MINIMUM COST STRATEGIES FOR SEQUESTERING CARBON IN FORESTS

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ABSTRACT

This paper examines the costs of meeting explicit targets for increments of carbon sequestered in forests when both forest management decisions and the area of forests can be varied. Costs are estimated as welfare losses in markets for forest and agricultural products. Results show greatest change in management actions when targets require large near-term flux increments, while land area change is largest when long-term increments are needed. Marginal costs per tonne of carbon flux do not vary greatly with the form of the target and are similar to findings of earlier studies for comparable size of average carbon flux increment.

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Sequestering carbon in forests and forest products is a potentially useful mechanism in global efforts to offset expanding greenhouse gas emissions (see, for example, United Nations, 1992). In the U.S., the Clinton Administration's 1993 Climate Action Plan called for near-term incremental carbon savings of some 10 million metric tonnes (Mmt) per year through various activities in the forest sector (Clinton and Gore, 1993)[1]. The potential for expanded rates of forest carbon sequestration or net carbon flux beyond 10 Mmt annually appears to be substantial, however, and an array of recent economic studies have examined the costs of attaining higher rates.[2] In most of these studies, the sole vehicle for expanding flux is the afforestation of agricultural land. Consideration of afforestation is certainly critical, since it will likely form the backbone of any program to obtain major expansions in forest carbon flux, but it need not be the only focus for policy action. Rates of forest carbon flux can also be modified through changes in management on existing and future forests, without drawing new land into the forest base. In addition, the time patterns of flux change attainable with afforestation alone are limited. Other management actions may be needed, particularly if large near-term flux increases are required.

This paper examines the costs of meeting incremental forest carbon flux targets in the U.S., when both forest management actions and the area of forests can vary. Costs are estimated as the welfare losses in the markets for forest and agricultural products incurred in pursuing various flux policies over the first five decades of the program. We consider a representative range of flux target scenarios and identify the mixes of management actions and land transfers needed to meet these targets at minimum social cost. In the following sections we describe the methods and models used to estimate costs, derivation of the example targets, and projection results. A concluding section discusses the implications of our analysis for forest carbon sequestration policy.

Methods for Estimating Costs and Carbon Flux

In reckoning the costs of carbon sequestration programs, many previous studies have limited attention to the direct costs of afforestation plus the compensation or subsidies required to induce owners of agricultural land to shift its use to forestry. The present analysis measures cost as the net change in producer and consumer surpluses in markets for forest and agricultural commodities.[3] We employ a model of the U.S. forest and agricultural markets in which the sectors are linked through the market for land. Alternative carbon flux targets are examined by constraining the model to find market solutions that allow achievement of the targets. Welfare differences between constrained and unconstrained results provide estimates of impacts on market participants and include the conversion and land use opportunity costs of previous studies.

This is, of course, a partial equilibrium analysis. Our model explicitly treats primary producers in both forest and agriculture sectors but includes only a portion of the vertical market structures, stopping short of final consumers. Welfare impact estimates derived from the model, under conditions described by Just, Hueth and Schmitz (1982), may reflect changes in the main markets of the forest and agriculture sectors but not in tributary factor or product markets where we have assumed (as is customary) fixed prices. Further, we do not consider any impacts on amenity, existence or other non-commodity values in the two sectors that might arise from changes induced by a carbon sequestration policy. Finally, we consider only adjustments in private forest land and management. While public forest lands will play some role in meeting carbon targets, policy directions are not at present clear and we have assumed that their management and harvests are held constant in their current form and levels in all projections.

Within the conditions noted above, the aim of the present study is to identify what can be termed minimum social cost strategies to achieve forest carbon flux targets and to characterize the associated resource and management changes comprising these strategies. While we offer some comments on the nature of public programs to implement these changes in the concluding section, specific analysis of policy vehicles is left to future research.

Market Model

Estimates of flux target costs were obtained from simulations using a merged model of the U.S. forest and agriculture sectors (Adams, et al 1996). The combined model employs a joint objective function, maximizing the present value of producers' and consumers' surpluses in the markets of the two sectors, and restrictions on the disposition of the land base that is suitable for use in either sector. The combined structure is an optimizing intertemporal spatial equilibrium market model that simulates prices, production, consumption and management actions in the two sectors. Producers are assumed to have full knowledge of current and future market conditions and access to perfect markets for capital. Simulations proceed on a decade time step with a nine decade time horizon to accommodate treatment of terminal inventories. We limit our policy analysis to results for the 50 year period from 1990 to 2040. All prices and costs are deflated (in 1990 dollars) and the real discount rate was 4 percent.

Treatment of the forest sector is restricted to the market for logs, which are distinguished by species (hardwood and softwood) and product (sawlogs, pulpwood and fuelwood). Demand functions for logs were derived from solutions of the TAMM and NAPAP models (Adams and Haynes, 1996; Ince, 1994). The resulting functions shift over the decades of the projection. They incorporate endogenous adjustments and substitution responses in the parent models, as would be observed in a 10 year period, and are more elastic than the short-run relations found in these models.[4] Log processing capacity is limited in each time period and decisions to purchase additional capacity are treated as endogenous. Output in certain product categories can be used as substitutes (sawlogs for pulpwood, pulpwood for fuelwood) and residue generated in sawlog processing can replace pulpwood. Export demand and import supply relations are used to represent options for log trade with other countries.

Private timber inventories are modeled using the "linear forest" structure described by Johansson and Löfgren (1985) or the "model II" form of Johnson and Scheurman (1977). We distinguish timberland by age class, forest type, management intensity, suitability for agriculture, and site quality, for nine domestic regions and two ownerships (industrial and nonindustrial). Harvest age, management intensity, and forest type decisions (when regenerating harvest land) are endogenous. Log supply from public lands is fixed.

An earlier equilibrium model described by Chang et al (1992) was expanded and adapted to describe the agricultural sector. Its objective maximizes the present value of consumer willingness-to-pay net of the costs of factors and transportation. Demand elasticity estimates were drawn from a variety of sources (see Chang et al for discussion) to reflect substitution options and potentials consistent with our 10 year time interval. Production activities are represented by potential budgets for different types of crops, cropping methods and options for secondary processing. Within in each region, crops compete for price-sensitive labor and irrigation water supplies and a land base, a portion of which is comprised of land converted from forests.

The land bases for agriculture and forestry are linked. We treat land use decisions on industrial ownerships as exogenous, but a portion of nonindustrial land is suitable for both uses and may move between them as land rents dictate. The extent of convertibility of forest land to agriculture was estimated from data in the National Resources Inventory and the Second RCA Appraisal (USDA, SCS, 1989; USDI, NRCS 1996). Limits on agricultural land that might be converted to forests were derived from Moulton and Richards (1990).

A mathematical outline of the model is given in the appendix. Notation and subscripts relating to time, region, products, ownership and land classification have been omitted, with the exception of the initial time summation in the objective function (appendix equation (1)) to suggest the intertemporal nature of the problem. In the forest sector decision variables include forest production (C), harvest and regeneration of existing and newly created forest stands over time (E and R), and the intensity of management on these areas (I). In the agriculture sector, endogenous variables include agricultural output (O), primary (crop/livestock) and secondary production (F and S) and use of price-sensitive agricultural inputs (L, irrigation water and labor). Land movements between forestry and agriculture are represented by the variable FTA, and from agriculture to forestry by ATF. Since there are many qualities of land represented in the model, both FTA and ATF can be non-zero in any period. The movement of land between sectors is controlled by equations (3), (5), (7) and (8). The value of an acre of forest land converted to agriculture is the opportunity cost of diverting it from forestry, plus costs of conversion (the function C_C), plus any implicit returns to the limits on land suitable for conversion (7). This is the shadow price of relation (3). Analogously, the value of an additional acre converted from agriculture to forestry, subject to limits on lands suitable for conversion in (8), is the shadow price of relation (5).

If the carbon target constraint (9) is operable, management activities in both sectors (E, R, I, F, S and L) may change and as well the extent and timing of any land transfers. There is one constraint (9) for each period, and we simulate alternative carbon flux trajectories by allowing T_C to vary in different patterns over the projection. The shadow price of this constraint in any period t is the present value of the costs in that and all subsequent periods of an extra unit of carbon flux in period t. Thus there is a "marginal cost of carbon" in each period, and these costs will vary with the time path of T_C.

Carbon Inventories

Our carbon accounting includes stocks on forest and agricultural lands and changes as lands move between sectors (Adams et al 1996)--this accounting underlies the functions ΔC_F and ΔC_A in equations (9) of the appendix. Forest carbon comprises five pools: tree, woody debris, soil, forest floor, and understory. The extent and relative importance of these pools vary as stands age and by region, forest type, site productivity, and management intensity. Carbon inventory change (carbon flux) can be influenced by modifying the mix of these forest characteristics as well as by changing the aggregate forest land base. When a stand is harvested, we estimate losses in the nonmerchantable pools (debris, soil, etc. other than tree boles), gains due to displacement of fossil fuels by use of wood for fuel, and carbon losses over time in products derived from the harvested portions of trees.[5] Differences in soil and understory pools as land shifts between forest and agricultural uses are also recognized. Carbon in soils and vegetation on agricultural lands is assumed to be a constant that varies by type of agricultural practice and region.

Forest Carbon Sequestration Options and Alternative Flux Targets

Much recent analysis of forest carbon sequestration has focused on expansion of the area of forests through afforestation of agricultural lands. Either in a one-time approach (planting some fixed area and allowing it to mature) or a cumulative program of plantings staggered over several periods, the basic time pattern of carbon flux achievable in the near term is limited to a gradually rising form. As planted stands increase in age their growth rises, peaks and then declines. The details of this pattern vary markedly by species, region and management regime [as Richards (1993) notes] but the basic form is the same. For a one-shot afforestation program, aggregate carbon flux of the plantation would follow this same general pattern. For a sequence of plantings the flux of the aggregate would show a longer "flatter" peak but would ultimately drop at some point after the final planting.

The benefits of sequestering carbon derive from the avoidance or reduction of damages resulting from climate change in the future. Greenhouse gas emissions are thought to contribute to climate change in a cumulative fashion. As a consequence, an incremental unit of carbon sequestered at some future point, when atmospheric concentrations of greenhouse gases have grown to high levels and climate has been modified, will have less impact on then extant climate conditions and damages than a unit sequestered at an earlier time. While little is known about the nature of damages likely to result from global change and the further link of these to accumulation of greenhouse gases, there is some likelihood that climate change and associated damages will respond only with a lag to (and at different rates than) changes in greenhouse gas emissions and atmospheric concentrations.

Given these potential lags between changes in net emissions, climate change and damage, policy analysts may wish to consider forest carbon sequestration options that have larger near-term flux targets than would result from plantations alone. Meeting such targets would entail changes in the management of existing stands and reforested areas as well as the expansion of the forest land base and the treatment of afforested lands.[6] Specific actions could involve: (i) changing harvest ages for existing stands, (ii) shifting the species planted and intensity of management on reforested or afforested areas, and (iii) altering the site, regional and ownership concentration of (i) and (ii). Even in the customary case of gradually rising flux targets, this same array of options should be considered as a potential means of reducing costs.

The effective carbon goal for the U.S. forest sector in the first *Climate Change Action Plan* (Clinton and Gore, 1993) was to maintain a stable to rising flux pattern over the next several decades. In the present study, we consider this and several other flux patterns within three broad classes: (1) constant flux, (2) increases in near-term flux, and (3) gradually rising flux, as detailed in Table 1. All of the targets are defined relative to a "base" case with no forest carbon policy. As illustrated in Figure 1, the base involves an increase in flux of some 1.25 gigatonnes per decade between the first and second decades with declining rates thereafter. The constant flux targets in the first group (e.g., 1A in Figure 1) emulate the general intent of the *Climate Action Plan* in maintaining stable fluxes at or above the second decade peak. This entails large flux increases relative to the base in both the near and long-term. Targets in group (2), in contrast, are less ambitious, aiming to increase near-term flux while requiring that future fluxes only maintain their positions relative to the base (and so may decline but never fall below the base). This group is further divided into a set forcing departure from the base in the 1990s decade (2C in Figure 1) and a second set with the departure delayed to the 2000s decade (2F in Figure 1). The third class follows the usual pattern of gradual flux increases associated with plantations, except in decades where the base flux is larger than the target would have been (3B in Figure 1).

Projection Results

A central concern of the present study is the identification of opportunities to meet forest carbon flux targets through modifications in forest management (beyond the customary approach of adding land to the forest base). Table 2 presents five measures or indicators of management actions (in addition to area change): harvest age, an area weighted index of the average management intensity or cultural class, average timber volume per unit area, species mix and the geographic concentration of forest inventory. Simulation results in Table 2 compare the base case and selected targets from the four classes defined in Table 1 which have roughly comparable average annual flux increments relative to the base (between 39 and 44 million mt per year). Changes during the first two decades are shown separately from those for the full 50 years to help identify actions needed to meet the near-term elements of the targets.

Land Base and Management Changes

In all cases, meeting targets entails shifting land from agriculture to forests at some point during the first 5 decades. Targets in classes 1 and 3, with large long-term flux targets, shift more area from agriculture over the projection but most of this occurs after the second decade. Targets in class 2, that roughly parallel base flux patterns, shift smaller areas but do so earlier to meet the high flux requirements in decades 2 and 3.

Since the weight of carbon in a forest system is a different measure of forest biomass than the timber volumes used in the model's harvest yield relations (these are the functions C_F and c, respectively, in equations (9) and (2)), changes in harvest age may be useful in varying rates of carbon uptake. Results in Table 2 indicate that for softwoods changes in average harvest age are employed mostly to meet long-term restrictions. For hardwoods, however, a somewhat larger part of the initial (1990s) inventory is comprised of older stands. As a result, harvest ages in the near-term may actually be reduced in some cases as these older stands are replaced with more rapidly growing hardwood regeneration. The overall percentage changes are small in both species, representing average adjustments of roughly one year for the targets shown.

Management intensity is represented in our model by a set of discrete classes with varying timber and carbon yields and costs. Higher management intensity classes have faster growth and carbon uptake. As indicated by the management intensity indexes in Table 2, early management intensification is particularly important in the scenarios requiring larger first decade flux increases (1A and 2C) and is larger for softwoods than hardwoods. Long-term management intensity changes, in contrast, are larger for hardwoods. This pattern reflects the array of management options available for the two species in the present analysis. Softwood growth can be increased in the near term through increased use of plantations (as opposed to natural regeneration). Hardwood management intensification, in contrast, involves variants of natural regeneration, with significant yield increases occurring only after several decades.

Timber volumes per unit area carried on forest lands (termed “stocking”) provide a further indication of management intensity. Consonant with findings on the intensity index, softwood stocking rises early in the projection and remains higher, while hardwood stocking increases occur mostly in periods 3 through 5. Expansion in hardwood stocking is smallest (or even negative) in scenarios with higher long-term targets.

Hardwood and softwood species grow at different rates and sequester different amounts of carbon. Thus the choice of species mix over time is a further potential tool in meeting carbon flux targets. In all cases in Table 2, the proportion of softwoods in total private forest area is reduced relative to the base. This occurs because the conversion of hardwood stands to softwoods on existing forest lands is reduced relative to the base in all the targets. Changes in softwood area are larger after the second decade and for the scenarios with large long-term targets (1A and 3B).[7]

A final issue, addressed in several recent forest carbon studies, is the geographic concentration of modifications in management and/or forest land area. Past studies have generally found that the South, with its rapidly growing coniferous species and large areas of marginal crop and pasture land, was the most effective location for carbon plantations. In the present study, however, the largest share of incremental forest lands comes in the North, particularly in the Lake States region. These area changes are translated in Table 2 to the fraction of total US timber inventories in the US South. We see that the share of Southern inventories is stable to declining in all target classes, with particularly large reductions in the cases with high fluxes in decades 4 and 5.

Costs of Carbon Flux Targets

Table 3 presents cost, carbon flux and land use transfer measures for the 13 target scenarios together with comparative estimates from four studies of forest carbon sequestration employing a national land base. Column [3] gives a commonly used measure of average discounted cost or "cost effectiveness" per tonne of carbon sequestered. This measure is computed as the decadal discounted value of total costs divided by the average decadal flux. For targets with roughly comparable increments in average annual flux (denoted in column [2] by *), average costs using this measure are not greatly dissimilar. Compared to the results of previous studies shown in Table 3, however, we find average costs to be roughly twice as large for cases with equivalent increments in average annual flux (recall that our costs derive from welfare estimates while earlier studies consider only direct plantation subsidy payments).

This average cost measure, or any of its variants (see Richards (1997) for a review), fails to account for the time pattern of benefits (loss or damage reductions) arising from changes in forest carbon flux. Since incremental carbon sequestration is spread through time, presumably its impacts are as well. To accommodate the time distribution of benefits, Richards (1993; 1997) suggests discounting the physical carbon flux values as well as the costs. This approach would yield an exact index if damage reductions were a fixed function of incremental carbon sequestered and if this link between damages and carbon was invariant over time. It is not obvious that this is the case, however, given the potential lags between atmospheric concentrations of greenhouse gases and climatic changes. Nonetheless, discounting of the physical volumes gives an indication of the direction of the effects of discounting benefits on the cost effectiveness (cost/benefit) measure. Column [4] provides a measure of this sort, being computed as the ratio of annualized discounted costs to annualized discounted flux increment. In this instance, scenarios with major flux increments late in the projection (2F, 3B) have higher costs than those with earlier increments (2C, 1A).

Column [5] of Table 3 gives, for each target, the annualized value of the shadow price of a one tonne per year increase in forest carbon flux in all years of the projection. In Figure 1 this change would appear as a uniform 10 million tonne per decade vertical shift in the flux target trajectories. The flux target constraints (9) limit period-to-period change in the carbon stock to be at least as large as the targets. Thus, a one tonne increase in any period's flux target (*ceteris paribus*) translates into a one tonne increase in carbon stock in that and all future periods. Raising the flux target in every period results in cumulating increments in the carbon stock. The cumulated shadow prices of the flux constraints over all periods is the present value of all future costs associated with a sustained one unit increase in flux. This is the marginal cost of forest carbon (as column [5] is headed) employed in this study. Given the policy importance of carbon flux, this is a reasonable approach to the definition of marginal costs. The time patterns of carbon stock and flux changes are also similar to those found in other studies where additional units of carbon were obtained exclusively by afforestation of additional land in the initial period of the analysis. The result, as in our study, would be an acceleration in the accumulation of the carbon stock and an upward shift in the flux pattern over time as more land is added.

As illustrated at the bottom of Table 3, estimates of the marginal cost of an extra tonne of carbon at comparable annual flux increments have increased modestly in past studies as models of the land use decision process have become more detailed and comprehensive. Adams et al (1993) find higher costs than Moulton and Richards (1990) in a long-run equilibrium analysis that considers a broader range of impacts, including those on consumers and producers in both agricultural and forest products markets. Parks and Hardie's (1995) estimates are still higher, in part because they employ a smaller land base than Moulton and Richards (Hardie and Parks, 1995). For comparable levels of average annual flux increase (*'s in column [1]), the present study yields marginal cost estimates within the range of earlier work. The form of the flux change appears to have only a limited impact on the level of marginal cost (ranging from $11-15/mt/year for scenarios 1A, 2C, 2F 3B). Variation within the classes of targets is greater, and the patterns of marginal costs within scenario groups are similar to those for average costs.

That our marginal cost results are similar to findings of past studies is noteworthy, given the markedly different nature of our modeling approach. Earlier studies with a national scope have generally focused on the process of shifting land from agriculture to forestry and, excepting Adams et al (1993), the reckoning of costs has been limited to direct government payments to producers (for planting and rent subsidies) using a fixed schedule of agricultural land rental values. Once subsidies exceed rent plus conversion differentials, land shifts uses. In the present study, costs are net changes in surpluses in both agricultural and forest markets for consumers as well as landowners/producers, rent schedules are dynamic because of explicit product markets, and land may shift in both directions.

Table 4 illustrates the potential distributional impacts of achieving the various flux targets. In the forest sector, consumers lose in all but one scenario, and these losses are not fully offset by gains to forest producers. The largest single source of loss for most targets is agricultural consumers. Like forest consumers, this group also loses in all but one case, while impacts on agricultural producers are mixed. Neither sector shows a net gain in any scenario.

Varying discount rate and inflation assumptions could confound comparisons of our results and those of earlier studies, though there do not appear to be great disparities in this respect. For example, both Parks and Hardie (1995) and Richards et al (1993) use deflated prices ($1987 and $1992, respectively) as we do ($1990) and real discount rates that are the same as, or bracket, the 4 percent rate used in our study. To consider this issue further, we developed simulations to explore the interest rate sensitivity of our results. Since the original carbon targets were defined relative to the base projection and the base projection changes when the discount rate is altered, it is not possible to compare the original scenarios run at alternative discount rates. For this purpose we employ a constant absolute flux target, similar in form to scenarios 1a-d (see Table 1 and Figure 1), with a level set at 1.8931 gigatonnes per decade for all decades. The following tabulation summarizes results:

INTEREST RATE (percent)	ANNUAL FLUX INCREASE FROM BASE (Mmt/yr)	AVERAGE COST: UNDISCOUNTED CARBON ($/mt)	AVERAGE COST: DISCOUNTED CARBON ($/mt)	MARGINAL COST ($/mt/YR)
3	56	31	35	27
4	72	26	28	21
5	82	22	26	17

As the interest rate rises, the model projects higher near-term harvests, lower long-term cut, and lower average carbon inventories in the base cases. Thus the constant flux target employed in these simulations requires larger flux increments relative to the base and entails larger undiscounted costs with rising interest rate. Nonetheless, the discounting impact of the rising rate is sufficient to yield falling average and marginal costs across the range of rates examined. Richards et al (1993) found rising marginal costs with interest rate, but this may be due (as they suggest) to their use of discounted carbon in their total and marginal cost computations.

Hardie and Parks' (1995) comparative analysis of cost results from forest carbon reserve studies suggests that treatment of land base and carbon yield curves may also play important roles in explaining differences between studies. Our *forest* land base includes all (commercial) timberland in the U.S. private forest sector and hence is larger than the base of past studies. This is critical to our objective of examining the potential role of variations in management practices as sources of additional carbon flux. At the same time a larger base could offer additional and cheaper alternatives for plantation establishment than were available to past studies and so draw our costs down. Our agricultural land base was derived from the same acreage and resource data as Moulton and Richards (1990) and Parks and Hardie (1995), and like the latter study we exclude the semi-arid lands of the

Northern and Southern Plains from consideration for afforestation. This could raise our costs relative to Moulton and Richards (1990) who included these areas, but not relative to Parks and Hardie (1990) who excluded them.

Stand level carbon yield estimates for the present study were derived from essentially the same source as past studies [Birdsey (1992)], but with additional adjustments for carbon dynamics in woody debris as suggested by Turner et al (1993). Once timber is harvested we also attempt an accounting for the “fate” of carbon in harvested products and the residuals left in the forest. While it is difficult to show a direct comparison, the carbon yield structure in the present study should be similar to that used in Parks and Hardie (1995) and, as Hardie and Parks (1995) illustrate, lower than yields used by Moulton and Richards (1990).

Conclusions

The foregoing results offer some new insights into the nature and extent of policy actions needed to increase rates of carbon sequestration in forests and differ in several ways from those of earlier studies. Our conjecture at the outset was that the minimum cost mix of management input and afforestation changes might vary with the type of target: land transfers and afforestation being more important for the long-term, management adjustments for the near-term. The comparisons in Table 2 seem to bear this out. Land transfers from agriculture are larger: (i) for targets that differ most from base fluxes late in the projection and (ii) in later periods within a given target when differences from the base expand over time. Management input changes can also act to increase the carbon uptake of the lands transferred. Thus for comparable average flux increases, land transfers in our analysis are generally smaller than those suggested in earlier studies, reflecting in part higher management inputs on these acres that increase their growth.

Our indicators of management input (average management intensity class and volume per unit area) rise in most cases but show the largest deviations from the base for targets with major near-term flux increments. The percentage changes are relatively small, but these represent shifts across millions of acres of forest land so their aggregate effects are large. An additional aspect of management, harvest age, was also found to change but in patterns that vary by species. For softwoods, rotations lengthen over all periods.[8] Hardwood rotation changes are mixed and may, in some cases, involve reductions in both the near and long term.

Results in this study suggest that efforts to expand forest carbon flux should have a rather different geographic and species focus than that proposed in past studies. In contrast to both Moulton and Richards (1990) and Parks and Hardie (1995), we find a greater emphasis on hardwood species to be appropriate in minimum cost strategies. Hardwood area increases under all targets. Some of this involves direct conversion of softwood to hardwood forests after harvest, but most derives from reductions in rates of hardwood-to-softwood conversion relative to the base. Related to this shift, our simulations also indicate that the bulk of the projected afforestation and management changes should occur in the North, mostly in the Lake States region. This is an area of large concentrations of hardwood forests in which hardwood stands can yield significant rates of carbon uptake. While our model recognizes the rapid growth potential of afforested stands in the South just as in previous studies, broader measures of costs and inclusion of welfare trade-offs across markets and regions act to shift the minimum cost solution away from the customary prescription of pine plantations on marginal Southern agricultural lands.

This study has emphasized the physical changes and associated costs of forest carbon sequestration strategies and has given little attention to the actual policy mechanisms or programs that might be required to implement the mix of actions indicated for a particular flux target. This is a significant issue in that the costs or complexity of administering an otherwise ideal plan may preclude its use. Since there are many examples of existing programs that attempt to induce land use changes through various subsidies, the central concern here is whether other aspects of management investment and rotation can be influenced. As with land use decisions, some form of subsidy would seem to be appropriate to induce more intensive management and longer rotations. The current SIP program at the federal level and an array of state programs offer examples of schemes designed to promote precisely these types of management changes (Alig et al, 1990). Payments to lengthen rotations in future stands would involve only minor conceptual extensions of these existing programs.

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Table 1. Carbon target definitions and carbon sequestration relative to base (no carbon policy) case for three classes of targets: (1A-1D) constant flux, (2A-2C and 2D-2F) departures from base flux in near term returning to base pattern thereafter, and (3A-3C) gradually rising flux.

TARGET	DEFINITION	AVERAGE ANNUAL FLUX MILLION mt	AVERAGE ANNUAL FLUX INCREASE OVER BASE MILLION mt
BASE	-	117.6	-
1A	MAX BASE FLUX ALL PERIODS	161.1	43.4
1B	MAX BASE FLUX + 100 million mt	171.1	53.4
1C	MAX BASE FLUX + 200 million mt	181.1	63.4
1D	MAX BASE FLUX + 300 million mt	191.1	73.4
2A	+200 million mt OVER BASE FROM 1990	137.6	20.0
2B	+300 million mt OVER BASE FROM 1990	147.6	30.0
2C	+440 million mt OVER BASE FROM 1990	161.6	44.0
2D	+200 million mt OVER BASE FROM 2000	133.6	16.0
2E	+300 million mt OVER BASE FROM 2000	141.6	24.0
2F	+550 million mt OVER BASE FROM 2000	161.6	44.0
3A	+400 million mt OVER 1990 BASE BY 2040	140.8	23.2
3B	+800 million mt OVER 1990 BASE BY 2040	157.1	39.4
3C	+1120 million mt OVER 1990 BASE BY 2040	171.5	53.8

Table 2, Results of carbon target simulations for selected targets, 2 and 5 decade intervals and softwood and hardwood species.

INTERVAL-->	FIRST 2 DECADES		ALL YEARS	
TARGET	SOFT	HARD	SOFT	HARD
NET LAND EXCHANGE: AG TO FOR +, FOR TO AG -				
	THOUSAND ACRES			
1A	3386		20342	
2C	10339		14332	
2F	13225		16826	
3B	3405		28465	
AVERAGE HARVEST AGE				
	PERCENTAGE CHANGE FROM BASE			
1A	0.1%	-2.5%	1.6%	0.7%
2C	0.3%	1.9%	1.6%	2.4%
2F	0.1%	0.4%	0.4%	1.3%
3B	0.3%	-4.5%	1.5%	-0.8%
MANAGEMENT INTENSITY INDEX				
	PERCENTAGE CHANGE FROM BASE			
1A	2.5%	1.0%	3.2%	4.9%
2C	3.4%	1.0%	2.4%	3.8%
2F	1.7%	0.0%	2.0%	2.2%
3B	0.8%	0.5%	2.4%	3.8%
VOLUME OF TIMBER PER UNIT AREA				
	PERCENTAGE CHANGE FROM BASE			
1A	2.8%	0.0%	5.8%	2.4%
2C	1.4%	0.9%	6.5%	4.0%
2F	1.4%	0.0%	4.5%	2.4%
3B	2.8%	-0.9%	3.2%	-0.8%
SOFTWOOD SPECIES AREA				
	PERCENT PRIVATE FOREST LAND IN SOFTWOODS			
BASE	37.1%		41.9%	
1A	36.5%		40.6%	
2C	37.1%		41.3%	
2F	36.9%		41.6%	
3B	36.3%		40.5%	
SOUTHERN INVENTORY				
	SOUTH AS PERCENT OF U.S. PRIVATE FOREST LAND			
BASE	54.0%	54.0%	59.0%	54.0%
1A	52.0%	54.0%	57.0%	51.0%
2C	52.0%	54.0%	57.0%	53.0%
2F	54.0%	54.0%	58.0%	53.0%
3B	53.0%	53.0%	58.0%	49.0%

Table 3. Estimated costs of carbon targets and costs from past studies.

TARGET OR SCENARIO	ANNUAL FLUX INCREASE (Average Base Flux 118 Mmt/YR) Million mt/YR	LAND SHIFT: AGRICULTURE TO FORESTS MILLION ACRES	AVERAGE COST: UNDISCOUNTED CARBON $/mt	AVERAGE COST: DISCOUNTED CARBON $/mt	MARGINA L COST $/mt/YR
	[1]	[2]	[3]	[4]	[5]
1A	43*	20	21	26	15
1B	53	25	23	27	17
1C	63	30	25	29	19
1D	73	34	26	29	21
2A	20	8	17	17	5
2B	30	10	19	19	8
2C	44*	14	22	22	11
2D	16	7	13	17	5
2	24	10	15	20	6
2F	44*	17	22	28	11
3A	23	16	15	33	12
3B	39*	28	18	37	15
3C	54	38	19	39	18
Moulton &	23	9	9	---	9
Richards (1990)	45*	21	10	---	11
Richards, et al (1993) [1]	44*	---	---	25	9 - 22
Adams, et al (1993)	29	---	3	---	13
	56	50	7	---	19
Parks & Hardie (1995)	44*	22	12	---	21
	88	---	22	---	51

NOTES:

* scenarios with roughly equivalent average annual flux increment relative to base referenced in text.

[1] Values estimated from figures for a 7.8 billion short ton program over 160 years. Marginal costs vary with assumptions on discount rate, agricultural land demand elasticity, and agricultural land availability. Carbon is discounted.

Table 4. Incidence of welfare impacts on consumers and producers in the forest and agriculture sectors due to carbon targets.

TARGET	FOREST CONSUMERS	FOREST PRODUCERS	AGRICULTURE CONSUMERS	AGRICULTURE PRODUCERS
	PRESENT VALUE OF CHANGE FROM BASE $ MILLION 1990			
1A	-1154	933	-2492	1197
1B	-1269	1022	-3463	1660
1C	-1395	1075	-4558	2061
1D	-1835	1460	-5373	2406
2A	170	-226	-925	491
2B	-150	73	-1779	892
2C	-674	507	-3305	1746
2D	-387	286	-182	-86
2E	-629	501	-476	-64
2F	-788	593	-2422	754
3A	-1327	1117	311	-733
3B	-1618	1251	-826	-315
3C	-1926	1376	-1722	-81

APPENDIX

SIMPLIFIED MATHEMATICAL REPRESENTATION OF LINKED FOREST AND AGRICULTURE SECTOR MODEL (TIME, REGION, PRODUCT, AND OWNERSHIP SUBSCRIPTS OMITTED)

$$
\begin{array}{llllllllll}
(1) & \text{Max} & \sum_{t=0}^{T}(1+i)^{-t}\Big[\int P_F(C)\,dC & -\,M(E,R,I) & -\,C_C(FTA) & & +\int P_A(A)\,dA & -\,O(F,S) & -\int S_L(L)\,dL\Big] & \\
(2) & \text{subject to} & C & -c(E,R,I) & & & & & \leq & 0 \\
(3) & & & P(E,R,I) & -\,FTA & +\,ATF & & & \leq & A_F \\
(4) & & & & & & A & -\,H(F,S) & \leq & 0 \\
(5) & & & & FTA & -\,ATF & & +\,A(F) & \leq & A_A \\
(6) & & & & & & & I(F) \quad -\,W & \leq & 0 \\
(7) & & & & FTA & -\,ATF & & & \leq & FA_{MAX} \\
(8) & & & & -\,FTA & +\,ATF & & & \leq & AF_{MAX} \\
(9) & & & \Delta C_F(E,R,I) & & & & +\,\Delta C_A(F) & \geq & T_C
\end{array}
$$

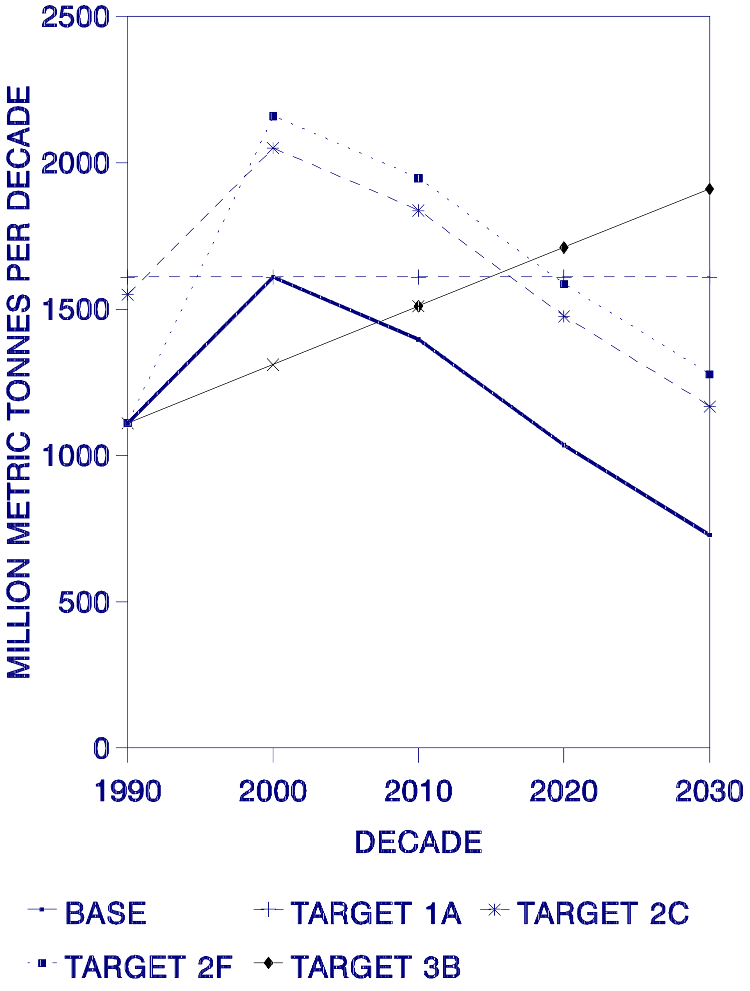
where

A	production of agricultural products,
$A(F)$	land used in crop/livestock production,
A_F, A_A	initial areas of forest and agricultural land
ATF	land moved from agriculture to forestry,
C	harvest from the forest sector,
$c(E,R,I)$	harvest of products from forest sector determined as a function, c, of existing and replanted stands and their management intensity,
$C_C(FTA)$	conversion costs for moving forest land to agricultural use,
E	forest stands existing at the start of the projection,
F	crop and livestock production,
FA_{MAX} AF_{MAX}	maximum area of land in forestry suitable for agriculture and land in agriculture suitable for forestry, respectively,
FTA	land moved from forestry to agriculture,
$H(F,S)$	yield of agricultural products from crop/livestock and secondary processing,
i	discount rate,
I	intensity of forest management,

L	price-sensitive inputs used in crop and livestock production as a function, I, of crop/livestock output (F),
$M(E,R,I)$	costs of harvest, planting and product shipment,
$O(F,S)$	costs of producing, processing and shipping agricultural products dependent on crop/livestock and secondary product output,
$P(E,R,I)$	regeneration of forest areas E and R at various management intensities, I,
$P_A(A)$	price dependent demand function for agricultural products,
$P_F(C)$	price dependent demand function for products from the domestic forest sector,
R	forest stands regenerated since the start of projection,
S	secondary agricultural processing,
$S_L(L)$	supplies of price-sensitive inputs used in crop and livestock production (irrigation water and labor),
T_C	target carbon flux.
$\Delta C_F, \Delta C_A$	changes in carbon inventory (carbon flux) on forest and agricultural lands, respectively,

The model was formulated and solved in the GAMS programming system (Brooke, Kendrick, and Meeraus, 1992).

Figure 1. Carbon flux trajectories for base case and selected targets.



Footnotes

1. The 1997 Climate Action Report (U.S. Department of State, 1997) recognizes that, due to funding limitations, forest sector actions are likely to achieve additional annual sequestration of only .4 Mmt by 2000 (rather than 10 Mmt) and 2.2 Mmt by 2010.

2. Studies include Moulton and Richards (1990), Adams et al (1993), Parks and Hardie (1995), Richards, Moulton, and Birdsey (1993), Sedjo et al (1995), and Stavins (1996).

3. Examples of the former approach include Moulton and Richards (1990), Parks and Hardie (1995), and Stavins (1996). Efforts to measure costs in a market context are less numerous and include Adams et al (1993).

4. For example, the demand for softwood sawtimber, the largest single volume category, is 2-3 times larger than comparable functions in the TAMM model.

5. The "fate" of carbon in different types of forest products influences the time path of carbon stocks. Thus the mix of forest products produced and used is a further issue in forest carbon policy. The three classes of products in the present model (sawlogs, pulpwood and fuelwood) have markedly different patterns of carbon storage and release in consumption. These patterns influence forest management and land transfer decisions in our model but we do not consider constraints on product mix as a policy tool in the present study.

6. Reforested stands refer to forest lands that are harvested and replanted or allowed to regenerate naturally. Afforestation refers to planting of lands previously in some non-forest use.

7. In the initial decade, softwoods comprise some 33.4% of the total timberland base of about 340 million acres. A reduction in softwoods from 33.4% to 32.4% (and a corresponding increase in the hardwood area from 66.6 to 67.6%) in the early periods of the projections would represent a movement of about 3.4 million acres. Thus, while the percentage shifts are small, the area changes involve millions of acres.

8. This outcome is similar to the findings of van Kooten et al (1995), though we do not place any explicit value on carbon flux as in their equilibrium rotation analysis.