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Potential impacts of carbon taxes on carbon flux in western Oregon private forests

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Abstract

This study considers a carbon tax system as a policy tool for encouraging carbon sequestration through modification of management in existing forests and examines its welfare impacts and costs of the carbon sequestered. The simulated carbon tax leads to reduced harvest and increased carbon stock in the standing trees and understory biomass. Changes in the level of silvicultural investments vary by owner, depending on the nature of their initial inventory. In general investment under the tax is concentrated in regimes that establish faster growing plantations. Average rotation age increases, varying in extent across ownerships and site qualities. The carbon tax reduces both consumer and producer surpluses in regional timber markets. Producers are compensated by the carbon subsidies, except at low carbon tax levels. Not all rates of carbon tax will attract interest from private owners if participation is voluntary. Estimates of the marginal cost of sequestering carbon in western Oregon private forests are shown to be within the range of costs for projects considering afforestation alone in some eastern regions of the United States.

Keywords: Carbon tax; Carbon sequestration; Market welfare; Marginal costs; Cost-effectiveness

1. Introduction

Human activities have increased the atmospheric concentrations of greenhouse gases, including carbon dioxide, primarily through the combustion of fossil fuels, agricultural production, and land-use changes (IPCC, 2001). Terrestrial ecosystems have been important sources and sinks of atmospheric carbon. Roughly half of terrestrial carbon is stored in forest vegetation as biomass and in organic soil, carbon pools which are subject to decrease or increase as a result of harvest, regrowth, or conversion to other land uses. Historically, changes in land use have been major factors affecting terrestrial carbon sinks. From 1850 to 1998, global changes in land use resulted in net cumulative CO_2 emissions estimated to have been 33% of total global emissions (IPCC, 2000). In the United States, Houghton et al. (1999) estimated that changes in land use released about 25 Pg of carbon to the atmosphere over the period 1700–1990 largely from the conversion of forests to agricultural lands.

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Several policies associated with forest land use and land-use change have been suggested as approaches to climate change mitigation. Particular attention has been given to afforestation projects on marginal agricultural lands (see Richards and Stokes, 2004). Shifts in management activities in existing forests can also enhance carbon uptake, through modification of silvicultural practices, longer rotation ages, and preservation of forestland from conversion. In regions where there is little agricultural land available to afforest and where land-use patterns are relatively stable, modifying management practices in existing forests may be the only feasible approach to significantly increasing forest carbon flux.

This study examines the welfare costs of a carbon tax and subsidy program (hereafter referred to as carbon tax) for enhancing the sequestration of carbon on the existing private forest land base. Under the carbon tax, forest owners are subsidized for the carbon they accumulate and taxed for the carbon released by harvesting. We develop a theoretical model of a forest owner's response to the carbon tax and demonstrate how the forest owner will adjust harvest in various circumstances. To develop specific case estimates of the impacts of the carbon tax on harvest and management actions and to examine the cost-effectiveness of the carbon tax as a mitigation option in the forestry sector, we employ a model of the log market in the western part of the state of Oregon, USA. This is a region with very limited options for afforestation. We derive the marginal costs of carbon sequestration in existing private forests in western Oregon and compare our results with those of previous studies that have looked solely at afforestation projects.

2. Past studies

Some past studies have included options for modifying management practices in existing forests as well as afforestation projects in their estimates of carbon sequestration costs. For the U.S., Adams et al. (1999) showed that large near-term carbon increments could be obtained by changing management actions in existing forests, while reaching long-term carbon flux targets depended heavily on afforestation. In a global study of carbon pricing, Sohngen and Mendelsohn (2003) projected that under the "expected" case of rising carbon prices, 36% of the incremental carbon sequestered in mid-high latitude forests would result from shifts in management activities on existing forests by 2100. The remainder would be due to afforestation.

Several policy mechanisms can be employed to sequester carbon in existing forests, which Richards et al. (1997) classify as either direct or indirect. Direct policies include production (i.e., carbon sequestration) on government land, government production on leased land, and input and output regulation on private lands (e.g., mandatory replanting after harvest or limiting carbon emitted through harvesting). Indirect policies are comprised of market-based incentives (e.g., taxes and subsidies and marketable permits) and institutional incentives (e.g., market reforms). On private lands, direct control of carbon storage through regulation is technically possible. In practice, however, it may entail high costs of monitoring and control and it imposes unwelcome restrictions on the owners' rights to use the land. The environmental economics literature suggests that, if properly designed and implemented, market-based instruments are often a more desirable approach, because they encourage individuals to undertake mitigation efforts that are in their own self-interest and that collectively achieve policy goals (Stavins, 2003).

Several studies have considered the carbon tax in the context of a single stand (van Kooten et al., 1995; Hoen and Solberg, 1997; Murray, 2000) and have investigated its effects on carbon sequestration and management activities in existing stands (Alavalapati et al., 2002) and on afforestation projects (Tassone et al., 2004; McKenney et al., 2004). At the forest level, Backéus et al. (2005) derived a trade-off curve between timber harvest and carbon storage over a large region, in a model where harvest is determined so as to maximize net present value given fixed future wood prices and carbon taxes. These studies find that inclusion of the subsidy revenues from carbon uptake results in longer rotation ages than in the absence of the carbon tax. To explain harvest decisions, these studies have commonly employed a variant of the Hartman (1976) model, which maximizes the present value of net returns from timber and carbon sequestration over all future rotations. This approach describes the impacts of the carbon tax on decisions and economic returns at the stand level, but does not consider impacts broadly on producers and consumers in a market where the tax is applied to all landowners over multiple time periods. Further analysis is needed to measure the change in social benefits (consumer and producer surpluses) caused by the carbon tax together with any price and/or income changes that may result (Cropper and Oates, 1992).

For policy makers, some measure of the cost-effectiveness of carbon sequestration programs suggested for the forestry sector is critical in considering the role of forest carbon policies in regional or national strategies to meet net emission targets. As Parks and Hardie (1995) argue, direct monetary incentives should be provided for the program that accomplishes the greatest sequestration of atmospheric carbon per dollar spent. Hoen and Solberg (1994) estimated the marginal cost of sequestering an additional unit of carbon in terms of the present value of timber revenues foregone from producing different levels of discounted carbon sequestration in existing forests. Murray (2000) also estimated the stand level marginal opportunity costs of the carbon tax for three forest types as the ratio of reduction in timber value to the change in carbon storage. Both of these approaches demonstrate how much present income from timber production would be lost to sequester an additional unit of carbon. Like the studies noted above, however, they do not provide information on costs incurred by other market participants or reflect market adjustments to harvest changes.

3. A theoretical model of private owner response to the carbon tax

Suppose a forest owner holds forests across a range of ages and its goal is to maximize present net income from growing trees over time.[1] Initial inventory is given by v_0 and a fixed amount of inventory of standing trees, $\bar{v}$, remains at the end of the final period. The timber growth is represented by a strictly concave function of the post-harvest stock of standing trees, $F(v)$. Assume that government introduces the carbon tax that pays a subsidy for carbon uptake in the standing trees, but levies a tax for carbon emission by harvesting, with a specific tax level at each time t. Under this mechanism, the forest owner's problem is to find the optimal harvest schedule, (H_1^*, H_2^*, H_3^*), that maximizes present value of income from timber production plus the net subsidy from carbon sequestration over time subject to constraints on the growing stock of timber and harvest limits for each period. That is,

$$\begin{aligned}\underset{\{H_1,H_2,H_3\}}{\text{Maximize}}\ \pi = {} & p_1H_1 + \frac{1}{1+r}p_2H_2 + \frac{1}{(1+r)^2}p_3H_3 \\ & + p_1^c\alpha F(v_0) - p_1^c\alpha H_1 + \frac{1}{1+r}p_2^c\alpha F(v_1) \\ & - \frac{1}{1+r}p_2^c\alpha H_2 + \frac{1}{(1+r)^2}p_3^c\alpha F(v_2) \\ & - \frac{1}{(1+r)^2}p_3^c\alpha H_3 \qquad (1)\end{aligned}$$

$$\begin{aligned}\text{s.t.}\quad & v_1 = v_0 + F(v_0) - H_1 > 0 \\ & v_2 = v_1 + F(v_1) - H_2 > 0 \\ & v_3 = v_2 + F(v_2) - H_3 = \bar{v} \\ & H_1, H_2, H_3, \geq 0\end{aligned}$$

where p_t is the stumpage price at time t, p_t^c is the tax level ($/tonne) at time t, α is tonnes of carbon per unit tree biomass, and r is the discount rate of the owner. The first three terms of the objective function represent the present value of net income from timber production and the remaining terms indicate the present value of subsidies and taxes on carbon flux. The tax in this case is levied on the "observable" or simple periodic carbon change in the forests.[2]

In problem (1), constraints on the first and second harvests are nonbinding, only the third constraint is active, and the third-period harvest can be expressed in terms of the first and second harvests. Thus, by substitution, problem (1) can be expressed as a function of H_1 and H_2 alone. Differentiating with respect to H_1 and H_2 and setting the results equal to zero, the first order conditions appear (after rearrangement) as:

$$\begin{aligned}p_t - p_t^c\alpha = {} & \frac{1+F'(v_t)}{1+r}[p_{t+1} - p_{t+1}^c\alpha] \\ & + \frac{1}{1+r}p_{t+1}^c\alpha F'(v_t) \qquad \text{for } t = 1, 2. \qquad (2)\end{aligned}$$

[1] The model includes only three explicit periods. Ovaskainen (1992) discusses the generalization to any number of periods.

[2] The objective function of the maximization problem (1) can also be expressed as: $\pi = p_1H_1 + \beta p_2H_2 + \beta^2p_3H_3 + p_1^c\alpha(v_1 - v_0) + \beta p_2^c\alpha(v_2 - v_1) + \beta^2p_3^c\alpha(v_3 - v_2)$, where it is clear that the tax/subsidy is paid on the observed period to period change in inventory.

With a non-zero carbon tax, the left-hand side of condition (2) is the marginal revenue of current harvest expressed as timber income less the tax for carbon emission by harvesting and the right-hand side is marginal cost of delaying current harvest which is the discounted after-tax income from harvest plus the subsidy for incremental carbon accumulated by postponing current harvest.

When stumpage prices are the same as the no-tax baseline (as is assumed in past studies at the stand level), condition (2) indicates that the optimal harvest is determined by the carbon tax levels in current and future periods. If the carbon tax level is constant over time, condition (2) can be expressed as follows.

$$p_t = \frac{1+F'(v_t)}{1+r}p_{t+1} + \frac{r}{1+r}p^{c}\alpha \quad \text{for } t=1,2. \qquad (3)$$

Since the fraction $0<(r/1+r)<1$ for $r>0$, Eq. (3) indicates that the marginal opportunity cost (the right-hand side) increases relative to the base under the constant tax. Thus, the following conditions should be satisfied.

$$F'(v_t^{*})<F'(v_t^{B}),\ v_t^{*}>v_t^{B},\ \text{and}\ H_t^{*}<H_t^{B} \qquad \text{for } t=1,2,$$

where v^{B} and H^{B} are the post-harvest stock of standing trees and harvest without the carbon tax and v_t^{*} is the optimal stock with the carbon tax. Since the growth function is assumed to be concave (i.e., $F''(\cdot)<0$), the post-harvest stock of standing trees under the carbon tax is greater than that of the baseline. That is, the forest owner will reduce harvest relative to the baseline level in a process similar to lengthening the optimal rotation age at the stand level. In addition, as the carbon tax increases, harvesting appears less profitable.

Now suppose that the carbon tax rises at the compound rate $\delta>0$, so that $p_t^{c}=p^{c}(1+\delta)^{t}$. Rising rates might be introduced if anticipated damages from global climate change rise in the future (see, for example, Table 6.11 in Pearce et al., 1996; Sohngen and Mendelsohn, 2003). Then, condition (2) can be rewritten as follows.

$$p_t = \frac{1+F'(v_t)}{1+r}p_{t+1} + \frac{r-\delta}{1+r}p^{c}\alpha \qquad \text{for } t=1,2. \qquad (4)$$

If the rate of increase of the carbon tax is equal to the discount rate, Eq. (4) indicates that the optimal conditions both with and without the carbon tax are identical and the harvest levels of both cases are equal. If the rate of increase of the tax level is less than the discount rate, then the net subsidy is positive and harvest is smaller than the baseline. In contrast, when the carbon tax rises faster than the discount rate, the marginal opportunity cost of postponing harvest decreases and more harvest will occur than in the baseline. That is, at least in the short-run, if the rate of increase of the carbon tax is greater than the adjusted discount rate, forest carbon stock will decline.

Similar results are obtained for an owner that maximizes utility derived from consumption of both priced and non-priced goods, if the utility function is additively separable in the utility derived from both goods (for an example see Ovaskainen, 1992, p. 48). In this case the carbon tax reduces harvest relative to the no-tax baseline, and the same conclusions hold as for the present value objective when the tax level rises. In more complex utility formulations, it is often not possible to establish signs of responses to the tax *a priori*.

4. Empirical model

In timber markets, forest owners' decisions on management under the carbon tax are realized as changes in total supply of timber from private lands. From a policy maker's perspective then, timber market responses are an important concern in evaluating the overall impacts of a carbon policy. In this paper, we developed a market-level model integrated with the carbon tax based on the western Oregon portion of a timber market model described by Adams and Latta (2006).

The regional willingness to pay for logs by wood processors is computed under the derived demand function for logs in the production of lumber and plywood in western Oregon. Producer surplus for forest owners is implicitly obtained from revenue from timber sales less all costs for timber production such as harvesting, log transport, and silvicultural practices. Thus, the total area under the demand curves less costs of management, harvesting, and transport yields Samuelson's (1952) "net social surplus" denoted by

$$\mathrm{NSS}_t(Q_t,K_t,S_t) = \int_0^{Q_t} P_t(q,K_t)\mathrm{d}q - \mathrm{CH}_t(S_t) \qquad (5)$$

where $P_t(q, K_t)$ is the timber demand function in period t, Q_t is total western Oregon timber consumption in period t, K_t is the quantity of capital stock in period t measured as maximum log processing capacity, and S_t is total supply of timber from western Oregon private forests in period t. Timber supply or harvest, in turn, is determined by the combination of land and management regime allocations to two categories of land: X_t, the area of existing stands at the start of the projection allocated to various management regimes that are to be harvested in period t, and N_t, the area of new stands regenerated after the start of the projection allocated to the various management regimes that are to be cut again in period t.

Ignoring current and future emissions of carbon in woody debris and dead trees already on the ground, subsidies (or taxes) would be paid to (or by) forest owners according to the change of carbon stock in the standing trees and understory. We assume that all private forest owners in western Oregon will participate in the carbon tax program and overall social welfare can be computed simply as the sum of net social surplus in timber markets and social benefits from carbon sequestration. That is, net subsidy at period t, $NS_t(X_t, N_t)$, is expressed as

$$\mathrm{NS}_t(X_t, N_t) = \sum_{j=1}^{J} p_t^{\mathrm{c}}[\mathrm{CS}_{j,t}^{\mathrm{F}}(X_t, N_t) - \mathrm{CS}_{j,t-1}^{\mathrm{F}}(X_{t-1}, N_{t-1})] \quad (6)$$

where $\mathrm{CS}_{j,t}^{\mathrm{F}}$ is the carbon stock in the post-harvest stock of the standing trees and understory biomass in the management unit j at period t. Carbon stock is estimated by combining forest inventory data on merchantable stand characteristics with biomass/merchantable volume ratios and carbon densities for various components of stand biomass and the soil (Hoover et al., 2000).

We assume that regional wood processors can adjust their mill capacity (capital stock) to changes in regional factor costs to ensure their competitiveness in national wood products markets. Capacity adjustment is assumed to entail costs following a two-tier scheme. All operating capacity which limits log consumption by wood processors incurs a minimum per unit maintenance expenditure, k_{m}, in each period. Capacity expansion or investment, E_t, entails higher costs per unit, k_{u}. Both costs are deducted from the market surplus objective function.

The market equilibrium problem, therefore, comprises a discrete time optimal control problem with control variables X_t, N_t, and E_t and dynamics given by the constraints on the disposition of the total inventory area among management–harvesting activities, demand–supply balance, and capacity adjustment.[3] A simple mathematical form of the intertemporal market model is:

$$\begin{aligned}
&\underset{\{X_t,N_t,E_t\}}{\text{Maximize}} \sum_{t=0}^{T} [\mathrm{NSS}_t(Q_t, K_t, S_t) + \mathrm{NS}_t(X_t, N_t) - k_{\mathrm{m}}K_t - k_{\mathrm{u}}E_t](1+r)^{-t} \\
&\text{s.t. } \sum_t X_t = A \qquad \text{Allocation of existing area} \\
&\sum_{t \leq j} N_{t,j} \leq X_t + \sum_{k<t} N_{k,t} \ \forall t \qquad \text{Future area of even-aged stand} \\
&S_t = X_t V_t^{\mathrm{X}} + \sum_{k<t} N_{k,t} V_{t-k}^{\mathrm{N}} \ \forall t \qquad \text{Harvest} \\
&Q_t = S_t \ \forall t \qquad \text{Demand-supply balance} \\
&K_t = (1-\tau)K_{t-1} + E_t \ \forall t \qquad \text{Capital stock investment} \\
&\lambda K_t \geq Q_t \ \forall t \qquad \text{Log consumption limit}
\end{aligned} \quad (7)$$

where A is the total inventory area, V_t^{X} is the vector of volume for existing stands at period t, V_t^{N} is the vector of volume for regenerated stands before t periods, τ is depreciation rate of capital stock (capacity), and λ is the minimum capital stock utilization rate.

The market model described to this point treats both industrial and nonindustrial private forest (NIPF) owners as present value maximizers, setting rotation ages so as to maximize the land expectation value of stands. Previous studies of NIPF management objectives, however, have found that non-market outputs of forests are an important concern for these owners as well as net discounted revenues (Kuuluvainen et al., 1996; Kline et al., 2000). To mimic the effects of these more diverse objectives, we assume that NIPF owners restrict their harvests so as to maintain larger proportions of older stands in their inventory than is the case for industrial owners. This restriction is implemented by constraining the proportions of both young and mature forests in future inventories to fall within the bounds observed in historical NIPF inventory data.

Projections are made for 100 years with a 5-year time step. In this paper, however, we examine only the first 60 years of the projection as the policy-relevant

[3] In practice, additional constraints are required in the model to represent the effects of existing forest policies. Details are given in Adams et al. (2002).

period and to avoid undue influence of the terminal conditions. The simulations reported here use a real discount rate of 6% for all owners. Lower discount rates (e.g., 4%) lead to a reduced near-term harvest in the baseline case (Adams et al., 2002) and thus smaller amount of carbon would be sequestered under the non-zero carbon tax.

5. Results

Using the empirical model described in Section 4, we projected harvest, prices, timber management investment, and wood and carbon inventories on western Oregon private forest lands under a range of fixed levels of the carbon tax (p_t^c \$/tonne) and varying rates of carbon tax growth. These results provide the basis for estimating the impacts of the carbon tax on timber harvest and the costs of carbon sequestration.

5.1. Current carbon stocks and baseline projection

We first consider our model's estimate of the current carbon stock on private lands. Several studies have reported estimates of forest carbon stock for regions that included our study area, but they have all included public as well as private ownerships. As a consequence Table 1 shows estimates by carbon pool on a per hectare basis. Methods differ widely across studies. Heath et al. (2003) and Birdsey and Lewis (2003) use carbon density approaches based on merchantable inventory similar to ours, while Law et al. (2004) produced a carbon budget for the forested region of western Oregon using a spatially nested hierarchy of field and remote-sensing observations and a process model, Biome-BGG. Our estimates are within the range of previous studies for live biomass and soil carbon but well below the range for dead biomass. Apart from differences in the estimation processes used in all studies to approximate the size of this pool, our value may be lower due to the exclusion of public lands with their large areas of undisturbed old-growth stands and high volumes of large woody debris. Summing across all pools, estimates of the total carbon stock from past studies range from 220 to 388 tonnes/ha. Our total is 219 tonnes/ha.

The baseline projection provides an estimate of carbon stock and harvest potentials of western Oregon private forests when there are no changes in current regulatory policies or market conditions and no carbon tax. Simulation results show that total estimated carbon stock of western Oregon private forests in 2000 is 561 million metric tonnes (Mtonne) gradually rising to 635 Mtonne by 2065, a 13% increment. There is a large net accumulation in the woody debris pool since harvest volumes increase steadily in the near future. At the owner level, carbon stocks on industrial and nonindustrial lands are estimated at 384 Mtonne and 177 Mtonne, respectively, in 2000, increasing to 430 Mtonne for industrial lands and 205 Mtonne for nonindustrial lands by 2065. For the standing tree and understory biomass which is the pool subject to subsidization and taxes, about 153 Mtonne and 89 Mtonne of carbon are stored on industrial lands and nonindustrial lands, respectively, in 2000, increasing to 161 Mtonne for industrial lands and 99 Mtonne for nonindustrial lands by 2065.

Table 1
Alternative estimates of carbon stock (tonnes/ha) from previous studies

	Region/ owners	Area (1000 ha)	Live biomass	Dead biomass	Soil
Heath et al. (2003)[a]	WA+OR+ CA/all	36,486	102.8	45.6	91.1
Birdsey and Lewis (2003)[b]	OR/all	12,027	82.3	42.4	95.2
Law et al. (2004)	Western OR/all	8200	128.6–196.8	38.4–49.5	111.9–142.4
This study	Western OR/ private only	2569	91.2	29.6	97.7

[a] Estimates of carbon stock for Pacific coast region in 1997.
[b] Estimates of carbon stock for Oregon in 1997.

5.2. Change in average harvest and carbon storage

Implementing the carbon tax system, Table 2 illustrates that there is some reduction in harvest and increase in average carbon stock in the standing tree and understory biomass for both owner groups at all tax levels. For low carbon tax levels, average harvest declines only modestly because large near-term reductions are offset by harvests in excess of base levels in later periods. Harvest rises in the longer-term in part, because of rapidly accumulating inventory. At higher tax levels, harvest remains below the base for most or all of the first 50 years of the projection.

Several factors including management intensity, catastrophic mortality, and harvest can affect carbon in

Table 2
Average harvest, average carbon stock, and discounted total silvicultural investment under various levels of a carbon tax in western Oregon private forests, 2005–2065

Tax level ($/ tonne C)	Average harvest (million ft^3)		Average carbon stock (million tonne C)		Silvicultural investment (1992 $US million)	
	Industrial	NIPF	Industrial	NIPF	Industrial	NIPF
0	664.6	217.8	148.2	91.6	354.9	75.4
10	653.3	213.2	159.0	96.2	337.4	74.1
20	640.8	212.3	168.4	98.2	328.9	75.4
30	628.4	207.7	179.5	100.7	314.1	76.2
40	613.5	203.9	193.3	104.3	300.1	79.5
50	595.1	200.3	207.7	107.2	292.9	83.5
60	576.9	188.7	223.4	112.0	279.8	87.0
70	559.9	174.0	238.3	115.8	264.6	87.1
80	539.8	165.6	250.8	120.4	246.8	88.9
90	514.7	158.4	264.0	125.5	233.9	89.8
100	494.7	147.0	278.3	129.9	213.6	89.6

forests. Ignoring uncertainties (e.g., forest fire and insects) and holding all inputs constant, the only way to expand carbon storage in standing trees relative to the baseline is to reduce harvests. Timber production and carbon sequestration are multiple outputs competing for the same land base resource. Table 2 provides a trade-off relation between average carbon in standing trees and average timber production. Inspection of the table reveals that industrial lands accumulate more carbon than nonindustrial lands for the same reduction in timber harvest. This is due primarily to the relative productivity of the lands (industry ownerships have higher average site index) and existing age distribution of forests (industry lands have more area in younger age classes).

5.3. Change in investments, management activities and rotation ages

Additional carbon can also be sequestered, without reducing harvest, by modifying forest management practices and investments such as the species of trees planted, fertilization, and site preparation after harvest. From a carbon perspective, planting is preferable to natural regeneration because it allows earlier forest establishment and growth in total biomass (Turner and Long, 1975). In the market model, however, altering management regimes to increase carbon storage involves costs which lower net social surplus (see Eq. (5)). Thus, the *a priori* effects of the modification of management regimes and investments caused by the carbon tax are ambiguous.

The distribution of existing and newly planted area (X_t and N_t) across silvicultural regimes over time is endogenous in our model. Projected discounted total investments for silvicultural activities by ownership are shown in Table 2. These include costs for site preparation, planting, and management for precommercial thinning and fertilization. As private forest owners reduce harvest in the presence of the carbon tax, total private investment also contracts, but the responses differ by ownership. Industrial owners, owning younger and higher productivity forests, reduce their investment primarily by abandoning regimes that involve treatment beyond regeneration. For a carbon tax of $100, anticipated investments decline by nearly 40% relative to the base case, shifting more regeneration activity into plantations rather than natural seeding. Carbon sequestration benefits also encourage NIPF owners' to concentrate activity in plantations, but the result is an expansion of investment by nearly 20% relative to the baseline at the $100 tax level. Note that Sohngen and Mendelsohn (2003) found a net increase in private investment in mid-high latitudes in their global analysis.

To illustrate the effects of the carbon tax on management activities, Table 3 shows the projected percentage of area by broad type of silvicultural regime for existing and new stands in 2065. For new stands, the proportion of lands allocated to intensive management regimes declines because of the higher near-term carbon taxes even though these promise higher yields and more carbon subsidies in future years. Area allocation to "Regen only" plantation stands increases to more than 50% at a $100 carbon tax, since the potential subsidies overweigh plantation costs. In contrast, natural regeneration is less costly but carbon returns are delayed, so this regime is less preferable at high carbon tax levels. The large increases in the share of "Grow only" in existing stands reflect these same considerations. Partial cutting rises, in part, because it allows higher rates of carbon sequestration while avoiding a clearcut and the high tax payment.

Given the benefits of carbon subsidies, forest owners reduce harvest relative to the baseline and, as the carbon tax level rises, the optimal rotation increases. Our results on the area-weighted average rotation ages for various carbon tax levels are shown in Fig. 1. With the exception

Table 3
Percent of timberland area allocated to management intensity classes in 2065 in western Oregon private forests

Tax level ($/tonne C)	Existing stands			New stands			
	Grow only	Intensively managed	Partial cutting	Naturally regenerated stands		Planted stands	
				Regen only	Intensively managed	Regen only	Intensively managed
0	7.5	1.5	7.3	28.8	15.5	16.9	22.5
10	9.0	0.7	6.6	34.0	10.2	16.6	22.9
20	9.6	0.6	7.0	36.0	6.8	17.7	22.4
30	10.0	0.7	8.0	38.7	3.3	18.0	21.4
40	10.8	0.8	8.7	37.5	1.2	21.5	19.6
50	10.6	0.8	11.2	32.0	0.6	29.1	15.7
60	11.7	0.8	13.1	26.2	0.3	35.2	12.8
70	13.5	1.2	14.7	21.2	0.2	40.5	8.8
80	15.3	1.2	14.7	18.9	0.1	43.8	6.0
90	18.0	1.3	14.2	15.4	0.1	48.0	3.0
100	20.4	1.8	14.0	13.0	0.1	49.6	1.2

Note: "Intensively managed" represents the areas receiving precommercial and commercial thinning and fertilization, while "Regen only" represents the areas with no other management activities after regeneration. Percentages sum to 100 across the columns, reflecting the allocation of the full private land base in 2065.

of low site quality lands, there are significant differences in rotation age changes by owners and land quality.[4] Rotation age on industrial lands is more sensitive to the carbon tax than on nonindustrial lands. Rotation is particularly sensitive to changes in the tax on low site quality lands at low tax levels. Some single stand studies have found that it may be socially optimal never to harvest stands under very high carbon tax levels. This effect can be seen in Table 3 as larger and larger percentages of the total private land base remaining in "Existing stands" in the "Grow only" regime as the tax level rises.

5.4. Change in welfare and cost-effectiveness of the carbon tax

In this study we differentiate between the direct and indirect costs induced by the carbon tax.[5] Direct costs are the net subsidies or net financial input of the government for achieving a specific level of carbon sequestration, while indirect costs are changes in net social surplus in timber markets which are not intended by the carbon tax policy. The simple theoretical model of the forest owner's harvest decision in Section 3 showed that, at least in the short-run, the forest owner will reduce harvest levels under the carbon tax. As a result the aggregate supply of timber from western Oregon private forests is expected to decline. In regional timber markets, this reduction causes a loss of net social surplus (i.e., indirect cost) which is offset by the net subsidy from carbon sequestration (i.e., direct cost) transferred to forest owners.

Under the carbon tax, the regional timber supply curve shifts leftward since forest owners reduce their harvest levels. Responding to a decrease in timber supply, regional wood processors adjust their milling capacity, which leads to a leftward shift in the timber

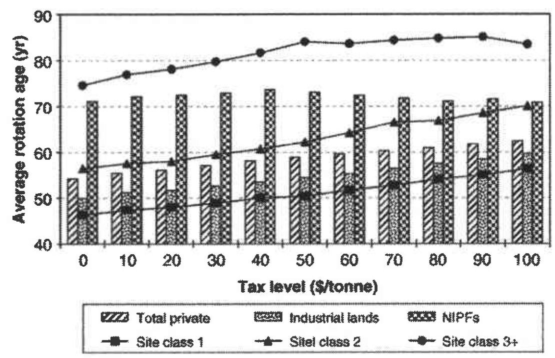

Fig. 1. Average rotation age relative to the baseline by owners and site classes in western Oregon private forests, 2005–2065.

[4] Since most of the low-productivity stands are allocated to partial cutting or reserved lands at high carbon tax levels, change in the average rotation age on these lands is small.

[5] The levelization/discounting approach is employed for benefits and costs of carbon sequestration to account for the timing differences of costs and carbon capture. See Richards and Stokes (2004).

Table 4
Annualized change in welfare, net subsidy, and carbon sequestration and the marginal and average costs under the carbon tax in western Oregon private forests, 2005–2065

Tax level ($/tonne C)	Market surplus ($ million)		Net subsidy ($ million)	Carbon sequestration (1000's tonnes C)	Marginal project cost ($/tonne C)	Marginal social cost ($/tonne C)[a]	Average project cost ($/tonne C)	Average social cost ($/tonne C)
	Consumer surplus	Producer surplus						
0	0.0	0.0	0.0	−308	0.0	0.0	0.0	0.0
10	−0.9	−3.0	1.8	182	3.7	11.6	3.7	11.6
20	−1.7	−8.6	11.0	550	25.0	42.5	12.8	24.9
30	−14.0	−16.9	28.6	952	43.7	94.8	22.7	47.2
40	−38.4	−31.6	59.7	1492	57.6	130.2	33.2	72.1
50	−66.3	−48.5	99.8	1996	79.6	168.7	43.3	93.2
60	−104.2	−74.8	157.0	2617	92.1	195.4	53.7	114.9
70	−139.0	−100.4	219.6	3137	120.3	236.3	63.7	133.2
80	−175.0	−128.3	291.3	3641	142.2	268.9	73.8	150.6
90	−215.0	−160.3	374.1	4157	160.7	300.4	83.8	167.8
100	−260.5	−197.4	470.1	4701	176.4	328.5	93.9	185.3

Note: All monetary amounts are in 1992 dollars; annualized consumer and producer surplus of baseline is $992 and $1597 million, respectively; discount rate is 6%.

[a] Marginal social cost=(decrease in net social surplus+increase in net subsidy)/(increase in carbon sequestration).

demand curve. As a result, there is a change in the welfare (surplus) positions of market participants. As shown in Table 4, introduction of a carbon tax leads to reductions in both consumer and producer surplus. In regional timber markets, timber consumers (wood processors) are always made worse off due to contracting timber supply and rising prices, while timber producers (forest owners) are better off despite lower harvest as a result of the net subsidy payments (producer surplus+net subsidy>0) except at carbon taxes of $20 per tonne or less. In this latter case, producer losses exceed the subsidy (Table 4). If the program were voluntary it presumably wouldn't be adopted for carbon prices in this range.

The hypothetical carbon tax in this study pays owners for changes in the carbon in standing trees and understory biomass, what we've termed "observable" carbon. But some of this carbon would have been sequestered in the absence of the program, so estimating the program's actual carbon costs requires comparison of expenditure with any carbon increments above the baseline or "additional" carbon. Specifically, marginal costs are estimated by the ratio of change in discounted costs to the change in additional carbon sequestration. We compute two marginal costs: marginal project costs and marginal social costs. The former represents the marginal cost of actual government spending (i.e., direct costs) to achieve a given level of carbon sequestration, while the latter indicates the marginal cost that society (including regional wood processors) face. It is computed as the change in net social surplus (i.e., direct and indirect costs). Table 4 provides estimates of both average and marginal costs computed in both ways. Marginal and average social costs are substantially higher than the marginal project costs because of the inclusion of consumer and producer losses.

Most past studies on the costs of carbon sequestration in the forest sector differ markedly from ours in methods, geographic scope and assumptions, and nearly all have focused on afforestation of agricultural land as the vehicle for raising net carbon flux. Recent reviews have surveyed

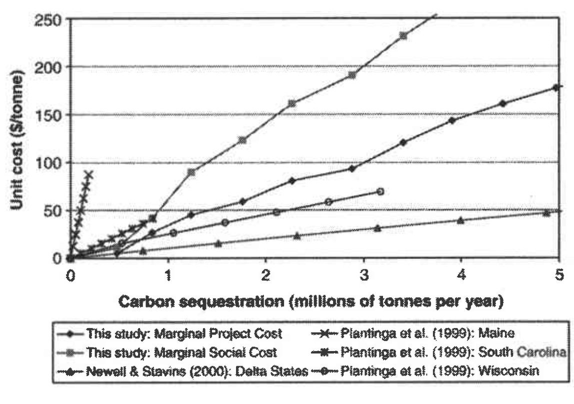

Fig. 2. Marginal cost curves of carbon sequestration in western Oregon private forests, 2005–2065, with comparisons to results from selected studies examining states and regions.

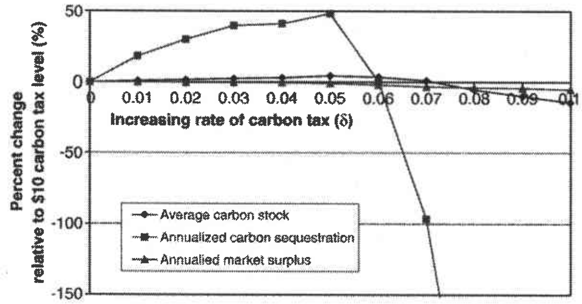

Fig. 3. Effects of increasing carbon tax on carbon sequestration and market welfare in western Oregon private forests, 2005–2065. Tax rises at rates δ from \$10/tonne.

these results in an attempt to draw some generalizations about the potential costs of forest carbon sequestration policies (van Kooten et al., 2004; Richards and Stokes, 2004; Stavins and Richards, 2005). To compare the cost-effectiveness of the carbon tax policy for existing private forests in western Oregon, the marginal cost curves in Table 4 were recalculated using the normalization procedure suggested by Stavins and Richards (2005).[6] Fig. 2 shows the marginal cost curves for this study and two previous studies on carbon sequestration costs at the state or regional level using afforestation alone (Stavins, 1999; Newell and Stavins, 2000; Plantinga et al., 1999). The costs of sequestering carbon in existing private forests in western Oregon lie between Plantinga et al. (1999) for Wisconsin and above those of Newell and Stavins (2000) for Mississippi Delta counties at very low rates of sequestration and in the general range of the Plantinga et al. findings for higher rates.

5.5. Effect of a rising carbon tax

Both the total incremental carbon that accumulated with the carbon tax as well as the timing of the flux increments are important. Since the benefits and costs obtained from carbon sequestration are discounted, a constant carbon tax level over time implies that carbon sequestered in current or near-term periods is more valuable than in the future. In contrast, future carbon uptake is emphasized by a rising carbon tax over time. Several studies using integrated assessment models to compute economically efficient policies to mitigate climate change have estimated that marginal damages from carbon emissions would rise over time (Pearce et al., 1996; Sohngen and Mendelsohn, 2003). van 't Veld and Plantinga (2005) argued that these findings may support mitigation policies that employ carbon prices rising at roughly the same rate as damages. Our simple model for a forest owner's harvest decision shows that if the carbon tax level is expected to increase over time above a certain critical rate, at least in the short term, more harvest will occur, which leads to reducing carbon stocks relative to the baseline case. Recent studies have also found that rising carbon prices over time provide incentive to delay carbon sequestration projects and as a result, optimal carbon sequestration under rising carbon prices will supply less than that of a constant price case (van 't Veld and Plantinga, 2005).

We simulated the western Oregon model with different rates of tax growth to examine the effects on carbon sequestration and regional timber markets. Fig. 3 presents the percent change in average and annualized carbon sequestration and market welfare (both annualized as in the previous section) relative to the constant \$10 carbon tax case. Within a range of increasing rates, more carbon is sequestered relative to the constant tax case. Higher rates of increase, however, result in a net reduction in both the average and annualized carbon sequestered relative to the constant tax case, as near-term flux is reduced and long-term flux increased. Although, in initial and near-term periods, increased regeneration harvest may lower total surplus as a result of large carbon taxes, under the high rate of tax increase, future carbon benefits from these regenerated stands may be large enough to outweigh the initial loss. The impacts of a rising carbon tax on market welfare are relatively small. The net social surplus (consumer and producer surplus) in regional timber markets declines slightly as the rate of increase of the carbon tax rises.

6. Discussion

This study considers the carbon tax as a policy tool for encouraging carbon sequestration in existing forests (no afforestation options) and examines its welfare and carbon sequestration costs. When both carbon revenues

[6] All costs were converted to 1992 dollars using the U.S. Consumer Price Index. Carbon sequestration estimates were converted to equivalent annual carbon flows over a 60-year time horizon, and a 5% discount rate was applied.

and costs are included in forest management decisions, forest owners will reduce their planned harvests and investments and lengthen the average rotation. Both regional wood processors and forest owners suffer surplus losses in timber markets, but the latter will be at least partially subsidized by carbon payments.

Our results differ from, and extend, past findings in several important ways:

i) Initial inventory conditions and growth potential (site quality) can markedly alter the carbon sequestration–timber harvest trade-offs, as we saw in comparing industrial and NIPF ownerships.
ii) Silvicultural investments will change in response to a carbon tax, with variations depending on inventory and growth potential of the land base.
iii) Modifications of management on existing forest land in western Oregon can be cost competitive with afforestation in sequestering additional forest carbon, even when costs include losses of net social surplus in regional timber markets not considered in other studies. The land productivity and high growth rates of forests in western Oregon relative to other U.S. regions provide the opportunity to consider the carbon tax as a regional mitigation policy in the forestry sector.
iv) Not all rates of carbon tax will attract interest from private owners if participation is voluntary. Results in Table 4 indicate that a carbon tax lower than $20 per tonne would not offset private owner losses. This is obtained because a net reduction in carbon stock of the standing trees and understory biomass is expected in the baseline by 2042. As a result owners face a steady stream of near-term tax payments that outweigh the prospect of future subsidy gains until the tax rate exceeds $20/tonne — the gains from lengthening rotation must exceed near-term tax payments. In contrast, when net carbon is sequestered in the baseline, forest owners are willing to participate in the policy even for a very low carbon tax.

This outcome emphasizes the complex and controversial nature of identifying the baseline carbon flux – as recognized in post-Kyoto deliberations – because of non-uniqueness, uncertainties, and leakage (IPCC, 2000; Chomitz, 2002). In practice, the baseline may be determined by a negotiation process between forest owners participating in the carbon tax program and the government implementing it (Sohngen and Mendelsohn, 2003).

Finally, in considering our results it must be recognized that this study provides only partial equilibrium analysis of carbon sequestration and timber markets. The effects of the carbon tax are examined only in the western Oregon timber markets and carbon in western Oregon private forests that are directly affected. Leakage may be expected if we consider the project within a broader spatial or temporal context such as carbon in woody residue in forests, forest products and landfills and the carbon stock of other region's forests (Chomitz, 2002; Aukland et al., 2003; Murray et al., 2004).

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