Estimating Long-Term Carbon Sequestration Patterns in Even- and Uneven-Aged Southern Pine Stands

Don C. Bragg[1] and James M. Guldin[2]

Abstract—Carbon (C) sequestration has become an increasingly important consideration for forest management in North America, and has particular potential in pine-dominated forests of the southern United States. Using existing literature on plantations and long-term studies of naturally regenerated loblolly (*Pinus taeda*) and shortleaf (*Pinus echinata*) pine-dominated stands on the Crossett Experimental Forest, allometric biomass equations, and reasonable assumptions about forest product life cycles, we projected the net C pools of the following silvicultural systems over a 100-year period: a short rotation loblolly pine plantation (4 rotations); a seed tree-based (natural origin) even-aged loblolly/shortleaf pine stand (2 rotations); and an uneven-aged loblolly/shortleaf pine stand (20 cutting-cycle harvests under the selection method). Both the seed tree stand and the intensively managed pine plantation produced large (if fluctuating) quantities (up to almost 190 tons/ha) of aboveground live biomass. Though not as productive as the even-aged treatments, the uneven-aged pine stands produced a steady stream of sequestered C in the form of high quality sawtimber while simultaneously maintaining a steady stock of 61.5 to 78.5 tons/ha of live aboveground biomass. Belowground C sequestration was also substantial in uneven-aged stands, with a fairly constant 13.3 to 16.9 tons/ha of coarse roots in the standing live pine crop. While shorter rotation even-aged stands tend to produce smaller coarse roots, their higher stocking levels more than offset this, and hence these stands have more live belowground biomass during most of the rotation (up to almost 41 tons/ha). By the end of the 100-year simulation, the even-aged stands had sequestered approximately 120 tons/ha of C in live tree and product pools, or about 50 percent more than the uneven-aged stand. The uneven-aged stand, however, maintained a more stable residual live tree C store, and fluctuated (only ± 2 tons/ha/yr) far less than either even-aged treatment. Averaged over the period, annual C storage ranged from 0.38 to 1.11 to 1.16 tons/ha for the uneven-aged, seed tree, and plantation, respectively. Though it is difficult to compare these values to other simulations, the data show that managing loblolly pine stands is an effective way to sequester C, even if their patterns differ appreciably.

Keywords: Crossett Experimental Forest, Loblolly pine, shortleaf pine, silviculture

In: Jain, Theresa B.; Graham, Russell T.; and Sandquist, Jonathan, tech. eds. 2010. Integrated management of carbon sequestration and biomass utilization opportunities in a changing climate: Proceedings of the 2009 National Silviculture Workshop; 2009 June 15-18; Boise, ID. Proceedings RMRS-P-61. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station. 351 p.

[1] Research Forester, USDA Forest Service, Southern Research Station, Monticello, AR.

[2] Supervisory Ecologist and Project Leader, USDA Forest Service, Southern Research Station, Hot Springs, AR.

Introduction

Bioenergy production and carbon (C) sequestration have become a major emphasis for silviculture in recent years (for example, Gan and Smith 2007; Mead and Pimentel 2006). To date, afforestation has garnered the bulk of the economic interest because current commercial markets for C sequestration require the long-term accumulation of atmospheric C on locations presently lacking tree cover (Birdsey 2006). However, foresters and policy makers are trying to modify the nature of these markets to get credit for C accumulated in and the forest products

generated from existing stands. If successful, this broadening of C credits for silvicultural practices other than afforestation may significantly boost the income potential on millions of hectares of productive timberlands.

The possibility of C credits is fueling research into understanding the differences between management practices and their ability to sequester C, which in turn has raised a number of questions. For instance, are there quantifiable differences between long-term C sequestration patterns by silvicultural system? Many people assume that productivity is a reasonable measure of C accumulation, and therefore, fast growing pine plantations may be considered most desirable. However, much of the long-term C storage benefits may be found in end product usage. Commodities such as dimensional lumber or plywood last much longer than short-lived products (such as paper) that are often the primary output of short-rotation plantations (Johnsen and others 2001; Markewitz 2006). Would naturally regenerated southern pine stands geared towards quality sawlog production sequester more C over the long-term than a short-rotation, intensively managed pine plantation that produces more fiber than boards?

We will address these questions using long-term data accumulated on the USDA Forest Service's Crossett Experimental Forest (CEF) and adjacent industrial lands in extreme southern Arkansas. The naturally regenerated forests of the CEF are predominantly loblolly pine (*Pinus taeda* L.), with lesser amounts of shortleaf pine (*Pinus echinata* Mill.) and limited quantities of oaks (*Quercus* spp.), gums (*Liquidambar styraciflua* L. and *Nyssa sylvatica* Marsh.), and other hardwoods. The CEF is characteristic of mesic, relatively productive Upper West Gulf Coastal Plain upland sites, most of which have been in timber production for decades, and many of which have been recently converted to intensively cultured loblolly pine plantations (Wear and Greis 2002). This makes the results from studies on the CEF an appropriate source of information to compare long-term C sequestration patterns under different silvicultural systems.

Methods

Silvicultural Systems

To consider broad-scale differences between silvicultural systems rather than specific real-world stands, a number of "model" systems will be used to represent stand dynamics related to C sequestration. These idealized systems are based on examples of long-term growth and yield from southern pine stands in the Upper West Gulf Coastal Plain, which has a rich history of diverse and sustainable forestry varying from even-aged plantations to uneven-aged selection. As with all silvicultural systems, there are a number of possible conditions and management objectives—the treatments described below follow typical standards and practices for loblolly pine-dominated forests in southern Arkansas.

Uneven-aged stand—The loblolly pine-dominated uneven-aged stand in this exercise was modeled after examples of the selection method using periodic cutting-cycle harvests provided in Baker and others (1996), primarily adapted from data on the CEF's Good and Poor Farm Forestry Forties. Our simulated stand has a reverse J-shaped distribution, with a residual basal area of 13.8 m^2/ha and 345 stems/ha (merchantable pines only), a maximum d.b.h. of 53.3 cm, and a q-factor of approximately 1.2 for 2.5 cm d.b.h. classes (table 1). In the 5 years following any given cutting-cycle harvest, this stand is assumed to reach 17.2 m^2/ha of basal area and just under 400 merchantable pines/ha, producing 22.0 m^3/ha of sawtimber.

Table 1—Structure of uneven-aged loblolly pine-dominated stand immediately post-harvest (year = 0) and immediately prior to the next harvest (year = 5).

D.b.h. class midpoint	Live pine stocking by d.b.h. class		Live pine basal area by d.b.h. class		5-year harvested sawtimber volume
	Year = 0	Year = 5	Year = 0	Year = 5	
cm	*- - - - - trees/ha - - - - -*		*- - - - - m^2/ha - - - - - -*		*- - - - m^3/ha [a]- - - -*
			Submerchantable stems		
1.3	579.4	695.2	0.07	0.09	—
2.5	331.1	397.3	0.17	0.20	—
5.1	189.2	227.0	0.38	0.46	—
7.6	108.1	129.7	0.49	0.59	—
Subtotals:	1207.8	1449.2	1.11	1.34	—
			Merchantable stems		
10.2	61.8	74.1	0.50	0.60	—
12.7	46.2	49.4	0.59	0.63	—
15.2	40.8	44.5	0.74	0.81	—
17.8	35.8	39.5	0.89	0.98	—
20.3	30.9	34.6	1.00	1.12	—
22.8	25.9	29.7	1.07	1.22	—
25.4	24.5	24.7	1.24	1.25	0.05
27.9	18.5	20.0	1.14	1.23	0.55
30.5	13.6	17.3	0.99	1.26	1.65
33.0	11.4	14.6	0.97	1.25	1.84
35.6	9.4	12.1	0.93	1.20	1.92
38.1	7.7	10.4	0.87	1.18	2.31
40.6	6.7	9.6	0.87	1.25	2.98
43.2	5.4	7.4	0.80	1.09	2.31
45.7	3.5	4.9	0.57	0.81	2.00
48.3	2.0	3.7	0.36	0.68	2.68
50.8	1.2	2.5	0.25	0.50	2.17
53.3	0.0	0.7	0.00	0.17	1.47
Subtotals:	345.3	399.7	13.78	17.23	21.93
Grand totals:	1553.1	1848.9	14.89	18.57	21.93

[a] Calculated from equations in Farrar and others (1984) for sawtimber-sized pines only.

Seed tree stand—There are many possible permutations in how to conduct seed tree management in southern pine stands, depending on initial conditions, desired rotation length, the number of seed trees to retain following the regeneration harvest, the duration of overwood retention, etc. For convenience, we chose a strategy that incorporated a 50-year rotation (hence, 2 full rotations during our 100-year simulation period) and retained just under 20 seed trees/ha. We assume that 12,355 new loblolly pines/ha are successfully established after the regeneration cut, and all of the seed trees are harvested in year 5 in conjunction with a precommercial thinning to reduce the number of pines to 1,347 stems/ha by year 6. Commercial thinnings were performed in years 18, 25, 35, and 43, reducing stand density down to 494, 309, 222, and 124 pines/ha, respectively. After 50 years under this prescription, loblolly pines in the simulation were assumed to reach an average of 47.8 cm in d.b.h. An excellent description of the shelterwood system in loblolly pine-dominated stands in this region is presented in Zeide and Sharer (2000). Specific data used to develop this silvicultural regime were adapted from a variety of studies in even-aged, naturally regenerated, loblolly pine-dominated stands on the CEF, including Cain (1996), Cain and Shelton (2001, 2003), and Bragg (2010).

Plantation—The plantation used to exemplify artificial regeneration typical of this region assumed that 1,347 seedlings/ha of 1-0 genetically improved loblolly pine stock were planted on 2.4- by 3.0-meter spacing and were managed on a 25-year rotation. Although plantations in this region commonly recruit volunteer pines from nearby seed sources, we assumed that site preparation and release eliminated these unwanted volunteers. At 11 and 17 years, commercial thinning treatments were implemented to reduce this stocking to 445 and 222 pines/ha, respectively. At 25 years, when these improved loblolly pines were assumed to average 37.1 cm at d.b.h., all trees were cut and the site was replanted. For convenience of the calculation, we assumed that loblolly pines were immediately planted to 1,347 seedlings/ha after logging was completed so that no year went without the presence of a plantation (though in the real world, plantation re-establishment often occurs months to a couple years after harvest).

Model Design and Assumptions

Modularity—This modeling exercise assumes modularity of the treatments, with each silvicultural system module based on either cutting cycle (5-year cutting cycle for the uneven-aged example) or rotation length (25-year rotation for the plantation example or 50-year rotation for the seed tree example). Each module within each treatment is modeled exactly the same, with identical stand developmental trajectories and treatment implementations. Furthermore, no mortality or other stochastic events are assumed, making all of the modules in this system deterministic. However, biomass and sequestered C values are carried over from one module to the next, producing a running total. Hence, the results reported are for a single projection in Excel™ (in other words, no replication). While this focuses on the silvicultural treatments under idealized circumstances, it also likely produces overly optimistic growth and yield predictions.

Tree allometry—To standardize biomass values, a nationally derived set of estimators was applied. What the equations of Jenkins and others (2003) sacrifice in terms of local accuracy is offset by the needs of this simulation to segment individual trees into their primary biomass components (in other words, coarse roots, stem wood, stem bark, branches, and foliage) in a compatible system. Undoubtedly, in any given stand (even intensely managed pine plantations) there will be individual-based differences in attributes such as species, wood density, shoot:root ratio, bark thickness, leaf area efficiency, decay presence, among many other variables. We do not have the ability to account for all of these differences—hence, we are better off recognizing this inadequacy and emulating a "standard" tree following well-described factors we can control (for example, silvicultural system, rotation or cutting cycle length, stand density).

Jenkins and others (2003) used a series of published equations on biomass for different tree species groups to derive "pseudodata" that were then used to generate a set of equations for species groups based on a number of factors, including phylogenetic relationship, adequacy of the original equations and data, and similarity of wood specific gravity. Each species group equation was fit to a common logarithmic model form:

$$B = \frac{e^{b_0 + b_1 \ln d.b.h.}}{1000} \qquad [1]$$

where B = total aboveground biomass (in metric tons), $d.b.h.$ = diameter at breast height, and b_0 and b_1 are group-specific coefficients. Note that in this paper, all biomass or C sequestration weights are given in terms of oven-dry metric tons (1 metric ton = 1,000 kilograms = 1 megagram). Because we considered only loblolly and shortleaf pine-dominated natural stands and loblolly pine plantations,

we used their pine species group coefficients (b_0 = -2.5356 and b_1 = 2.4349, table 4 in Jenkins and others (2003)).

Jenkins and others (2003, their table 6) also developed a series of coefficients to estimate the proportions of different tree components for conifers based on the following ratio equation:

$$R_i = e^{b_{0,i}+b_{1,i}/d.b.h.} \quad [2]$$

where R_i = the ratio (0.0 to 1.0) of component i to total aboveground biomass. Note that the coarse root component is in addition to the biomass calculated in equation [1], and that the proportion of branch biomass (R_{BRANCH}) = 1.0 – R_{WOOD} – R_{BARK} – $R_{FOLIAGE}$. The ratios predicted by equation [2] do not explain a lot of the variation in the data they were derived from, but follow logical proportioning patterns, and vary reasonably as a function of tree diameter. Future iterations of this effort may be improved with the adaptation of more conceptually robust allometric relationships (for example, Enquist 2002; Enquist and Niklas 2002).

Biomass and post-harvest C storage pools—Live tree biomass (both above- and belowground) is tracked every year from the start of the even-aged stands. For uneven-aged stands, the residual contains the live trees retained to meet the minimum basal area target (in this case, 13.8 m^2/ha)—neither the seed tree stand nor the plantation has such a consistent base C storage.

Once harvested, there are two post-harvest biomass pools that each tree is proportioned to—the fast (short-term) and slow (long-term) pools. These pools represent the dynamics of felled trees post-harvest whether utilized as forest products or left on the site as slash. Fast pool biomass consists of finer materials such as smaller roots, bark, foliage, and certain portions of the bole that either decompose quickly or are converted into short-lived consumer goods such as paper products. Slow pool biomass is assumed to be larger portions of the bole and large coarse roots that are left on-site as coarse woody debris or converted into long-lived consumer goods such as boards or structural panels. These pools assume half-lives of 1 year for the fast pool and 50 years for the slow pool (Birdsey 1996) using the following exponential decay function:

$$\Psi_t = \Psi_0 e^{-\lambda t} \quad [3]$$

where the original harvested biomass (Ψ_0, fast or slow) reduces to Ψ_t after t years. For equation [3], the decay coefficient λ = 0.69315 for the fast pool and 0.01386 for the slow pool.

All stems less than 25.4 cm d.b.h. are automatically assigned to the fast pool because of their rapid decay or use as short-lived consumer products. Large bolewood was partitioned into slow and fast pools based on the lumber recovery work of Fonseca (2005, his table 6.6). For 25 cm d.b.h. stems, only 30 percent of their stem wood is assigned to the slow pool because the rest is either converted to sawdust, slabs, chips, or planer shavings, or is in part of the bole that is too small to decay slowly. The proportion of slow pool biomass from stem wood gradually increases to 45 percent when the tree reaches 40 cm d.b.h., and is held constant at this ratio no matter how much larger the stem gets. The 55 to 70 percent of bole biomass not assigned to the slow pool is transferred to the fast pool for time-related decay, as were all of the foliage, bark, and branches.

To convert from biomass (in both the live biomass and post-harvest pools) to weight of sequestered C only, we simply multiplied the biomass total by 0.5 (Johnsen and others 2004; Skog 2008). For this paper, sequestered C weight was defined as the sum of the above- and belowground live C weight plus the weight of the C in the current fast and slow post-harvest pools for any given year.

Other assumptions—Because this research is initial and exploratory, certain significant C pools are not expressly included in this analysis. For instance, the only vegetation being tracked are the crop loblolly pines that are either planted or explicitly included in the modular natural regeneration scenario. No other non-pine vegetation (for example, grasses, forbs, shrubs, vines, hardwoods, etc.) is tracked in the C pools. Likewise, no "volunteer" pines are incorporated in plantations, nor are pines that would otherwise seed in following the thinnings of even-aged natural stands. Though all of these components are noticeable parts of the ecosystem C pools, we lacked good, quantifiable information on how they would respond to the specific treatments presented over time, and therefore, we chose not to include them. Note, however, that the uneven-aged stand did assume continuous pine regeneration since this is how this stand condition perpetuates itself (rather than relying on discrete establishment events).

Two other dynamic components likely to be very important but poorly described are the soil and forest floor C pools (Birdsey 2006). Rather than trying to estimate these values and simulate their behavior, we will assume there are no significant differences between the size of the pools in any of the silvicultural treatments we are comparing. Studies performed on loblolly pine stands in the southeastern US have provided mixed results regarding these components, with some treatments decreasing and others increasing soil C (for example, Laiho and others 2003; Samuelson and others 2004). Most of these studies are relatively short-term (less than 10 years) and often focus on soil C dynamics for plantations managed under a gradient of treatment intensity rather than mature loblolly pine stands of natural origin. So, given the paucity of reliable information, we believed the bulk of the belowground contribution to C sequestration in these pine stands would be best dealt with in a later analysis. Hence, the only subsurface sequestration components in this paper are the coarse roots.

There are also C emission impacts related to harvest system and equipment type/usage by silvicultural system (Eriksson and others 2007; Markewitz 2006). Because this particular part of the C cycle depends strongly on the type of equipment and how it is used, coupled with the quantities of fossil fuel-based fertilizers and other chemicals applied and the nature of the site being treated, we have chosen to assume that there are no significant differences between our silvicultural systems. Ignoring this component is not likely to have a marked influence on overall C dynamics, anyhow—Markewitz (2006) estimated that cumulative C emissions for all silvicultural activities on an intensive fiber farming system using southern pines over an entire 25 year rotation was only about 3 tons/ha.

Finally, we did not explore the economic ramifications of these treatments (or any variations of them), so any conclusions on the efficacy of these silvicultural regimes are based on their ability to store C in either slow or fast post-harvest pools or residual (live) crop tree biomass on the site. We also did not assume any post-harvest consumer products were recycled, nor did we include C offsets due to product displacement or substitution.

Results

Aboveground Live Tree Biomass

Marked differences arose between the biomass patterns between these silvicultural systems in loblolly pine dominated stands (fig. 1). The seed tree (natural origin) stand, starting from the regeneration cut, contained more biomass (19.2 tons versus 0.0 tons/ha) than the plantation, which started from a true clearcut. Aboveground biomass in the seed tree increased rapidly as both the newly established

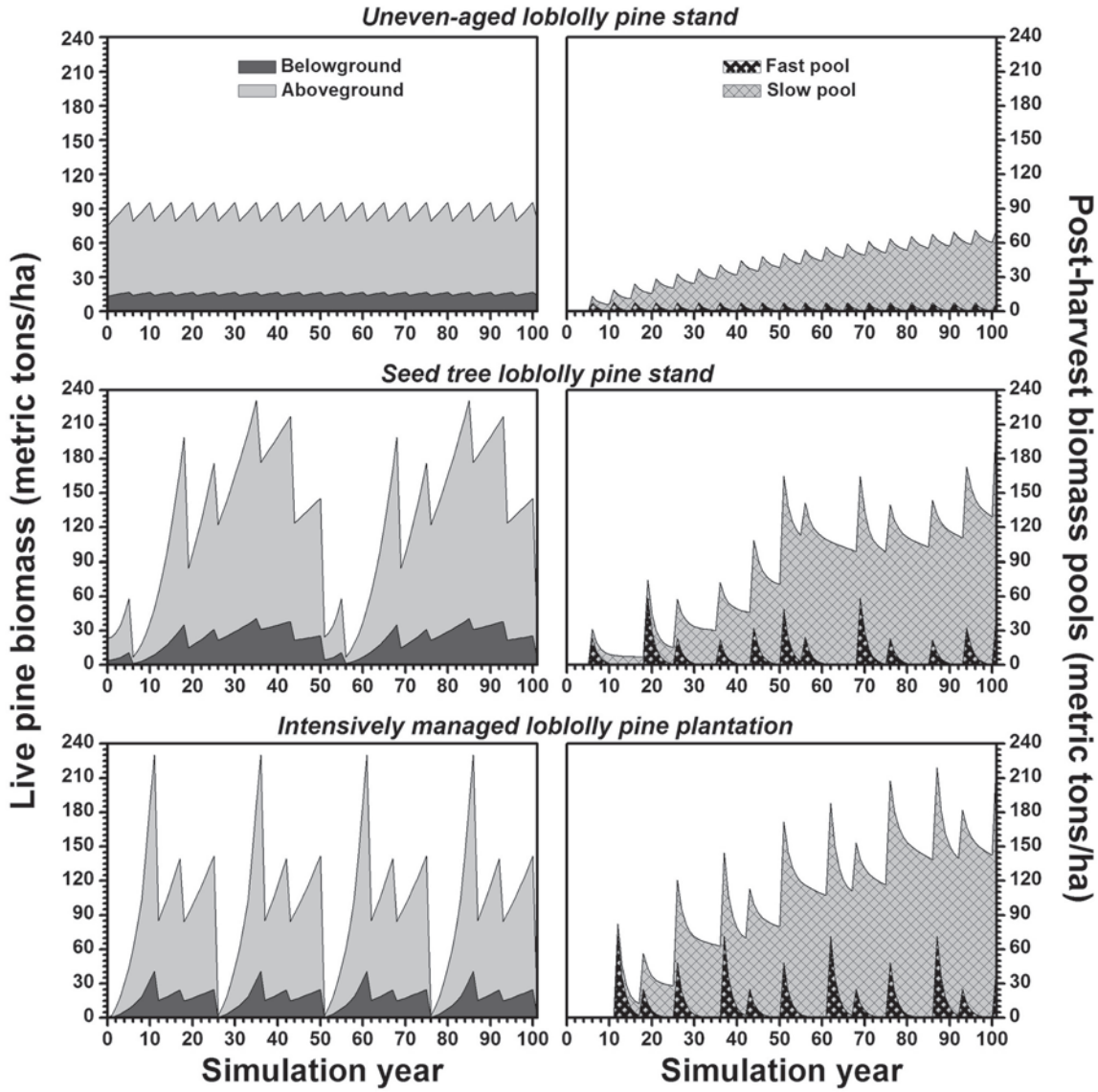

Figure 1—Biomass fractions in live loblolly pines (aboveground biomass + coarse roots) and contributions to different post-harvest product biomass based on fast (1-year half-life) and slow (50-year half-life) decomposition (loss) pools for three silvicultural systems.

pine seedlings and overwood pine grew quickly, reaching 47.2 tons/ha in year 5. The harvest of the seed trees and concurrent precommercial thinning resulted in a sharp decrease in biomass, noticeably below the level of the similarly stocked loblolly pine plantation. This biomass difference after 6 years (5.6 versus 49.5 tons/ha) is attributable to the significantly larger size of the improved pine seedlings in the plantation, which had been growing at a low density since planting compared to the considerably higher stocking of the natural origin seedlings during the first 5 years of their life.

The seed tree stand and the plantation both rapidly added biomass during the remainder of their rotations, periodically experiencing sharp drops as thinning operations and regeneration harvests removed biomass (fig. 1). Not surprisingly, the more intensively managed even-aged stands experienced substantially higher peak live biomass totals than the uneven-aged stand. Both even-aged stands

approached 190 tons/ha of aboveground live biomass—the plantation reached just under 190 tons/ha first, immediately prior to the first commercial thinning at age 11, before fluctuating between 69 and 117 tons/ha for the rest of the rotation. The seed tree stand peaked much later in its rotation, just exceeding 190 tons/ha in year 35 (right before the third thinning). The seed tree stand contained between 100 and 150 tons/ha of live pine biomass during the last 3 decades.

In contrast to the even-aged stands, biomass in the well-regulated uneven-aged stand managed under the selection system (Baker and others 1996) varied little over time. Immediately following each cutting-cycle harvest, the simulated uneven-aged loblolly pine-dominated stand started out at 61.5 tons/ha of live pine aboveground biomass and quickly increased to 78.5 tons/ha 5 years later (fig. 1). The closely controlled stand density of the uneven-aged stand kept any of the high or low aboveground live pine biomass amounts from fluctuating nearly as much as the even-aged stands.

Belowground Live Tree Biomass

Because belowground live tree biomass was determined as a relatively fixed proportion of aboveground live pine biomass (a function of diameter), this component closely paralleled the aboveground patterns. Even-aged stands peaked near 41 tons/ha of belowground biomass when aboveground biomass was peaking at 190 tons/ha, and would decline to less than 2 tons/ha at the end of each cutting cycle while the new stands were establishing themselves (fig. 1). The uneven-aged stand varied between 13.3 and 16.9 tons/ha of live pine belowground biomass across the entire 100-year simulation period.

Post-harvest Biomass Pools

The harvested biomass showed a steady increase in quantity for the slow pools (fig. 1). In all cases, the slow pools decayed at a rate that did not reach equilibrium with new inputs during the 100-year simulation period. Thus, all of the silvicultural treatments continually added to their respective slow biomass pools. Fast biomass pools, however, decayed quickly enough so that even the fairly substantial (greater than 60 tons/ha) periodic contributions by either even-aged treatment failed to build upon other pulses of fast pool biomass, and typically remained at less than 1 ton/ha during most of the simulation period.

C Sequestration Patterns

Long-term C stocks varied considerably over time, with the highest fluctuations once again being found in the even-aged treatments (fig. 2). The combination of above- and belowground biomass with the post-harvest product pools helped to dampen some of the more pronounced oscillations in the even-aged stands, but both still experienced dramatic changes. At their peaks, both even-aged stands exceeded 160 tons of C in their respective simulated stand developmental trajectories (before settling down to about 120 tons C at 100 years), and seem destined to continue to accumulate C well into the future.

The uneven-aged stand surpassed the other even-aged treatments in C storage only briefly during the first 3 simulated decades—from the first 8 to 14 years for the plantation and seed tree stands, respectively, and then again between 26 and 31 years after the logging and reestablishment of the plantation (fig. 2). C steadily accumulated in the uneven-aged stand and its related post-harvest pools from a low of 37.4 tons/ha to about 76 tons/ha at the end of the 100-year simulation period. Variation from year to year in the uneven-aged stand showed a much more stable pattern, with fluctuations of less than 2 tons/ha typical during the simulation.

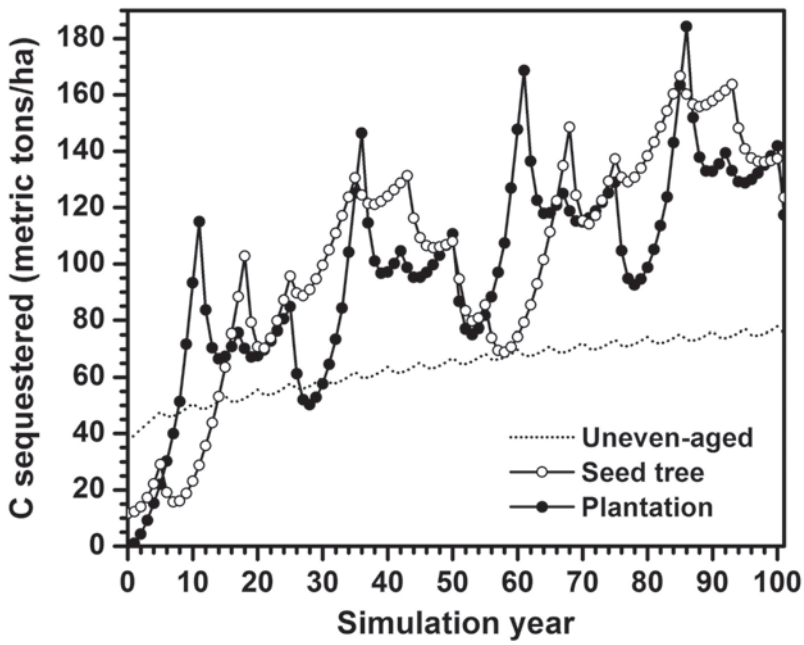

Figure 2—Sequestered carbon (C) in above- and belowground live trees and fast and slow product pools over a 100-year simulation of three silvicultural systems in loblolly pine stands.

Considerable variation appears in C storage patterns from one year to the next (fig. 3), although this pattern was far less pronounced for the uneven-aged stand. The uneven-aged scenario varied by ± 2.2 tons/ha/yr (standard deviation (SD) = 1.36 tons/ha/yr)), compared to between +14.4 and -24.2 (SD = 7.25) tons/ha/yr for the seed tree stand and +21.7 and -32.3 (SD = 11.90) tons/ha/yr in the pine plantation. Over the 100-year simulation period, average annual C sequestration was positive for all treatments, ranging from 0.38 tons/ha/yr in the uneven-aged stand to 1.11 tons/ha/yr for the seed tree stand to 1.16 tons/ha/yr for the plantation.

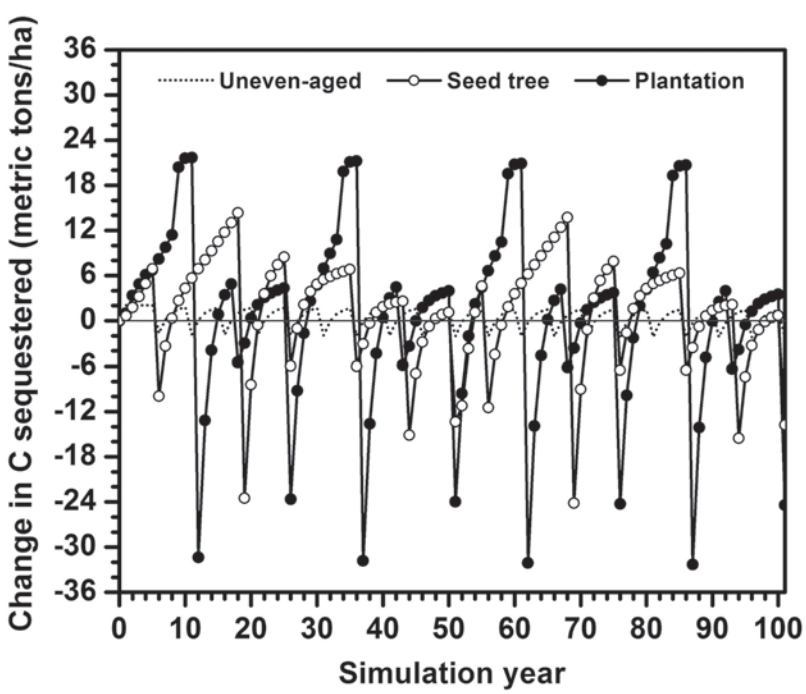

Figure 3—Change in sequestered carbon (C) from one year to the next during the 100-year simulation period as a function of silvicultural system in loblolly pine-dominated stands.

Discussion

This preliminary study makes a number of key oversimplifications in order to examine silvicultural systems in isolation. For instance, some of our assumptions (such as the decay coefficients for the fast and slow pools) apply commonly accepted values, but no sensitivity testing is presented here to evaluate the consequences of altering the rates of change on C sequestration patterns. Given the wide range of differences between fast and slow pool behavior with the two extremes of decay rates, we would expect this to vary considerably based on the values used. For instance, it may be more appropriate to use a slower decay rate for the belowground slow pool for the large sawtimber trees produced in the natural origin stands, as these stumps are often resin-soaked and therefore much more resistant to decay than younger, faster-grown plantation stumps of comparable size. The multitudes of possible management activities, coupled with the likelihood of stochastic mortality events, changing climate patterns, and even developments in the genetic improvement of loblolly pine may also drastically affect the outcomes of the silvicultural scenarios presented. It is simply not possible to determine every possible interaction and predict their influence on the outcomes.

The aforementioned qualifications notwithstanding, it is obvious that C sequestration patterns in southern pine stands, when the fate of the materials produced from them is included, show considerable potential to offset some atmospheric CO_2 increases. The sustained accumulation of C in this study is comparable to other simulation-based research (for example, Baral and Guha 2004; Johnsen and others 2001) and suggests that the active management of southern pinelands may increase atmospheric CO_2 sequestration over no-treatment options.

C storage patterns fluctuate dramatically in managed ecosystems, especially those under even-aged management (fig. 3). Because of how this exercise was designed, large negative values in the live biomass portion of this metric only occur in a single year, as regeneration and residual tree growth immediately begin accumulating new C. Any prolonged deficits in C storage shown in figure 3 reflect periods after major timber harvests, when new growth fails to offset C losses due to post-harvest product decay. Even with these prolonged deficits, stand-level C accumulation over the whole simulation period was positive for each treatment, ranging from 0.38 to 1.16 metric tons/ha/yr.

However, it is hard to compare these results with other published studies because different components are often used to derive C accumulation. For instance, Luyssaert and others (2008) used carbon flux estimates to find that old-growth temperate and boreal forests sequestered an average of 2.4 tons of C per hectare per year, a majority (83 percent) of which was attributed to C stored in coarse woody debris (CWD), roots, and soil organic matter. While the CWD pool in their study is analogous to our post-harvest product pools, Luyssaert and others (2008) also incorporated fine root biomass in their root category (we only considered coarse roots) and our study has no information on soil organic matter. It is also unclear how Luyssaert and others (2008) accounted for the decomposition of wood. Other estimates of C sequestration by temperate forests (for example, Baral and Guha 2004; Hall and others 1991) consider only C accumulation via growth, and do not account for simultaneous losses to the system. If couched in accretion-only terms, average annual C accumulation values of 0.81, 3.36, and 4.82 tons/ha/yr were calculated for the uneven-aged stand, the seed tree stand, and the plantation in this study, respectively. Undoubtedly, these values would increase even more if soil C storage was also factored into these estimates.

The long-term C sequestration benefits of southern pine forests under management also depend on the end-use of the biomass produced. Shifting products

from slow pool into fast pool consumer goods (for example, dimension lumber or plywood into paper products) would have a marked effect on C sequestration, especially if this happens at large scales. While this study has focused on C storage based on either biomass retained on the landscape or preserved within long-term commercial products, net C benefits may also be derived if woody biomass (rather than fossil fuels) are used to produce energy or other derived products (for example, Baral and Guha 2004; Frederick and others 2008; Gan and Smith 2007; Hall and others 1991), replaces corn-based ethanol with cellulosic ethanol (Piñeiro and others 2009), or is substituted for higher C-emitting building materials such as steel or concrete (Perez-Garcia and others 2005).

Conclusions

Undoubtedly, our results are sensitive to a number of possible variables, including the decay coefficient used for both fast and slow pools, mortality of individual pines as a function of treatment and random factors, regeneration success or failure, and differences in wood density related to genetics and growth habit. Our goal was not to consider all possible conditions and permutations related to the C cycle, but to explore the role of silvicultural practices on an aspect of stand management (C sequestration) only poorly considered to date.

Hence, we believe our results show that C sequestration patterns in southern pine-dominated forests depend considerably on the silvicultural system being applied. According to our projections and the work of others (for example, Johnsen and others 2001; Smith and others 2006), all of the conventional management practices used in loblolly pine ecosystems of the southern US have potential to accumulate C in standing timber, the soil, and long-term end products. Intensively managed loblolly pine plantations, due to their high rate of fiber production (and assuming that most of their products end up in slow decaying uses), were predicted to accumulate C at the highest rate over the course of a 100-year simulation.

However, it is possible to have mature, natural origin southern pine forests produce significant amounts of C storage. Loblolly pine-dominated stands managed under a seed tree regeneration approach accumulated C at a rate very comparable to a loblolly pine plantation. The timing of harvest and regeneration in the two even-aged harvest regimes produced some differences in C sequestration patterns, but both were predicted to store around 120 metric tons of C per hectare after 100 years of growth and harvesting. This total is at least 50 percent higher than that accumulated under uneven-aged management of loblolly pine-dominated stands at the end of the same period.

The perpetual understocking of uneven-aged southern pine stands to ensure adequate regeneration also assures lower C sequestration. Uneven-aged pine stands are also much less variable in their C accumulation patterns, since they always retain a large quantity of live biomass on the site. However, it may be possible to manage uneven-aged southern pine stands on a more irregular basis with cutting cycles longer than conventional 5-year intervals. Doing so would likely result in increased rates of C accumulation somewhat similar to that seen in the seed tree method, and concurrently would increase C sequestration while retaining the continuous cover canopy attributes sought by managers who utilize this silvicultural system.

The opportunities presented by bioenergy and C sequestration may have particular appeal for public lands management in the southeastern US. Given that few governmental agencies can engage in the large-scale industrial forestry of intensively cultured loblolly pine plantations, the ability to produce significant C storage while harvesting high-value timber products under naturally regenerated,

sustainable forest conditions would seem to fulfill multiple resource objectives simultaneously. To ensure this, it is vital that work (for example, Johnsen and others 2004; Mayfield and others 2007) considering the possibility of using forests for bioenergy and C sequestration in the southeastern US be expanded to include the unique statutory, regulatory, and policy obstacles that may supersede these opportunities on federal lands.

Acknowledgments

We would like to thank the following for their contributions to this paper: Teddy Reynolds (Reynolds Forestry Consulting) and Mike Shelton (USDA Forest Service, Southern Research Station), plus all of the former USFS scientists and staff who helped collect the long-term data on the CEF.

References

Baker, James B.; Cain, Michael D.; Guldin, James M.; Murphy, Paul A.; Shelton, Michael G. 1996. Uneven-aged silviculture for the loblolly and shortleaf pine forest cover types. Gen. Tech. Rep. SO-118. Asheville, NC: U.S. Department of Agriculture, Forest Service, Southern Research Station. 65 p.

Baral, Anil; Guha, Gauri S. 2004. Trees for carbon sequestration or fossil fuel substitution: the issue of cost vs. carbon benefit. Biomass and Bioenergy. 27: 41-55.

Birdsey, Richard A. 1996. Carbon storage for major forest types and regions in the conterminous United States. P. 1-25 in Sampson, R. Neil; Hair, Dwight (eds.). Forests and Global Change Volume Two - Forest Management Opportunities. Washington, DC: American Forests.

Birdsey, Richard A. 2006. Carbon accounting rules and guidelines for the United States forest sector. Journal of Environmental Quality. 35: 1518-1524.

Bragg, Don C. 2010. Pine seed tree growth and yield on the Crossett Experimental Forest. P. 343-348 in Stanturf, John A. (ed.). Proceedings of the 14th Biennial Southern Silvicultural Research Conference. Gen. Tech. Rep. SRS-121. Asheville, NC: U.S. Department of Agriculture, Forest Service, Southern Research Station.

Cain, Michael D. 1996. Growth expectations from alternative thinning regimes and prescribed burning in naturally regenerated loblolly-shortleaf pine stands through age 20. Forest Ecology and Management. 81: 227-241.

Cain, Michael D.; Shelton, Michael G. 2001. Natural loblolly and shortleaf pine productivity through 53 years of management under four reproduction cutting methods. Southern Journal of Applied Forestry. 25(1): 7-16.

Cain, Michael D.; Shelton, Michael G. 2003. Effects of alternative thinning regimes and prescribed burning in natural, even-aged loblolly-shortleaf pine stands: 25 year results. Southern Journal of Applied Forestry. 27(1): 18-29.

Enquist, Brian J. 2002. Universal scaling in tree and vascular plant allometry: toward a general quantitative theory linking plant form and function from cells to ecosystems. Tree Physiology. 22: 1045-1064.

Enquist, Brian J.; Niklas, Karl J. 2002. Global allocation rules for patterns of biomass partitioning in seed plants. Science. 295: 1517-1520.

Eriksson, Erik; Gillespie, Andrew R.; Gustavsson, Leif; Langvall, Ola; Olsson, Mats; Sathre, Roger; Stendahl, Johan. 2007. Integrated carbon analysis of forest management practices and wood substitution. Canadian Journal of Forest Research. 37: 671-681.

Farrar, Robert M.; Murphy, Paul A.; Willett, R. Larry. 1984. Tables for estimating growth and yield of uneven-aged stands of loblolly-shortleaf pine on average sites in the West Gulf Area. Bull. 874. Fayetteville, AR: University of Arkansas, Division of Agriculture. 21 p.

Fonseca, M.A. 2005. The measurement of round wood: methodologies and conversion ratios. Oxfordshire, UK: CABI Publishing. 269 p.

Frederick, W.J.; Lien, S.J.; Courchene, C.E.; DeMartini, N.A.; Ragauskas, A.J.; Iisa, K. 2008. Co-production of ethanol and cellulose fiber from southern pine: a technical and economic assessment. Biomass and Bioenergy. 32: 1293-1302.

Gan, Jianbang; Smith, C.T. 2007. Co-benefits of utilizing logging residues for bioenergy production: the case for East Texas, USA. Biomass and Bioenergy. 31: 623-630.

Hall, D.O.; Mynick, H.E.; Williams, R.H. 1991. Alternative roles for biomass in coping with greenhouse warming. Science & Global Security. 2: 113-151.

Jenkins, Jennifer C.; Chojnacky, David C.; Heath, Linda S.; Birdsey, Richard A. 2003. National-scale biomass estimators for United States tree species. Forest Science. 49(1): 12-35.

Johnsen, Kurt H.; Teskey, Bob; Samuelson, Lisa; Butnor, John; Sampson, David; Sanchez, Felipe; Maier, Chris; McKeand, Steve. 2004. Carbon sequestration in loblolly pine plantations: methods, limitations, and research needs for estimating storage pools. P. 373-381 in Rauscher, H. Michael; Johnsen, K. Southern Forest Science: Past, Present, Future. Gen. Tech. Rep. SRS-75. Asheville, NC: U.S. Department of Agriculture, Forest Service, Southern Research Station.

Johnsen, Kurt H.; Wear, D.; Oren, R.; Teskey, Robert O.; Sanchez, Felipe; Will, R.; Butnor, John; Markewitz, D.; Richter, D.; Rials, T.; Allen, H.L.; Seiler, J.; Ellsworth, D.; Maier, Chris; Katul, G.; Dougherty, P.M. 2001. Meeting global policy commitments: carbon sequestration and southern pine forests. Journal of Forestry. 99(4): 14-21.

Laiho, Raija; Sanchez, Felipe; Tiarks, Allan; Dougherty, Phillip M.; Trettin, Carl C. 2003. Impacts of intensive forestry on early rotation trends in site carbon pools in the southeastern US. Forest Ecology and Management. 174: 177-189.

Luyssaert, Sebastiaan; -Detlef Schulze, E.; Börner, Annett; Knohl, Alexander; Hessenmöller; Law, Beverly E.; Ciais, Philippe; Grace, John. 2008. Old-growth forests as global carbon sinks. Nature. 455: 213-215.

Markewitz, Daniel. 2006. Fossil fuel carbon emissions from silviculture: impacts on net carbon sequestration in forests. Forest Ecology and Management. 236: 153-161.

Mayfield, Chyrel A.; Foster, C. Darwin; Smith, C. Tattersall; Gan, Jianbang; Fox, Susan. 2007. Opportunities, barriers, and strategies for forest bioenergy and bio-based product development in the southern United States. Biomass and Bioenergy. 31: 631-637.

Mead, Donald J.; Pimentel, David. 2006. Use of energy analyses in silvicultural decision-making. Biomass and Bioenergy. 30: 357-362.

Perez-Garcia, John; Lippke, Bruce; Comnick, Jeffrey; Manriquez, Carolina. 2005. An assessment of carbon pools, storage, and wood products market substitution using life-cycle analysis results. Wood and Fiber Science. 37: 140-148.

Piñeiro, Gervasio; Jobbágy, Esteban G.; Baker, Justin; Murray, Brian C.; Jackson, Robert B. 2009. Set-asides can be better climate investment than corn ethanol. Ecological Applications. 19(2): 277-282.

Samuelson, Lisa J.; Johnsen, Kurt; Stokes, Tom; Lu, Weinlang. 2004. Intensive management modifies soil CO_2 efflux in 6-year-old *Pinus taeda* L. stands. Forest Ecology and Management. 200: 335-345.

Skog, Kenneth E. 2008. Sequestration of carbon in harvested wood products for the United States. Forest Products Journal. 58(6): 56-72.

Smith, James E.; Heath, Linda S.; Skog, Kenneth E.; Birdsey, Richard A. 2006. Methods for calculating forest ecosystem and harvested carbon with standard estimates for forest types of the United States. Gen. Tech. Rep. NE-343. Newtown Square, PA: U.S. Department of Agriculture, Forest Service, Northeastern Research Station. 216 p.

Wear, David N.; Greis, John G. 2002. Southern forest resource assessment. Gen. Tech. Rep. SRS-53. Asheville, NC: U.S. Department of Agriculture, Forest Service, Southern Research Station. 635 p.

Zeide, B. and D. Sharer. 2000. Good forestry at a glance: a guide for managing even-aged loblolly pine stands. Arkansas Agricultural Experiment Station Series 003. Fayetteville, AR: University of Arkansas, Arkansas Agricultural Experiment Station. 19 p.

The content of this paper reflects the views of the authors, who are responsible for the facts and accuracy of the information presented herein.