conner and Hartsell, 2002; Zhang and Polyakov, 2010; Wear and Greis, 2011). In an era when land managers are increasingly focused on non-traditional options such as biofuel production and C sequestration for their properties, the roles of naturally regenerated and planted southern pine stands should be revisited.

This research supports the hypothesis that historic old pine-dominated forests in the Midsouth contained significantly less biomass in living trees than their modern-day analogs. In this region, the biomass of contemporary well-managed forests is lower than that found in modern unmanaged old forests, and more similar to historic stands. This suggests that per unit area of forest cover, modern managed landscapes are comparable in their standing biomass to historic old forests because density regulation via silvicultural treatments acts similarly to that imposed by the historical disturbance regimes, particularly fire. The loss of very large trees, though a structural and functional alteration to the dynamics of southeastern pine-dominated forests, has been largely offset by increased stand densities, and hence regional forest C storage probably differs much less from historic levels than may have been previously assumed. Furthermore, large-scale restoration projects in contemporary old forests will likely further reduce aboveground biomass, an unavoidable consequence of returning past stand conditions.

As in most cases when historical data are used to quantify past stand conditions, more information is needed to confirm the results of this study. One outcome of this work is the inadequacy of relying solely upon the extrapolation of pine sawtimber-only volume information to estimate historic biomass in mixed composition old forests. A combination of a number of different data sources, including lumber yields, detailed stand tables, visual and anecdotal accounts, and individual tree biomass should be used to better estimate historic stand biomass. With further refinement, it may eventually be possible to use these reconstructed biomass estimates to approximate other less tractable historic C pools, such as dead wood or soil C.

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