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ABSTRACT: *This study determined the profitability and financially optimal thinning and final harvest rotation of loblolly pine (*Pinus taeda*) managed exclusively for timber production or for dual products of timber production and carbon sequestration. The results suggest that 1) depending on landowner's alternative rate of return, the inclusion of carbon revenues in forest management may shorten or prolong the optimal timber-carbon rotation length, compared to the optimal rotation that maximizes timber value only; 2) the effect of carbon revenues on the optimal rotation length and the percentage gain in soil expectation value is larger on low-productivity sites than on high-productivity sites, and is larger for high interest rates than for low interest rates; and 3) low-productivity, unprofitable sites may become profitable when carbon revenue is included and optimized together with the timber revenue. South. J. Appl. For. 30(1):21–29.*

Key Words: Carbon sequestration, optimal management regime, soil expectation value, forest management.

Along with commercial timber, forests also produce nontimber resources such as water, range forage, outdoor recreation, and minerals (Klemperer 1996). Since the demands for forest nontimber goods and services have increased, the production of these goods and services often competes with timber use and has become a land management issue (Davis et al. 2001). Depending on the sites and species present, optimal harvesting decisions in long-term forest planning should be made based on the tradeoffs between timber and nontimber benefits. Hartman (1976) analyzed the optimal harvest age of a standing forest if the forest provides a flow of valuable services in addition to the value of the timber when it is harvested. He concluded that the value of recreational or other services provided by a standing forest may well have an important impact on when or whether to harvest. Thus, models that consider only the timber value of a forest and fail to include a significant flow of valuable services generated from a standing forest are likely to provide inadequate information for forest management planners. The effects of nontimber values on the rotation of Douglas-fir in the Pacific Northwest were investigated by Calish et al. (1978). They concluded that when nontimber values are included, economically optimum rotations for Douglas-fir may be shortened or lengthened, compared to similar calculations based on timber values alone.

Another nontimber value provided by forests is carbon sequestration. Forests are widely recognized as carbon sinks. Trees and other vegetation sequester carbon in the biomass and soils of forests through the photosynthetic conversion of CO_2, one of the major greenhouse gases, to carbon (Birdsey 1992). On average, trees are approximately 25 percent carbon by weight (live trees are approximately 50 percent water by weight, and oven-dried wood is approximately 50 percent carbon by weight) (Department of Energy, www.eia.doe.gov/oiaf/1,605/vr98rpt/download.HTML. Feb. 15, 2005). Forestland stores more carbon than land in other uses such as agriculture; therefore, forests can play an important role in offsetting human-produced carbon emissions. Carbon sequestered in forests on a national scale is substantial; the US Department of Agriculture (USDA) Forest Service estimates that all the forests in the United States combined sequestered a net of approximately 281 million metric tons of carbon per year from 1952 to 1992, offsetting approximately 25 percent of United States anthropogenic emissions of carbon during that period (Birdsey and Health 1995). Enhancing the natural processes that remove CO_2 from the atmosphere is thought to be one of the most cost-effective means of reducing atmospheric CO_2.

Incentive-based strategies such as carbon taxes and subsidies would affect the forest management decision and the

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choice of financially optimal rotation. Several studies have been conducted to investigate how a subsidy/tax regime related to carbon flows in a forest stand may impact the financially optimal forest management. When a carbon subsidy/tax scheme was introduced, the optimal rotation ages for Norway spruce increase substantially, and this regime might impact the timber supply and the timber market (Hoen 1994). In the case where both timber and CO_2 benefits and costs are valued, the optimal rotation age of spruce increases with increasing CO_2 price and, under moderate CO_2 prices, the optimal rotation age decreases with increasing real rates of discount (Hoen and Solberg 1997). Considering the effect of carbon taxes and subsidies on optimal forest rotation age and supply of carbon services, van Kooten et al. (1995) concluded that inclusion of external benefits from carbon uptake extends rotation age approximately 20% longer than the financial rotation age, which maximizes net present value of timber income alone. Stainback and Alavalapati (2002) had a similar finding that the value of forestland and the rotation age of slash pine increase when carbon subsidies and taxes are included, thereby producing a greater timber volume with a greater proportion sold as sawtimber instead of pulpwood.

The US Department of Energy has selected carbon sequestration as a family of methods for capturing greenhouse gases that otherwise could contribute to global climate change. This affordable and environmentally safe sequestration approach is expected to offer a way to stabilize atmospheric levels of CO_2 without requiring the United States and other countries to make large-scale and potentially costly changes to their energy infrastructures. It is inevitable that management practices exclusive to timber yields need to be changed as a result of increased demand for environmental improvement. If a carbon credit market is developed between nonindustrial private forest [nonindustrial private forestland (NIPF)] landowners and CO_2-emitting companies in the future, an income opportunity may arise for landowners interested in managing their forests for timber production and carbon sequestration. An important, emerging area of research in carbon sequestration is to capture the value of stored carbon and detect how a carbon market might work to motivate changes in silvicultural practices and forest establishment practices that would lead to increased carbon sequestration, thereby increasing financial returns (Field 2001). Changing management practices to sequester carbon in forest biomass can increase the net present value of the flow of net CO_2 fixations (NPV_{CO_2}) (Hoen and Solberg 1994). The efficiency of carbon sequestration through silvicultural management can vary dramatically depending on site-dependent characteristics such as forest growth rate, stand density, and the efficiency of utilizing forest products (Marland and Marland 1992).

Identifying financially optimal management regimes that generate the maximum financial returns from timber and carbon benefits can be environmentally judicious and financially profitable for the NIPF landowners. The financially optimal rotation depends on the interest rate used, costs of inputs (silvicultural treatments), and prices of outputs (timber volume and carbon storage). Depending on the region and species, the costs and revenues of forest management with the goals of timber production and/or carbon sequestration will be different throughout the country. Furthermore, precommercial thinning (not in the scope of this study) and other thinning operations complicate the determination of optimal rotation and calculation of profitability by introducing thinning costs and revenues into the cash flow and generating more merchantable volume growth. Therefore, it is critical to determine the effect of carbon revenues on the rotation and profitability for each of the major commercial species in the United States. Under the scenario of a possible future carbon credit-trading market established between NIPF landowners and CO_2-emitting companies, this study was designed to 1) determine the financially optimal management regime for loblolly pine in East Texas and 2) calculate the profitability of managing loblolly pine plantations for the dual products of timber and carbon storage. Because this dual-output (timber and carbon storage) analysis article is a followup and comparison study of optimal timber management regimes conducted by Huang and Kronrad (2002), both studies used the same real price/cost increases, stumpage prices, and management costs.

Methods

It was assumed that forest landowners would manage their forests in a way that would maximize the present value of a flow of net annual incomes from sequestering carbon and harvesting timber. The goal of maximizing the present value of profits could be achieved by determining the optimal time to thin the stand, the number and intensity of the thinnings, and the optimal time to conduct the final harvest according to the quality of the soil, the landowner's alternative rate of return (ARR), and the value of the forest products: timber and carbon storage. Loblolly Pine Management Optimizer (LOPMOP) was developed to simultaneously determine the optimal rotation age, timing, frequency, and intensity of thinning(s) for loblolly pine plantations on NIPF lands in East Texas. This program used PTAEDA2 (Burkhart et al. 1987), a forest stand simulator, to predict stand growth data on diameter, height, and volume from establishment to final harvest. PTAEDA2 was linked to a financial program that performed cash flow analyses and calculated net present worth and the soil expectation value (SEV). Site indices 50, 60, 70, 80, and 90 (base age 25), the range of site indices most commonly observed, were used in these analyses. The maximum possible rotation length was limited to age 60 with a choice of up to three thinnings during the rotation. The first thinning would be a combination of low and row thinning. The second and third thinning would be a low thinning only. The first thinning could not be conducted until the stand was at least 10 years of age. The minimum number of years between thinnings, or between a thinning and the final harvest, could not be less than five. For all computer simulations, a thinning and final harvest regime was considered operable only if it passed the following two threshold constraints: 1) every thinning or final harvest had to yield a minimum of six cords of pulpwood and/or sawtimber per acre; 2) the number of residual trees after each thinning had to be at least 80 per acre. Four thinning intensities were used: 20, 25, 30, or 35% of basal area removal. The same thinning intensities were used at all thinnings for a specific optimal solution regardless of the number of thinnings or age of thinning.

Economic Evaluation

Six ARRs, which span the range of before-tax real rates of return available for most landowners, were chosen for the economic analyses: 2.5, 5.0, 7.5, 10.0, 12.5, and 15.0%. The annual real rates of price increase for sawtimber and pulpwood were assumed to be 2.0 and 1.0% (Texas Forest Service 1984–1998), respectively. The annual real rate of cost increase for labor and nonlabor activities was assumed to be 1.1% (Council of Economic Advisors 1998). The price of sawtimber was assumed to be $450/board feet (Doyle) (Texas Forest Service 1997–1998) and pulpwood price was assumed to be $35/cord (Texas Forest Service 1998), which is consistent with Huang and Kronrad (2002).

The analyses included all appropriate forest management activities. In general, management costs are incurred for establishing, maintaining, and harvesting the pine plantation. In this study, all the current management costs came from a survey of forest consultants. The property tax cost was not included because it was assumed that the revenue from a hunting lease would offset the cost of property taxes. Assumed management activities, costs, and frequencies of occurrence for pine plantations in this analysis are presented in Table 1.

A Market for Carbon Credits

This study assumed that a market would develop in which economic entities would pay landowners for each additional ton of carbon stored in their plantation. Landowners would want to maximize the net revenue from the production of sawtimber, pulpwood, and carbon storage. Sawtimber and pulpwood have market prices that are easily determined. Carbon, on the other hand, presently is not a tradable commodity with a market price. Therefore, in these analyses, the price of carbon was assumed to be $10, $50, or $100 for each additional ton of carbon that landowners were able to sequester in their loblolly pine plantation. This range of carbon prices includes the values of carbon credits most commonly discussed in the literature (Moulton and Richards 1990, Adams et al. 1993, Parks and Hardie 1995, Richards 1997). Economic analyses for timber production management only ($0 carbon value) were also conducted to produce baseline data. Dry-weight equations developed by Baldwin (1987) were used to calculate the amount of dry weight biomass in the aboveground portion of loblolly pine. It was then assumed that the roots of loblolly pine trees account for 19% of the total (above- plus belowground) tree biomass (Kinerson et al. 1977). The net amount of carbon in trees was estimated to be 50% of dry biomass (Dewar and Cannell 1992).

It was assumed that as trees grew, landowners would receive an annual payment based on the amount of carbon sequestered in a given year. When a stand's mortality was greater than its growth, or a thinning or a final harvest was conducted, landowners would have to repay the carbon credit buyers for the loss of tree biomass in which the carbon was stored. This repayment was calculated based on how many tons of carbon were lost from the stand and how much each ton of carbon was worth. The same carbon value was used for the repayment for the loss of carbon as was used for the sequestration of carbon. All financial gains and losses from carbon sequestration during the rotation were included in the discounted cash flow analyses. No repayment was required for wood used to produce long-lived wood products because they are considered sequestered carbon. It was assumed that all the merchantable portions of pulpwood (dbh larger than 5 in. but smaller than 10 in. to a 4 in. top diameter) and sawtimber (dbh larger than 10 in. to a 6 in. top diameter) would be made into long-lived wood products.

Given the range of site indices, real ARRs, and carbon prices, discounted cash flow analyses were conducted to obtain net present values for all the operable management regimes. SEVs were calculated using the Faustmann formula. The management regime that had the highest SEV was chosen as the financially optimal thinning and final harvest schedule for each combination of site index and landowner ARR.

Results and Discussion

The production functions of loblolly pine and carbon sequestration, which represent the biological process and

Table 1. Management activities, costs, and frequencies for economic analysis of loblolly pine plantations in East Texas.

Activity	Cost ($/ac)	Frequency	Start	End
Boundary location	$20	Once	Year 0	
Boundary maintenance	$2	Every 10 years	Year 10	Final harvest
Management plans (initial)	$5	Once	Year 0	
Management plans (updates)	$10	Every 10 years	Year 10	Final harvest
Site preparation (chop)	$90	Once	Year 0	
Site preparation (herbicide)	$85	Once	Year 0	
Hand planting, labor	$45	Once	Year 0	
Seedlings (605 seedlings/ac)	$30	Once	Year 0	
Burning	$40	Every 5 years	Year 10	Final harvest
Thinning and final harvest costs	10% of revenues	As necessary		

describe the relationship between input (time) and output (timber volume or carbon storage), are presented in Figures 1 and 2, respectively. Using the assumed planting density, the timber yield functions shown in Figure 1 present the simulation results from PTAEDA2 for a range of site indices. Mortality built into PTAEDA2 is greater and occurs sooner on high site indices (80 and 90) and medium site index (70) than on low site indices (50 and 60) (Ralph L. Amateis, personal communication, Virginia Polytechnic Institute and State University, Feb. 16, 2005). Figure 1 indicates that after stands reach approximately age 40, the mortality on high site indices exceeds the growth that results in the loss of timber volume; however, the growth on low site indices is able to offset the lower mortality and leads to increased timber production throughout time. Figure 2 presents the carbon storage (above- and belowground tree biomass) of live trees throughout the life of stand. Higher mortality on high site indices makes prolonging rotations to increase carbon storage ineffective; however, longer rotations on low site indices, which have lower mortality, will give stands more time to accumulate biomass, thereby enhancing carbon sequestration.

Given the range of prices for carbon credit, the optimal rotation and profitability in terms of timber production and/or carbon sequestration were calculated for loblolly pine plantations in East Texas. Table 2 presents the optimal schedules for site indices 50 through 90 at six interest rates (2.5 to 15.0%) and four carbon prices ($0, $10, $50, and $100/ton). The SEV derived from a loblolly pine plantation managed for timber production only and for the combination of timber production and carbon sequestration is denoted by SEVtp and SEVtc, respectively (Table 3). The SEVtp were calculated without counting the benefits of carbon sequestration. Since the carbon benefits are still available even in the timber production stands, the SEVtp were recalculated to include the carbon benefit and denoted as SEVtp + C (Table 4).

Timber as a Single Output (Carbon = $0/ton)

When loblolly pine plantations are managed to maximize financial return from timber production only, the optimal rotation length decreases as site index increases (Table 2). For example, the rotation age decreases from 59 (SI 50) to 38 (SI 90) given an ARR of 2.5%, and decreases from 29 (SI 50) to 22 (SI 90) when the ARR is 10%. Table 2 also shows that as ARR increases, rotation length decreases. For example, the rotation length decreases from age 59 (ARR 2.5%) to 18 (ARR 15.0%) for site index 50, and decreases from age 38 (ARR 2.5%) to 21 (ARR 15.0%) for site index 90. Two thinnings are financially optimal for most site index-ARR combinations in general but three thinnings become optimal for high site indices when ARR is low (2.5 or 5%) or medium (7.5%). No thinnings are used where site index is low and ARR is high (15%). These sites are unprofitable, and they have a short optimal rotation length of 18 years. Because the competition for growing space varies based on site productivity, the timing of the first thinning varies with site index and should occur earlier on higher quality sites. It occurs as early as year 13 (SI 90) or as late as 33 (SI 50) or 47 (SI 60) when ARR is 2.5%. Thinning intensity gradually decreases as site index increases, which results in high-quality sites having more

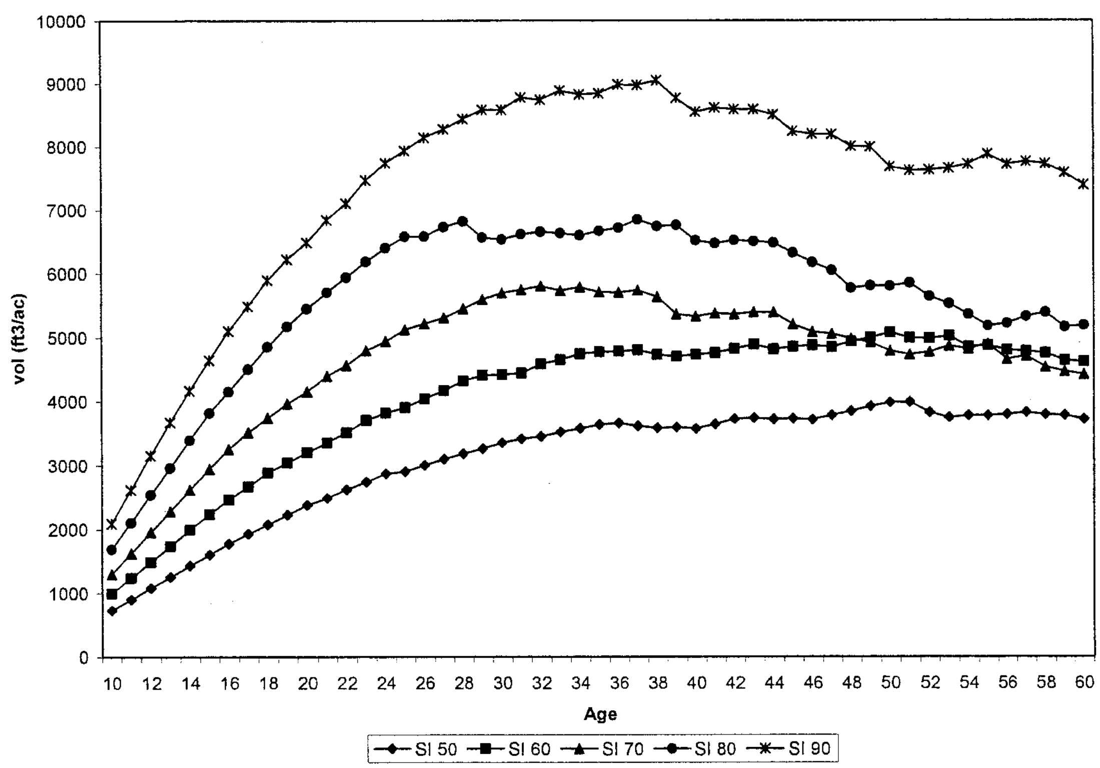

Figure 1. Production functions of loblolly pine for site indices 50–90, base age 25.

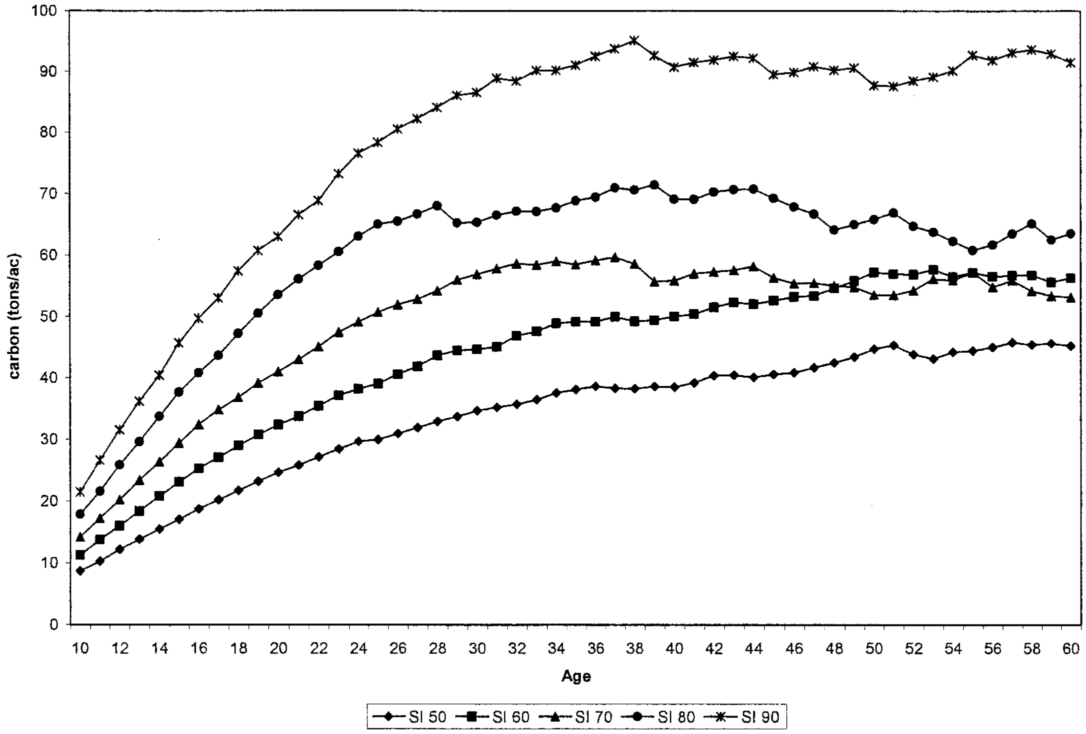

Figure 2. Production functions of carbon sequestration (above- and belowground biomass) for site indices 50–90, base age 25.

Table 2. Financially optimal thinning and final harvest schedules (planting density 9′ × 8′) for loblolly pine plantations managed exclusively for timber production[a] (C = \$0/ton) or for timber production and carbon sequestration (C = \$10, \$50, or \$100/ton) in East Texas.

ARR	SI	C = \$0/ton	C = \$10/ton	Δ*R*	C = \$50/ton	Δ*R*	C = \$100/ton	Δ*R*
2.5%	50	33–**59**[b] (25%)[c]	33–**59** (25%)	0%	33–**59** (25%)	0%	33–**59** (25%)	0%
	60	47–**54** (30%)	47–**54** (30%)	0%	47–**54** (30%)	0%	47–**54** (30%)	0%
	70	25–36–**43** (20%)	25–36–**43** (20%)	0%	25–36–**43** (20%)	0%	25–36–**43** (20%)	0%
	80	14–20–35–**41** (30%)	25–36–**41** (20%)	0%	25–**36** (20%)	−12%	25–**34** (20%)	−17%
	90	13–19–28–**38** (25%)	27–**34** (25%)	−11%	27–**34** (25%)	−11%	27–**34** (25%)	−11%
5.0%	50	23–28–**48** (30%)	24–30–**44** (25%)	−8%	24–30–**44** (25%)	−8%	24–30–**44** (25%)	−8%
	60	19–25–**39** (30%)	19–25–**39** (30%)	0%	33–**39** (30%)	0%	33–**39** (30%)	0%
	70	16–21–**33** (30%)	16–21–**33** (30%)	0%	25–**34** (20%)	3%	25–**34** (20%)	3%
	80	13–18–**34** (30%)	13–18–**34** (30%)	0%	25–**30** (20%)	−12%	25–**30** (20%)	−12%
	90	14–22–27–**32** (25%)	14–23–**31** (25%)	−3%	**29**	−9%	**29**	−9%
7.5%	50	<19–25–**34**>[d](35%)	<19–25–**34**> (35%)	0%	24–30–**42** (25%)	24%	24–**42** (25%)	24%
	60	19–24–**31** (30%)	19–24–**31** (30%)	0%	28–**33** (35%)	6%	**34**	10%
	70	13–18–**29** (35%)	17–22–**29** (25%)	0%	24–**29** (20%)	0%	25–**34** (20%)	17%
	80	19–25–**30** (35%)	19–25–**30** (35%)	0%	25–**30** (20%)	0%	25–**30** (20%)	0%
	90	11–16–22–**27** (30%)	19–**27** (35%)	0%	**27**	0%	**29**	7%
10.0%	50	<19–24–**29**> (35%)	<20–25–**32**> (35%)	10%	24–**33** (25%)	14%	31–**36** (30%)	24%
	60	<17–22–**28**> (35%)	19–24–**29** (30%)	4%	**28**	0%	**34**	21%
	70	13–18–**24** (35%)	13–18–**24** (35%)	0%	24–**29** (20%)	21%	24–**29** (20%)	21%
	80	13–18–**24** (30%)	13–18–**26** (25%)	8%	22–**27** (35%)	13%	25–**30** (20%)	25%
	90	11–16–**22** (30%)	11–16–**22** (30%)	0%	**24**	9%	**26**	18%
12.5%	50	**<19>**	<19–24–**29**> (35%)	53%	24–**29** (25%)	53%	31–**36** (30%)	89%
	60	<16–21–**27**> (35%)	<17–22–**28**> (35%)	4%	**28**	4%	**28**	4%
	70	<13–18–**24**> (35%)	13–18–**24** (35%)	0%	17–22–**29** (25%)	21%	24–**29** (20%)	21%
	80	13–18–**23** (30%)	13–18–**23** (30%)	0%	19–**27** (35%)	17%	23–**28** (20%)	22%
	90	11–16–**21** (30%)	11–16–**21** (30%)	0%	**24**	14%	**24**	14%
15.0%	50	**<18>**	**<19>**	6%	24–**29** (25%)	61%	31–**36** (30%)	100%
	60	**<18>**	**<19>**	0%	**28**	56%	28	56%
	70	<13–18–**24**> (35%)	<13–18–**24**> (35%)	0%	16–**24** (20%)	0%	24–**29** (20%)	21%
	80	<12–18–**23**> (35%)	13–18–**23** (30%)	0%	19–**24** (35%)	4%	**25**	9%
	90	11–16–**21** (30%)	11–16–**21** (30%)	0%	**24**	14%	**24**	14%

[a] Data from Huang and Kronrad (2002).
[b] Bold type indicates the age of final harvest, and the number(s) to the left indicates age(s) at thinning(s).
[c] Number in parentheses indicates the percentage of basal area removed during thinning.
[d] <> indicates a negative SEVtp or SEVtc. Schedules shown minimize losses.

Table 3. The soil expectation value ($/ac) of the financially optimal rotations (planting density 9′ × 8′) for loblolly pine plantations managed exclusively for timber production[a] (SEVtp) or for joint timber production and carbon sequestration (SEVtc) in East Texas.

		C = $0/ton	C = $10/ton		C = $50/ton		C = $100/ton	
ARR	SI	SEVtp	SEVtc	Gain[b]	SEVtc	Gain	SEVtc	Gain
2.5%	50	1,683.14	1,997.25	19%	3,253.69	93%	4,824.24	187%
	60	2,939.04	3,355.85	14%	5,023.09	71%	7,107.14	142%
	70	4,344.29	4,882.56	12%	7,035.64	62%	9,726.99	124%
	80	6,656.63	7,318.91	10%	10,030.53	51%	13,533.44	103%
	90	9,406.64	10,236.68	9%	13,737.85	46%	18,114.31	93%
5.0%	50	164.31	334.98	104%	1,029.80	527%	1,898.32	1055%
	60	551.81	767.53	39%	1,692.95	207%	2,876.77	421%
	70	1,081.25	1,347.16	25%	2,516.40	133%	4,022.71	272%
	80	1,965.76	2,296.54	17%	3,809.68	94%	5,721.21	191%
	90	2,870.04	3,310.04	15%	5,146.25	79%	7,497.92	161%
7.5%	50	−112.15	−2.33		472.66		1,085.20	
	60	77.82	227.82	193%	831.81	969%	1,641.40	2009%
	70	322.24	500.68	55%	1,277.23	296%	2,299.68	614%
	80	707.11	950.95	34%	1,963.55	178%	3,262.16	361%
	90	1,168.84	1,451.08	24%	2,652.42	127%	4,230.96	262%
10.0%	50	−202.95	−119.07		233.63		695.13	
	60	−104.21	8.15		459.90		1,055.94	
	70	51.24	175.19	242%	733.22	1331%	1,487.44	2803%
	80	249.18	414.78	66%	1,145.77	360%	2,095.58	741%
	90	532.53	723.50	36%	1,581.93	197%	2,717.84	410%
12.5%	50	−238.84	−175.02		101.94		463.39	
	60	−183.72	−99.41		254.32		720.89	
	70	−83.10	15.19		435.98		1,023.98	
	80	34.30	160.36	368%	710.08	1970%	1,439.75	4098%
	90	215.08	362.99	69%	1,002.77	366%	1,883.36	776%
15.0%	50	−254.79	−203.75		18.96		311.02	
	60	−221.52	−154.68		127.64		503.79	
	70	−158.06	−77.69		259.74		727.81	
	80	−84.85	17.03		452.05		1,032.66	
	90	35.63	155.58	337%	654.31	1736%	1,359.78	3716%

[a] Data from Huang and Kronrad (2002).
[b] Gain = (SEVtc − SEVtp)/SEVtp.

sawlogs at final harvest. Thinning intensity increases as ARR increases, which generates more timber revenue at an earlier age. Forest management practices exclusive of timber yields is profitable for NIPF landowners for all site indices when ARR is low. When the ARR is 15.0%, only site index 90 land is profitable under timber management. For a more complete discussion of profitability and optimal management regimes, see Huang (1999) and Huang and Kronrad (2002).

Dual Products of Timber and Carbon (C = $10, $50, and $100/ton)

As the price of carbon increases and ARR is 2.5 or 5%, the financially optimal rotation length of a pine plantation in East Texas managed for the joint production of timber and carbon sequestration remains constant or decreases. This finding is not consistent with the results of the previous studies (Hoen and Solberg 1997, Zhou 2001, Stainback and Alavalapati 2002) that found rotation length increases as carbon price increases. The possible explanations include the following: first, the mortality functions used in these studies were not as great as PTAEDA2, and it will take longer for these stands to reach a maximum biomass and amount of carbon sequestered. Second, when the ARR is low, the total benefit of carbon sequestration throughout time is nearly offset by the total cost of the carbon release, and the net benefit of forest carbon sequestration approaches zero. Consequently, carbon sequestration only slightly affects the optimal rotation. Third, the financially optimal rotation is longer for low ARR, and it approaches the age when mortality is higher than growth (Figures 1 and 2); therefore, to avoid the substantial financial loss derived from the release of carbon, as the price of carbon increases, the optimal rotation length either remains the same on low-quality sites or decreases on high-quality sites. The probability that a tree remains alive in a given year was assumed to be a function of its competitive stress and individual vigor or photosynthetic potential (Burkhart et al. 1987). In PTAEDA2, survival probability is calculated based on crown ratio and pine competition index for each tree to stochastically determine annual mortality (Burkhart et al. 1987). Unlike previous studies (van Kooten et al. 1995, Zhou 2001, Stainback and Alavalapati 2002) that assumed that a carbon tax would only be imposed at the end of the rotation when the harvest occurs, this study imposed a repayment of service, namely the storage of carbon, no longer provided not only at the time of thinning and final harvest but also when mortality occurs. This assumption is more reasonable in a sense that the repayment was calculated annually according to the relationships of growth and loss of carbon storage. Because only live tree components (above- and belowground biomass) were evaluated, and dead standing trees were not considered as credits, the loss

Table 4. The soil expectation value difference ($/ac) between the SEVtc optimized for joint timber production and carbon sequestration and the SEVtp + C optimized for single timber production with carbon benefit on the side for loblolly pine plantations in East Texas.

		C = $10/ton			C = $50/ton			C = $100/ton		
ARR	SI	SEVtp + C	ΔSEV[a]	Gain[b]	SEVtp + C	ΔSEV	Gain	SEVtp + C	ΔSEV	Gain
2.5%	50	1,997.25	0.00	0%	3,253.69	0.00	0%	4,824.24	0.00	0%
	60	3,355.85	0.00	0%	5,023.09	0.00	0%	7,107.14	0.00	0%
	70	4,882.56	0.00	0%	7,035.64	0.00	0%	9,726.99	0.00	0%
	80	7,268.12	50.79	1%	9,714.08	316.45	3%	12,771.53	761.91	6%
	90	10,179.08	57.60	1%	13,268.84	469.01	4%	17,131.04	983.27	6%
5.0%	50	332.25	2.73	1%	1,004.01	25.79	3%	1,843.71	54.61	3%
	60	767.53	0.00	0%	1,630.41	62.54	4%	2,709.01	167.76	6%
	70	1,347.16	0.00	0%	2,410.80	105.60	4%	3,740.35	282.36	8%
	80	2,296.54	0.00	0%	3,619.66	190.02	5%	5,273.56	447.65	8%
	90	3,303.72	6.32	0%	5,038.44	107.81	2%	7,206.84	291.08	4%
7.5%	50	−2.33	0.00		436.95	35.71	8%	986.05	99.15	10%
	60	227.82	0.00	0%	827.82	3.99	0%	1,577.82	63.58	4%
	70	489.47	11.21	2%	1,158.39	118.84	10%	1,994.54	305.14	15%
	80	950.95	0.00	0%	1,926.31	37.24	2%	3,145.51	116.65	4%
	90	1,427.63	23.45	2%	2,462.79	189.63	8%	3,756.74	474.22	13%
10.0%	50	−119.97	0.90		211.95	21.68	10%	626.85	68.28	11%
	60	1.97	6.18	314%	426.69	33.21	8%	957.59	98.35	10%
	70	175.19	0.00	0%	670.99	62.23	9%	1,290.74	196.70	15%
	80	410.49	4.29	1%	1,055.73	90.04	9%	1,862.28	233.30	13%
	90	723.50	0.00	0%	1,487.38	94.55	6%	2,442.23	275.61	11%
12.5%	50	−177.20	2.18		69.36	32.58	47%	377.56	85.83	23%
	60	−101.15	1.74		229.13	25.19	11%	641.98	78.91	12%
	70	15.19	0.00	0%	408.35	27.63	7%	899.80	124.18	14%
	80	160.36	0.00	0%	664.60	45.48	7%	1,294.90	144.85	11%
	90	362.99	0.00	0%	954.63	48.14	5%	1,694.18	189.18	11%
15.0%	50	−205.21	1.46		−6.89	25.85		241.01	70.01	29%
	60	−156.23	1.55		104.93	22.71	22%	431.38	72.41	17%
	70	−77.69	0.00		243.79	15.95	7%	645.64	82.17	13%
	80	13.59	3.44	25%	407.35	44.70	11%	899.55	133.11	15%
	90	155.58	0.00	0%	635.38	18.93	3%	1,235.13	124.65	10%

[a] ΔSEV = SEVtc − SEVtp + C.
[b] Gain = ΔSEV/SEVtp + C.

of living tree biomass means the loss of carbon storage. The loss of carbon was valued at the same price as the accrual of carbon in the cash flow analyses of this study. When mortality is far greater than growth, the marginal timber revenues from leaving trees in the stand will not be large enough to offset the repayment of carbon loss. Thus, landowners will be better off harvesting their stands earlier to avoid repaying the carbon credit buyers for the loss of carbon storage.

When the ARR is 7.5% or higher, the rotation pattern follows previous studies, that concluded the optimal rotation increases as the carbon price increases. The optimal rotation of a timber-carbon stand managed for joint timber production and carbon sequestration is longer than for the stand managed exclusively for timber production. Moreover, the percentage change in the rotation length (denoted as ΔR in Table 2) increases with the increase of the interest rate, which implies that the effect of carbon benefits on the optimal rotation is relatively larger when the interest rate is high than when it is low. The value of ΔR increases as site index decreases, which indicates that the change in the rotation length increases with the decrease of the site index, other factors being equal. This implies that the inclusion of carbon benefit into forest management has a relatively greater impact on the optimal rotation on low-productive sites than on high-productive sites. Thinning intensity decreases and thinning frequency drops to zero in some cases for the purpose of producing more long-lived wood products and obtaining carbon credits.

Carbon sequestration benefits may turn an otherwise unprofitable pine plantation investment to a profitable one. In the case where the ARR is 10% and the site index is 60, when the carbon benefit is included and optimized together with the timber revenue, the optimal SEVtc increases from −$104.21 to $8.15 per acre at $10/ton of carbon (Table 3). The percentage gain in SEVtc increases as the interest rate increases. This indicates that if carbon benefits are included in forest management, the financial gains generally are larger when the interest rate is high than when it is low. In the case where the interest rate is high, the benefits of carbon sequestration will dominate total profits, especially when the carbon price is high. Furthermore, Table 3 shows that the percentage gain in SEVtc decreases as the site index increases. This implies that the financial gains are higher on low-productivity sites than on high-productivity sites. Compared to high-productivity sites, the financial gains of carbon sequestration on low-productivity sites contribute significantly to total profits.

The SEVtp of a stand managed for timber production only (C = $0/ton) presented in Table 3 were calculated without counting the benefits of carbon sequestration. Because the carbon benefits are still available even in the timber production stands, the SEV of the timber production stand was recalculated including the carbon benefit and denoted as SEVtp + C. Table 4 shows that the financial gain is lower when the investment is optimized only for timber production than when it is optimized for joint timber production and carbon sequestration. The differences between the SEVtc and SEVtp + C tend to increase with increasing carbon prices. In the case where the ARR is 2.5%, site index is 90, and carbon price is $100/ton, the monetary difference between the SEVtc ($18,114.31) optimized for joint timber production and carbon sequestration and the SEVtp + C ($17,131.04) optimized for single timber production including the sale of the carbon is $983.27 per acre, a 6% increase (Table 4). This indicates that the profits of forest management could be improved through incorporating carbon storage into product objectives and adjusting the thinning and final harvest schedules.

It should be noted that the methods used to quantify long-term carbon storage derived from forests have been diverse. Zhou (2001) assumed that for Scots pine in northern Sweden only carbon in sawtimber will go into long-term storage when the stand is harvested. Stainback and Alavalapati (2002) and Enzinger and Jeffs (2000) assumed that the portion of sawtimber and pulpwood that does not decay and sequesters carbon in long-lived products or in landfills is 0.80 and 0.35, respectively, for slash pine in north Florida and South Georgia. Plantinga and Birdsey (1994) assumed that 20.3% of the carbon in merchantable volumes of loblolly and shortleaf pine is sequestered. Van Kooten et al. (1995) assumed three percentages (0%, 50%, and 100%) for harvested timber that goes into long-term storage in structures and landfills. This study assumed that all merchantable portions of sawtimber and pulpwood size trees would be used to store carbon in long-lived products or in landfills. The rationale for this assumption is based on the utilization of timber in East Texas. Sawlogs are typically made into building materials and inexpensive furniture, and mill residues would be used to produce fiberboard, particleboard, or to generate electricity. Pulpwood is typically used in oriented strand board (OSB), fiberboard, or paper production and may end up in landfills or used as boiler fuel (energy production for mills) (Christopher D. MacDonald, personal communication, Temple Inland, Inc., May 28, 2004). Because of the differences in the methods of implementing repayment for carbon loss and quantifying long-term timber carbon storage, no comparisons among the results of this study and previous studies were made.

Conclusions

The changing role of forests in society provides new challenges to forest management planners through timber and nontimber forest management strategies. The results of this study indicate that the effect of revenues from carbon sequestration on the financially optimal management regime and profitability of forest management is significant. Four main conclusions can be drawn. First, the inclusion of carbon revenues in plantation management changes the optimal timber-carbon rotation length compared to the optimal rotation that maximizes only timber value; however, the magnitude and direction of change depends on the ARR and other factors. Second, the effect of carbon revenues on the optimal rotation length and the percentage gain in SEVtc is larger on low-productivity sites than on high-productivity sites. Third, the effect of carbon revenues on the optimal rotation length and the percentage gain in SEVtc is larger for high interest rates than for low interest rates. Finally, the revenue from selling carbon credits increases the profitability of pine plantations. As a result, when carbon sequestration revenues are included, NIPF landowners may extend their investments on low-productivity sites that would be unprofitable if carbon revenues are not counted.

Although the management objective of producing long-lived wood products will tend to delay the final harvest, applying unreasonably lengthy rotations to loblolly pine, a fast growing species, will increase mortality and reduce net carbon storage in the long run. This is especially true on high-productivity sites at greater densities. Specifically, the amount of carbon a tree can sequester depends on a number of variables such as species, stand age, site quality, planting density, and forest practices. NIPF landowners need to be aware of changes in carbon prices and their stand conditions, and adjust their management practices accordingly to maximize their revenue from the management of timber production and carbon sequestration.

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