THE INFLUENCE OF DIFFERENT MANAGEMENT STRATEGIES ON CANOPY COVER AND CARBON STORAGE IN LONGLEAF PINE FORESTS

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ABSTRACT

Longleaf pine (*Pinus palustris*) is amenable to management using even- or uneven-aged silvicultural methods. However, owing to its relative intolerance of shade, high-density management of longleaf pine is largely restricted to even-aged approaches. This paper uses predictions of stand dynamics from the Forest Vegetation Simulator to compare the flow of selected "ecosystem services" from longleaf pine stands managed under different regimes. Trends in canopy cover (a surrogate for the development of ground-layer vegetation and the ability to conduct frequent prescribed fires) and carbon sequestration were analyzed. Three different management scenarios were compared: 1) an even-aged pulpwood production goal; 2) a combined pulpwood and sawlog goal, also even-aged; and 3) an uneven-aged sawlog goal. Contemporary planting densities were used in the even-aged treatments (400 trees acre^{-1} [988 ha^{-1}]), and a moderate residual stocking was chosen for the uneven-aged treatment (BD*q*, where B = 50 ft^2 acre^{-1} [11.5 m^2 ha^{-1}], D = 20 inch diameter at breast height [50 cm], $q = 1.2$, respectively). Canopy cover was considerably less variable under the uneven-aged approach, ranging between 38 and 53%, compared to 0 and 83% for both of the even-aged treatments. The amount of carbon sequestered on-site and in forest products over the 90-year simulation was more similar among treatments than canopy cover, being lowest for the short-rotation even-aged (24.9 tons acre^{-1} [55.3 tonnes ha^{-1}]) and highest for the extended-rotation even-aged (32.6 tons acre^{-1} [72.5 tonnes ha^{-1}]) regimes; this value was intermediate for uneven-aged management (29.6 tons acre^{-1} [65.8 tonnes ha^{-1}]). Thus, in terms of satisfying the joint objectives of maintaining conditions conducive to ground-cover development and natural fire regimes, and sequestering carbon, the uneven-aged scenario performed best among those compared.

Keywords: canopy cover, carbon sequestration, ecosystem services, Forest Vegetation Simulator, longleaf pine, *Pinus palustris*.

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INTRODUCTION

Emerging markets for ecosystem services are presenting landowners with new opportunities to extract revenue from their forests, where historically there has been only timber. Among these, carbon sequestration is arguably the most broadly available, and therefore has the greatest potential to influence how forests are managed in the future (Ruddell et al. 2007, Malmsheimer et al. 2008). Carbon storage is directly proportional to forest biomass, making management actions that increase the production (and storage) of plant matter a logical choice for achieving this goal. However, focusing on any single management objective also has the potential to produce unintended and often adverse consequences. One such example is provided by the current state of forests in the western United States, some of which have accumulated unprecedented levels of biomass owing to fire exclusion, and are now highly vulnerable to catastrophic losses of biomass (carbon) due to wildfire (Hurteau et al. 2008). Thus, provision of these purportedly "green" assets should also require some level of assurance that their generation is not undermining other conservation values.

Considerable interest exists in restoring greatly diminished longleaf pine (*Pinus palustris*) ecosystems across their native range (Landers et al. 1995, Earley 2004, Frost 2006, Johnson and Gjerstad 2006). The natural disturbance regime that shaped longleaf pine ecosystems across much of its historic range prior to European settlement is thought to have consisted of small-scale canopy disturbances, primarily lightning strikes, and associated frequent low-intensity understory fire (Huffman et al. 2004, Outcalt 2008). As a result, stands tended to be multiaged, exhibit an open-canopied structure, and support a diverse array of pyrogenic ground cover (Platt et al. 1988). This is not to say that even-aged stand structures were not historically a part of the mix, particularly in coastal parts of the longleaf range more frequently exposed to hurricane-force winds (Gilliam et al. 2006). And while it is generally accepted that simply reforesting sites with longleaf pine, as opposed to other southern pines more often used in plantation forestry, e.g., loblolly (*Pinus taeda*) or slash pines (*Pinus elliottii*), is unlikely to achieve broad restoration goals, doing so on appropriate sites may still confer certain economic and ecological benefits relative to the status quo (Moser et al. 2003, Kush et al. 2004).

In this paper I used a stand dynamics model, the Forest Vegetation Simulator (FVS; Dixon 2003), to track carbon sequestration associated with three approaches to management in a longleaf pine forest. The various scenarios were chosen to represent a range of technically viable silvicultural methods that are more or less congruent with natural stand dynamics. Canopy cover, a correlate of ground-layer vegetation in this forest type, was also monitored in order to provide a constraint on the carbon sequestration goal.

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METHODS

Study Area

No field data were utilized in this study. The geographic range of the FVS model (see description in the following section) includes the southeastern United States.

Ecosystem Services

The dependent variables in this analysis are nontraditional forest products/outputs that have historically lacked value in the marketplace. The term "ecosystem services" can be used to encompass the subset of forest-derived outputs that provide societal benefits at no direct cost, other than to the landowner (http://www.fs.fed.us/ecosystemservices/index.shtml [accessed 25 Jan 2010]). Carbon stored in live and dead aboveground biomass, derived wood products, and energy captured during processing were considered in this analysis (Smith et al. 2006). The other variable analyzed, aggregate canopy cover at the stand level, provides a surrogate for the amount of sunlight reaching the ground, and thus the potential for the development of light-demanding ground-layer vegetation. The fact that healthy longleaf pine ecosystems are characterized by abundant and diverse pyrogenic ground cover makes this a logical variable to monitor in the context of ecosystem function in this forest type. An assumption of this analysis is that an appropriate fire regime (e.g., a 1- to 3-year return interval) is being maintained, even though it is not modeled explicitly. And while a frequent fire regime could be sustained under conditions of high canopy cover in longleaf pine forest owing to abundant needle-based fuels, the development of light-demanding ground-layer vegetation would not be expected.

The Forest Vegetation Simulator

The Southern Variant (SN) of the FVS model was used to forecast stand development. The Forest Vegetation Simulator is an empirically derived distance-independent single-tree-based stand dynamics model developed and supported by the U.S. Forest Service (Dixon 2003). At a minimum, users are required to provide the model with a list of trees by species, their initial size (typically in terms of diameter at breast height [dbh]), and a description of the inventory method (e.g., plot expansion factors). Though not required, information about site quality (site index; dominant height at age 50 years) and past growth rates (from increment cores or periodic inventories) can be used to fine-tune model outputs. Regeneration response following (harvest) disturbances are user specified within FVS-SN, similar to other eastern variants of the model. In order to do so, the user inputs the expected number of seedlings by species and height class. Although not a spatially explicit model, it is possible within FVS to specify whether regeneration will occur on plots with higher or lower than average stocking, or independent of stocking. The lower than average stocking option was used for the uneven-aged management scenario; it was a nonissue for the even-aged treatments.

The Fire and Fuels Extension (FFE), which comes bundled with the FVS model, incorporates a carbon reporting module useful for tracking carbon sequestered in the trees, harvested wood products, and captured as energy at the manufacturing center (Reinhardt et al. 2007, Hoover and Rebain 2008). Information about canopy cover, defined as the proportion of ground area occupied by tree crowns, is calculated by FVS based on relationships presented in Bechtold (2003), and can be requested as model output. The full suite of variables traditionally used in forestry growth and yield analysis are also provided.

The Southern Variant of the FVS model runs a nominal 5-year time step, so harvests were scheduled, and outputs summarized, in multiples of that interval. Site index, the variable used to indicate site quality in FVS, was set at 70 ft (24.4 m, age-50 basis) for longleaf pine in all three scenarios.

The reliability of the FVS model for predicting stand dynamics in longleaf pine stands may be considered an open question. Shaw et al. (2006) reported that the model required custom calibration in order to be useful for management purposes under conditions found on Fort Bragg military installation in North Carolina. Follow-up work by that same group has identified specific problem areas and offered potential solutions for using FVS in longleaf pine forests (DeRose et al. 2008, Vacchiano et al. 2008). No calibrations or adjustments were applied to the model in the current study owing to a lack of appropriate data. This study focuses on relative as opposed to absolute differences among treatments in recognition of such limitations.

The Management Scenarios

Three approaches to managing longleaf pine were compared, two-even aged and one uneven-aged (Table 1). The primary distinction between the two even-aged scenarios was rotation length. Specifically, one of the even-aged treatments involved a 50% longer rotation, and also a thinning to promote more rapid diameter growth of the crop trees, in order to have more sawlog-sized material available at the time of final harvest. By contrast, the short-rotation even-aged treatment was geared toward fiber production, i.e., pulpwood. The uneven-aged scenario was structured as a single-tree selection and quantified with the BD*q* method (Farrar et al. 1996, Guldin and Baker 1998), where B refers to the stocking level of the residual stand and is expressed in units of basal area (BA), D the maximum diameter to which trees will be grown prior to final harvest, and *q* is a ratio expressing the rate at which stem numbers increase between adjacent diameter classes, moving from largest to smallest, across the stand's diameter distribution. The following values were chosen for this study: $B = 50$ ft^2 acre^{-1} (11.5 m^2 ha^{-1}); $D = 20$ inches dbh (51 cm); and $q = 1.2 \times$ 2-inch (5-cm) dbh classes.

To ensure comparisons between scenarios were equitable, and primarily with regard to the carbon sequestration variable, initial conditions were assumed to be identical for all three treatments. Specifically, it was assumed that the residual (post-cutting cycle) structure specified for the uneven-aged treatment existed in all stands prior to beginning the simulation runs. Thus, in the case of the even-aged treatments, the areas were initially clearcut and then planted. While natural regeneration may be secured with even-aged regeneration methods, i.e., seed-tree or shelterwood cutting, clearcutting and planting is a far more common approach in

Table 1. Description of management scenarios for longleaf pine forecast using the Southern Variant of the Forest Vegetation Simulator (FVS-SN). All scenarios were run for a total of 90 years. A site index of 70 ft (24.4 m) at a base age of 50 was used.

Treatment	Planting density (TPA[a])	Timing	Description
Even-aged (short rotation)	400 TPA (988 ha^{-1}) with 90% survival	30-year rotations, 3 total for scenario	Short rotation length; no thinning; pulpwood production goal; clearcut and replant
Even-aged (extended rotation)	400 TPA with 90% survival	45-year rotations, 2 total for scenario	Medium rotation length; thin from below to BA = 50 ft^2 acre^{-1} (11.5 m^2 ha^{-1}) at age 30; pulpwood and small sawlog production goal; clearcut and replant
Uneven-aged (moderate density)	A regeneration response of 40 TPA (99 ha^{-1}) was specified at the time of each harvest.	10-year interval between stand entries (9 cutting cycles)	No rotation, per se; dominant trees are grown to age 90; BD*q* selection method (B = 50 ft^2 acre^{-1} [11.5 m^2 ha^{-1}], D = 20 inch dbh [50 cm], *q* = 1.2); medium to large sawlog goal; natural regeneration assumed

[a] TPA, trees per acre.

the southeastern United States (Fox et al. 2007), and therefore how these modeled scenarios were structured. Wood products associated with that harvest were passed to the FFE carbon accounting module in FVS and “stored” in the appropriate product category. By contrast, that same carbon continued to reside in live biomass, at least initially, in the case of the uneven-aged treatment. While FVS provides estimates of belowground carbon associated with tree roots, that component is poorly quantified, simply being represented as a proportional constant of aboveground biomass (carbon). For this reason, and because comparisons among management scenarios are intended to be made in relative terms, only aboveground carbon was considered in this analysis.

RESULTS

Carbon Storage

The amount of carbon sequestered under the three different management scenarios varied over time, primarily in response to the harvesting activities (Figure 1). In terms of forest carbon associated with standing aboveground biomass (Figure 1a), stocks were considerably more stable for the uneven-aged (range = 11.9–14.7 tons C acre^{-1} [26.4–32.7 tonnes C ha^{-1}]) than the even-aged treatments (range 0–24.2 tons C acre^{-1} [0–59.8 tonnes C ha^{-1}]) for the extended and short rotations, respectively. Averaged over the entire interval there were 13.4 tons C acre^{-1} (29.8 tonnes C ha^{-1}), 9.9 tons C acre^{-1} (22.0 tonnes C ha^{-1}), and 6.3 tons C acre^{-1} (14.0 tonnes C ha^{-1}) in this compartment for the uneven-aged, extended-, and short-rotation even-aged treatments, respectively.

The amount of carbon stored in wood products over the 90-year simulation was higher for the even-aged scenarios, and particularly for the extended-rotation treatment, where roughly twice (18.6 tons C acre^{-1} [41.3 tonnes C ha^{-1}]; extended rotation) and 50% more (12.6 tons C acre^{-1} [28.0 tonnes C ha^{-1}]; short rotation) carbon found its way into this pool than under uneven-aged management (8.2 tons C acre^{-1} [18.2 tonnes C ha^{-1}]) (Figure 1b). It is worth noting that the difference in this storage component between the two even-aged treatments is attributable to the product life cycle of sawlogs versus pulpwood. Expressed as a percentage of the total volume harvested, sawlogs accounted for 15 and 54% in the short- and extended-rotation even-aged treatments, respectively. By contrast, this value was 90% for the sawlog-focused uneven-aged treatment, although the total harvested volume in that scenario was considerably lower (4,144 ft^3 acre^{-1} [290 m^3 ha^{-1}] for the uneven-aged versus 9,379 and 7,884 ft^3 acre^{-1} [656 and 552 m^3 ha^{-1}] for the extended- and short-rotation even-aged treatments, respectively).

Despite these fairly dramatic differences among treatments when standing (forest) and stored (wood products) carbon were viewed separately, combining these components suggests all three scenarios were in fact quite similar with regard to the total amount of carbon sequestered over the 90-year period (Figure 1c). At 24.9 tons C acre^{-1} (55.3 tonnes C ha^{-1}), the short-rotation even-aged treatment sequestered the least carbon, the uneven-aged treatment was intermediate at 29.6 tons C acre^{-1} (65.8 tonnes C ha^{-1}), and the extended-rotation even-aged treatment came out on top having sequestered 32.6 tons C acre^{-1} (72.5 tonnes C ha^{-1}). The trajectory of total carbon sequestration was positive for all three management scenarios owing to the residual effect of the stored carbon component, which was most influential in the case of durable sawlogs.

Although not a scenario considered here, it is worth noting that considerably more carbon might have been sequestered over the interval under a no-management scenario. In fact, a plantation established at the same density as the managed even-aged treatments presented here (i.e., 400 trees acre^{-1} [988 ha^{-1}]) but simply allowed to develop without intervention for 90 years, was forecast to have sequestered 137.4 tons C acre^{-1} (305.4 tonnes C ha^{-1}), or roughly 4.5 times the amount under the managed scenarios considered here.

Tree Canopy Cover

Trends in canopy cover were markedly different under the even- and uneven-aged management (Figure 2). The modest level of canopy cover (approximately 40%) that existed at the beginning of the simulation for all three scenarios dropped to zero in response to the clearcut and plant actions associated with both even-aged treatments. Canopy cover in the even-aged treatments rebounded to around 40% approximately 10 years after planting. However, that level of canopy cover was quickly surpassed, and according to model predictions had increased to 64 and 76%

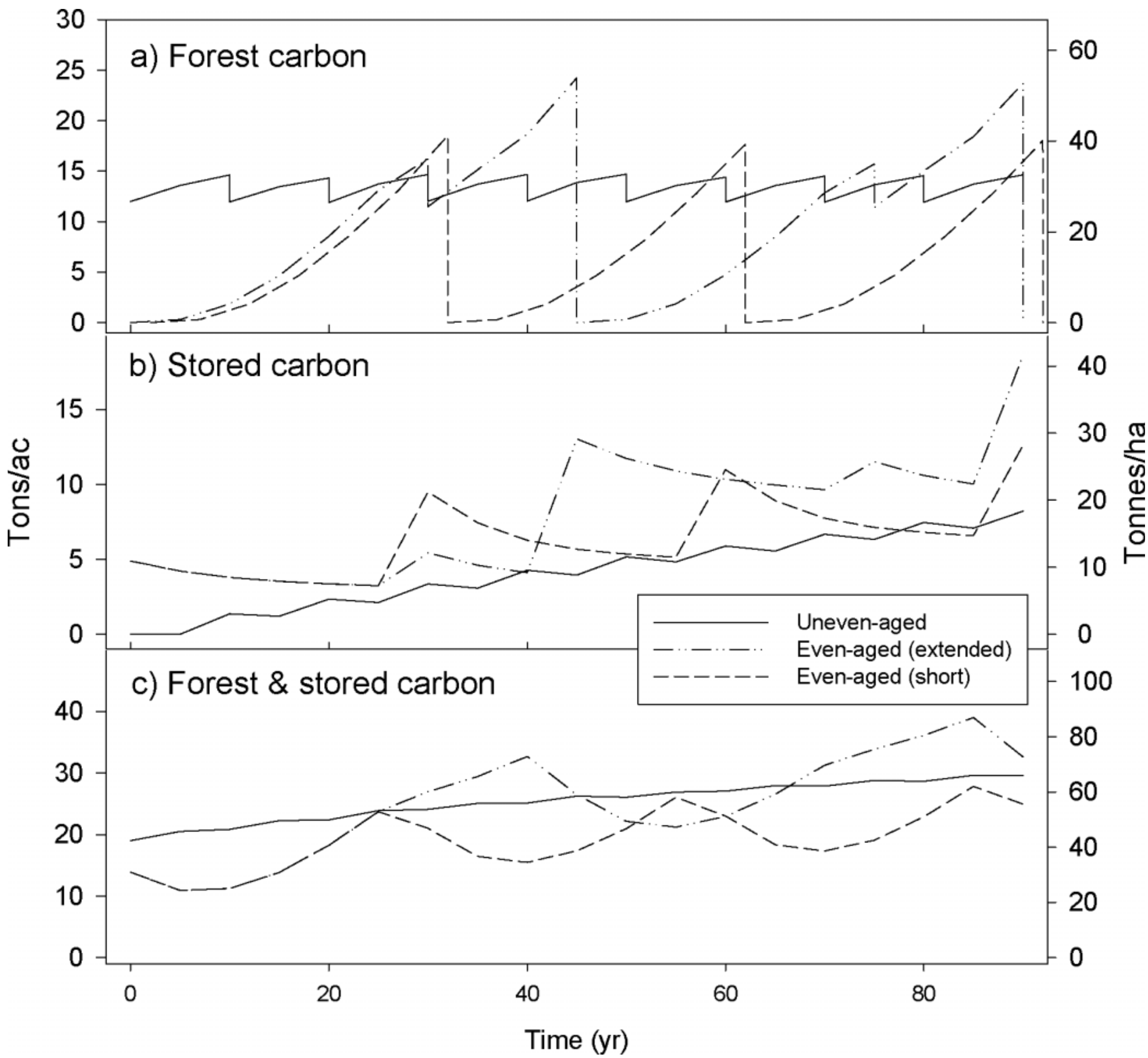

Figure 1. Estimated carbon storage under three approaches to management in a longleaf pine forest (Table 1) showing (a) the amount of carbon in aboveground biomass, (b) storage in wood products generated by harvests, and (c) a combination of these two compartments.

by ages 15 and 20, respectively, in these young, rapidly developing, even-aged stands. The thinning that took place at age 30 in the extended-rotation even-aged treatment reduced canopy cover by 20 percentage points, from 83% pre-cut (the maximum level predicted by the model) to 63% post-cut. Canopy cover rebounded again, topping out at 72% by the time of final harvest in the extended-rotation even-aged treatment (age 45). Canopy cover was zeroed out three (extended rotation) and four times (short rotation) for the even-aged scenarios over the 90-year simulation period.

By contrast, canopy cover fluctuated within a fairly narrow range for the uneven-aged treatment (Figure 2). According to model predictions, canopy cover averaged $43 \pm 3\%$ at the beginning, and $51 \pm 2\%$ at the end, of each 10-year cutting cycle. Unlike even-aged scenarios, canopy cover was never reduced to zero for the uneven-aged treatment and at most occupied half of the total ground area at the end of a cutting cycle immediately prior to a harvest.

DISCUSSION

In the southeastern United States where there has been a strong tendency to manage pine forests as even-aged plantations and on short rotations (Wear and Greis 2002, Allen et al. 2005, Fox et al. 2007), there is a countervailing need to restore structure and function associated with natural upland pine forests across some proportion of this landscape (Landers et al. 1995, Earley 2004, Frost 2006). Emerging

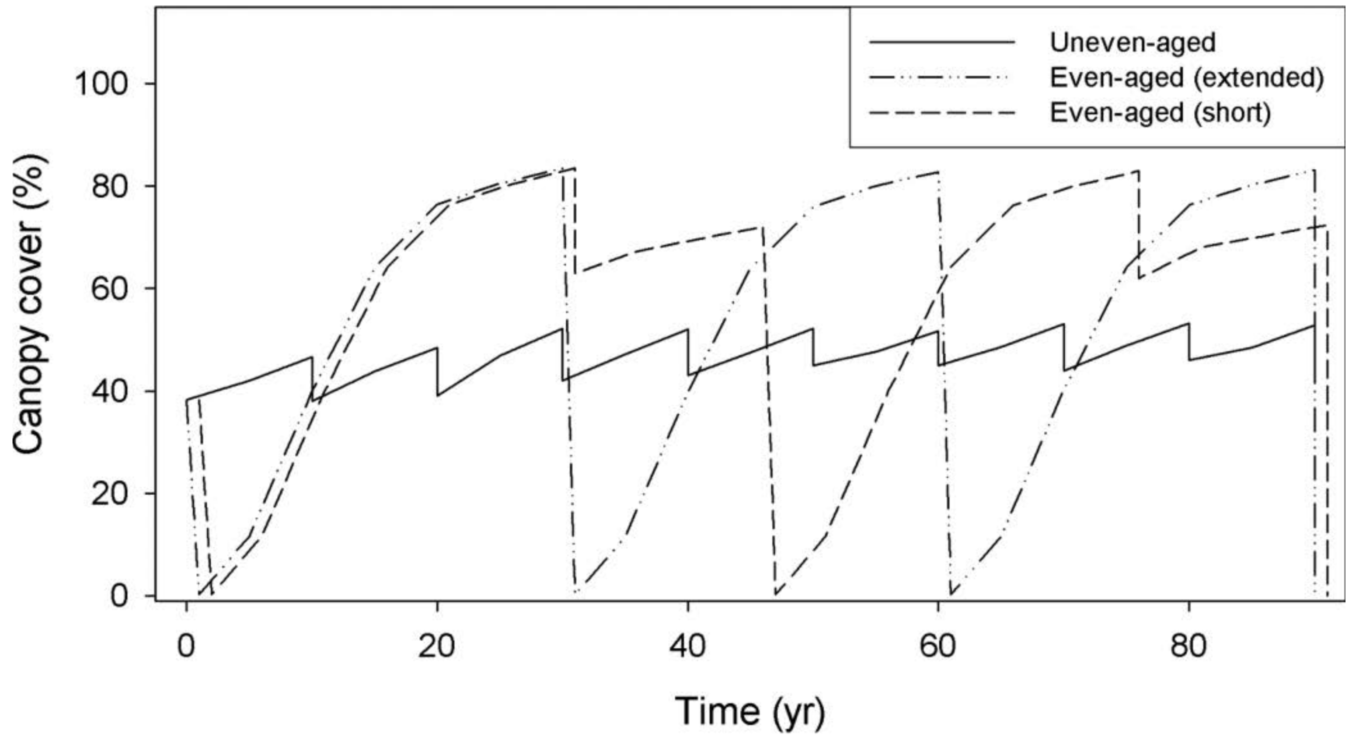

Figure 2. Trends in canopy cover associated with three approaches to management in a longleaf pine forest (Table 1).

markets for ecosystem services, in addition to timber, may help jumpstart this process (http://www.fs.fed.us/ecosystemservices/index.shtml [accessed 25 Jan 2010]). The analysis presented in this paper suggests that, at least when viewed in the context of selected conservation-based parameters, an approach to silviculture that promotes structural conditions more similar to those found in natural forests can outperform more traditional even-aged management. There is increasing recognition that approaches to silviculture that do not diverge appreciably from natural conditions tend to be more compatible with broad conservation objectives than those that do (Seymour 2005, Franklin et al. 2007).

Tree canopy cover is an important conservation-based parameter in upland pine forests and needs to be maintained below certain upper limits, i.e., approximately 50% (Moser and Palmer 1997, Masters et al. 2007), if healthy ground cover is to be maintained. The interaction between ground-layer vegetation and frequent fire is the primary driver of the extraordinary levels of diversity found in these ecosystems (Hermann et al. 1998, Peet 2006) and can become decoupled when sufficient light does not penetrate through the tree canopy. By this standard, only the moderate-density uneven-aged management regime was predicted to have the desired conditions. And while it may be technically possible to manage longleaf pine at higher densities, e.g., 60 ft^2 $acre^{-1}$ (13.8 m^2 ha^{-1}) (Farrar et al. 1996), with an uneven-aged approach, and thereby produce more timber (and ostensibly carbon), doing so might also risk negative impacts to ground cover (Masters et al. 2007). According to FVS projections, the end of cutting cycle BA of 64 ± 1 ft^2 $acre^{-1}$ (14.7 m^2 ha^{-1}) for the uneven-aged treatment corresponds to approximately 50% canopy cover, suggesting the chosen values for B of 50 ft^2 $acre^{-1}$ and cutting cycle length of 10 years were well suited to meeting the stated objective of maintaining a relatively open canopy.

It also would have been feasible to simulate alternative even-aged management scenarios involving greatly extended rotations and thinning to lower densities in order to bring canopy cover into line with recommendations. In fact, analogous approaches have been suggested for achieving conservation-based management goals in the context of the endangered red-cockaded woodpecker (*Picoides borealis*) (Rudolph and Conner 1996). While even-aged approaches may be capable of sustaining woodpecker populations over the short term, it seems likely they would grade into some form of multiaged management over time, albeit not necessarily as formally regulated as the BD*q* method discussed here. This would be particularly true for modestly sized properties where suitable habitat is being sought in perpetuity.

The choice of the BD*q* method for regulating stand structure in the uneven-aged management scenario was driven more by modeling constraints than a view that it represents the best approach for doing so. In fact, it is widely believed that the Stoddard–Neel approach (Jack et al. 2006, Masters et al. 2007), or perhaps group selection (which can be based on BD*q*; Farrar et al. 1996), are better suited to managing longleaf pine than single-tree selection based on BD*q* parameters. The choice of a relatively low *q* of 1.2, and correspondingly few small stems per unit area, was chosen to approximate the area under regeneration that might realistically be found in managed uneven-aged longleaf pine stands.

Emerging markets for the sequestration of atmospheric carbon dioxide by forests being managed in ways to help mitigate the negative impacts of climate change appear to have the potential to influence the way forest management decisions will be made in the future (Ruddell et al. 2007, Malmsheimer et al. 2008). It has been argued that longleaf pine is uniquely suited to management under this objective owing to its longevity, disease resistance, fire tolerance, and high wood density (Kush et al. 2004). Carbon accounting is a tricky business, particularly in relation to projects involving managed forests. Existing voluntary markets like the Chicago Climate Exchange and California Climate Action Registry recognize and credit, to various degrees, the carbon stored in wood products removed from forests in addition to what is being accumulated and stored in live and dead biomass and soils in situ. By contrast, the markets associated with mandatory cap and trade schemes (i.e., the Clean Development Mechanism of the Kyoto Protocol, and the Regional Greenhouse Gas Initiative) do not view forestry projects as liberally. Regardless, this analysis showed that similar amounts of carbon could be sequestered in managed longleaf pine forests by taking a moderate-density uneven-aged approach as for a couple of generic even-aged management regimes (Figure 1c). Even so, the amount of carbon sequestered in these managed forest scenarios was modest compared to what has been reported elsewhere for intensively managed southern pine plantations (Johnsen et al. 2001).

Fire-maintained upland pine ecosystems of the southeastern United States present a somewhat unique situation with regard to carbon sequestration, and depending on the accounting scheme employed, may not be well suited to generating carbon credits. For example, in order to maintain healthy ground cover and the ability to burn frequently, a relatively open canopy needs to be maintained. The open tree canopy that characterizes this savanna-like forest structure in the presence of frequent fire corresponds to a lower aboveground carbon state than exists where fire has been excluded and hardwoods allowed to encroach (Engstrom et al. 1984). Some evidence suggests that excluding fire from upland pine systems can result in an approximate doubling of aboveground woody biomass over a 40-year interval (K. Robertson, Tall Timbers Research Station, unpublished data). And while this may be beneficial from a carbon sequestration perspective, so doing entails accepting a marked loss of system structure and function (Engstrom et al. 1984), which is a high price to pay given the greatly diminished extent of this ecosystem type (Landers et al. 1995, Earley 2004, Frost 2006). On the other hand, this analysis only considered the response of aboveground carbon pools and there is some evidence suggesting that fire-maintained ecosystems may be sequestering more soil carbon than similar systems from which fire has been excluded, although the mechanism behind this additional storage is not well understood (K. Robertson, Tall Timbers Research Station, unpublished data). Soil carbon is considered more stable than that stored aboveground owing to differences in vulnerability to disturbance and formation of more recalcitrant forms not easily decomposed (Hoover 2003, Lehmann 2007). If accretion in this belowground "pool" of carbon is viewed favorably by emerging markets for this ecosystem service, it could provide some leverage for restoring natural fire regimes to the southeastern U.S. landscape.

In conclusion, of the approaches to forest management considered here, only the low-density uneven-aged regime was able to satisfy the joint conservation-based objectives of carbon sequestration and maintaining an open pine canopy. Other approaches that might also have been explored, e.g., low-density even-aged stands with greatly extended rotations or more densely stocked uneven-aged stands, may have fared better or worse than the chosen examples relative to the chosen criteria. However, the fact remains that certain characteristics of even-aged management, and high-density stands, are inherently limited in the context of conservation-based approaches to forest management in this ecosystem type.

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