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ANALYSIS

Carbon sequestration and the optimal management of New Hampshire timber stands

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A B S T R A C T

This paper explores the tradeoff between resource extraction and net carbon sequestration in managing representative timber stands in the state of New Hampshire in the northeastern United States. In the absence of policies to promote forest carbon storage, land owners have incentives to employ clear-cut harvesting regimes with relatively short rotation periods. Under conservative assumptions regarding the social benefits of carbon storage, optimal rotation periods are extended by between 16 and 133 years depending on the forest type under consideration. If policy-makers pursued a cost-effective strategy to stabilize atmospheric carbon dioxide concentrations at twice the pre-industrial norm, optimal rotation periods would be extended by a full 180–347 years. The analysis suggests that partial harvesting regimes (in which approximately 35% of timber volume is removed at 15-year intervals after the timber stand reaches an initial age of 45 years) provide relatively high net benefits under a variety of circumstances. This finding is relevant because partial harvesting is an accepted and relatively common practice that could be adopted more widely.

1. Introduction

Under the procedures established by the Kyoto Protocol, nations may offset carbon dioxide emissions by implementing projects and policies that enhance net carbon storage in forests. Although it withdrew from the Kyoto accord in March of 2001, the United States played a key role in negotiating the inclusion of emissions offsets in the emerging international climate change regime. In December of 2005, the governors of New Hampshire and six other northeastern states agreed to reduce their states' carbon dioxide emissions using a cap-and-trade framework focusing on the power sector (RGGI, 2005). In achieving this objective, the role of forest-sector emissions offsets is a continuing point of discussion.

In this paper, we consider the implications of carbon sequestration for the optimal management of forest resources in the state of New Hampshire. Like the neighboring states of Maine and Vermont, New Hampshire is heavily forested, with some 83% of the landscape covered by second-growth forests (U.S. Forest Service, 2005a). We focus on New Hampshire because variability in ecological and market conditions favors the use of a place-based research strategy. That said, New Hampshire's forests are in many respects representative of those in the surrounding region.

Although New Hampshire was largely deforested in the 18th and 19th centuries to provide timber, agricultural land, and pasture for sheep and other livestock, the subsequent decline of farming and grazing led to the substantial recovery

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of the state's forests. At present, New Hampshire forests are managed to support a mixture of timber harvesting and outdoor recreation. 78% of the state's forestland is privately owned, much of it by small holders who take an informal approach to land management (U.S. Forest Service, 2005a). Timber and paper companies, however, also control significant parcels of land, while 22% of New Hampshire forestlands are owned and managed by government agencies. Taken as a whole, timber extraction yielded net revenues of $34 million in 2002, coupled with downstream benefits in the state's paper, wood processing, and wood products industries (North East State Foresters Association, 2004).

Our analysis builds on the previous work of van Kooten et al. (1995), who incorporated the social benefits provided by carbon sequestration in a simplified model of forest management in the boreal forests of western Canada. In addition to the change in regional emphasis, however, our research extends van Kooten et al.'s analysis in two key respects. First, while van Kooten et al. assumed that the marginal benefit provided by carbon sequestration was fixed over time, here we consider a model in which the benefits provided by carbon sequestration change over time to reflect realistic assumptions about future economic and environmental conditions. Second, van Kooten et al. assumed that forest carbon storage was a simple function of timber volume. Here we adopt a more disaggregated approach that is grounded more directly in forest ecology.

The U.S. Department of Energy (2004) has developed a comprehensive dataset and analytical framework for evaluating the links between forest growth and carbon storage in various regions of the country. Drawing on this source, we construct and explore a streamlined model of timber growth, timber harvesting, and net carbon storage in both forest ecosystems and harvested wood products. Our focus is on representative timber stands in the five major forest types that together account for 96% of New Hampshire forests measured in terms of land area (U.S. Forest Service, 2005a):

- White, red, and jack pine forest (14%)
- Spruce-fir forest (12%)
- Oak-pine forest (7%)
- Oak-hickory forest (8%)
- Maple-beech-birch forest (53%).

The most prevalent forest type – maple-beech-birch forest – is well-known for its fall foliage and its role in the production of maple syrup. In general, New Hampshire's forests are managed to provide a mix of products that emphasizes high-value saw logs from mature trees. The exception is the spruce-fir forest type, which is harvested as a source of pulp for the paper mills of northern New England.

Integrating wood product prices from the New Hampshire Timberland Owners Association database (Paul Sendak, personal communication, 2005) with timber harvest data from the U.S. Forest Service (2005b), we compute average stumpage prices for each forest type that explicitly account for the mix of forest products provided by a given ecosystem and for the economic value of the forest as a function of its maturity at the time of harvest. Based on these assumptions, we are able to evaluate the present-value net benefits of both partial and clear-cut harvesting regimes under varying rotation periods. In our partial harvesting scenario, approximately 35% of timber is removed every 15 years once the timber stand reaches an initial age of 45 years (Rowland, 2001). The consideration of partial harvesting is important because many New Hampshire woodlands are managed on this basis, which allows land owners to reap a periodic stream of timber revenues in a manner that is consistent with maintaining wildlife habitat and aesthetic values (Beattie et al., 1993; Thorne and Sunquist, 2001).

Our study draws on Howarth's (2001) analysis of climate mitigation policy to gauge the anticipated value of carbon sequestration. In this work, global carbon dioxide emissions targets are chosen based on two plausible yet distinct policy regimes. In the first scenario, emissions targets are chosen to maximize the present-value net benefits of emissions mitigation, yielding a marginal abatement cost that rises from $25 to $75/metric ton of carbon (in 2005 dollars) over the course of the next century. In the second scenario, policy-makers aim to limit the atmospheric concentration of carbon dioxide to no more than a doubling relative to pre-industrial levels. In this latter case, specific emissions targets are chosen to minimize the present-value costs of achieving this climate stabilization target, yielding a marginal abatement cost that increases from $227 to $570/ton between 2005 and 2105. As Howarth describes in detail, these two scenarios differ primarily with regard to the approach decision-makers take to questions of intergenerational fairness in the face of scientific uncertainty.

We assume that carbon sequestration by forests provides benefits by reducing the need to restrict the carbon dioxide emissions generated by fossil fuel combustion and industrial production. Hence the marginal benefit of carbon sequestration may be measured in terms of the marginal cost of emissions abatement, assuming that policy-makers seek to minimize the total cost of achieving a given net emissions target (Howarth et al., 1993). This approach is consistent with the view that policy-makers should value the benefits of carbon sequestration in terms of the avoided cost of climate change. On the other hand, it is also consistent with the view that emissions abatement targets should be chosen based on moral principles that are not easily reduced to monetary terms, such as the goal of protecting future generations from poorly understood but potentially catastrophic environmental impacts (Woodward and Bishop, 1995).

2. The model

We consider a model of a typical timber stand in which harvestable timber volume $V(s)$ is an increasing function of stand age (s), or the number of years since the most recent clear-cut harvest. For the moment, we shall assume that the timber stand is periodically clear-cut when the stand age reaches a maximum value s_h that represents the prevailing rotation period that is employed in timber management. In this sense, our model is a patterned after the familiar optimal rotation framework pioneered by Faustmann (1849) and adopted by later authors such as Samuelson (1976). Below, however, we shall extend the model to allow for partial harvests of mixed-age stands. The model is numerically calibrated for each of the five major forest

Table 1 – Parameter values by forest type

		White–red-jack pine	Spruce-fir	Oak-pine	Oak-hickory	Maple-beech-birch
α_0	Maximum timber volume (m^3/ha)	431	703	392	852	400
α_1	Timber growth coefficient (%/year)	0.0066	0.0038	0.0115	0.0055	0.0103
α_2	Minimum stand age with positive timber volume (years)	4.47	13.35	7.77	3.51	9.59
P_{pole}	Poletimber price in 2005 ($/m^3)	19.8	14.9	26.5	26.9	22.7
P_{saw}	Sawtimber price in 2005 ($/m^3)	121	61	168	153	106
β_0	Sawtimber share coefficient (%)	6.37	7.27	1.91	9.72	1.38
β_1	Sawtimber share coefficient (years)	2.70	1.47	22.79	1.11	20.02
β_2	Sawtimber share coefficient (%)	5.40	6.70	0.77	9.04	0.55
γ_0	Maximum carbon storage in live biomass (t/ha)	155	226	196	350	213
γ_1	Live biomass growth coefficient (%/year)	0.0115	0.0060	0.0129	0.0087	0.0114
$C_{dead}(0)$	Initial carbon storage in dead and downed wood(t/ha)	20.5	44.2	39.2	22.0	38.7
δ_0	Decay rate of dead and downed wood (%/year)	0.045	0.079	0.064	0.060	0.073
δ_1	Formation coefficient for dead and downed wood	0.258	0.730	0.285	0.206	0.391
δ_2	Formation coefficient for dead and downed wood	0.358	0.428	0.523	0.431	0.478
C_{soil}	Soil carbon storage (t/ha)	196	193	82	85	140
ε	Average carbon content of wood (t/m^3)	0.268	0.255	0.268	0.287	0.327
ε_1	Carbon content of softwood pulpwood (t/m^3)	0.234	0.234	0.234	0.234	0.234
ε_2	Carbon content of softwood sawlogs (t/m^3)	0.234	0.234	0.234	0.234	0.234
ε_3	Carbon content of hardwood pulpwood (t/m^3)	0.357	0.357	0.357	0.357	0.357
ε_4	Carbon content of hardwood sawlogs (t/m^3)	0.357	0.357	0.357	0.357	0.357
h_1	% of harvest allocated to softwood pulpwood	0.208	0.492	0.172	0.181	0.127
h_2	% of harvest allocated to softwood sawlogs	0.500	0.322	0.538	0.375	0.113
h_3	% of harvest allocated to hardwood pulpwood	0.114	0.093	0.048	0.131	0.365
h_4	% of harvest allocated to hardwood sawlogs	0.149	0.071	0.215	0.276	0.340
ϕ_{01}	Decay rate of softwood pulp products (%/year)	0.0060	0.0060	0.0060	0.0060	0.0060
ϕ_{02}	Decay rate of softwood saw products (%/year)	0.0038	0.0038	0.0038	0.0038	0.0038
ϕ_{03}	Decay rate of hardwood pulp products (%/year)	0.0062	0.0062	0.0062	0.0062	0.0062
ϕ_{04}	Decay rate of hardwood saw products (%/year)	0.0042	0.0042	0.0042	0.0042	0.0042
ϕ_{11}	% of wood carbon stored in softwood pulp products	0.237	0.237	0.237	0.237	0.237
ϕ_{12}	% of wood carbon stored in softwood saw products	0.298	0.298	0.298	0.298	0.298
ϕ_{13}	% of wood carbon stored in hardwood pulp products	0.227	0.227	0.227	0.227	0.227
ϕ_{14}	% of wood carbon stored in hardwood saw products	0.187	0.187	0.187	0.187	0.187

types that grow in New Hampshire. The parameter values that hold in each case are summarized in Table 1.

In our analysis, timber volume is measured in cubic meters per hectare, growing over time according to the equation:

$$V(s) = \begin{cases} \alpha_0\left(1-(1-\alpha_1)^{(s-\alpha_2)}\right) & s\geq\alpha_2 \\ 0 & s<\alpha_2 \end{cases} \tag{1}$$

in which α_0 represents the maximum achievable timber volume, or the carrying capacity of the forest ecosystem. The parameter α_1 determines the rate of volume growth, while α_2 is the minimum stand age for which timber volume attains a positive value. The parameter values employed in the model were calibrated based on the forest yield tables reported by the U.S. Department of Energy (2004), which summarize the relationship between stand age and timber volume in typical forest stands in the Northeastern United States. These figures are in turn derived from a detailed analysis of data from the Forest Inventory and Assessment (FIA) Program of the U.S. Forest Service (Mills and Kincaid, 1992; Haynes, 2003).

In the initial period of the analysis (date $t=0$, corresponding to the calendar year 2005), we assume that the forest has just undergone a clear-cut harvest so that it has an initial stand age of $s=0$. The entire forest is re-cut at each date $t=s_h*i$ for harvest $i=1,2,3,\ldots$, generating a harvest of $H(t)=V(s_h)$ cubic meters of timber.[1,2] The net economic benefits of the harvest are determined by the stumpage price $P(s,t)$, or the price of timber net of extraction costs, measured in 2005 dollars per

[1] The term s_h*i arises because s_h indicates the fixed period of time between each successive harvest, while i is an index that pertains to the ordinal sequence of harvests. To give an example, a rotation period of $s_h=45$ would imply harvests occur at each date $t=45$, 90, 135, …

[2] We limit attention to the case in which the interval between successive harvests is constant over time. More generally, time-varying harvest intervals might emerge as optimal for the model considered in this paper, especially when carbon storage values are factored into the analysis and when the benefits of timber harvesting and carbon sequestration evolve at different rates. The focus on constant harvest intervals, however, simplifies the analysis and discussion of the results reported below. Sensitivity analysis suggests that allowing for time-varying rotation periods does not affect the model's qualitative performance.

cubic meter of harvested wood. This stumpage price represents both the profit earned by the timber owner and the net benefit that an incremental unit of timber provides to society as a whole. In our analysis, the stumpage price follows the empirical relationship:

$$P(s,t) = (P_{\mathrm{pole}}[1 - f_{\mathrm{saw}}(s)] + P_{\mathrm{saw}} f_{\mathrm{saw}}(s))1.01^t. \tag{2}$$

In this expression, P_{pole} represents the stumpage price of poletimber — the small diameter, low-value trees that dominate young timber stands and are used primarily to provide pulp and fuel wood. In technical terms, poletimber consists of trees with diameters of 5–9 in. at breast height (dbh) for softwood species and 5–11 in. dbh for hardwoods. In contrast, P_{saw} represents the average price paid for sawtimber — large diameter, mature trees that provide saw logs, veneer, and other high-value products. These two prices are weighted according to the share of sawtimber in the forest stand, $f_{\mathrm{saw}}(s)$, which is an increasing function of stand age. Based on Sendak et al.'s (2003) analysis of the Northern New England timber market, we assume that real timber prices will increase at an annual rate of 1.0%. This price rise reflects the plausible assumption that timber demand will increase more rapidly than supply due to the interplay between economic growth and limits on forest productivity as well as internal and external pressures on the New England area due to population growth within and immediately adjacent to the region (Friedland et al., 2004).

Calculating the average stumpage prices for pole- and sawtimber is a conceptually straightforward task that requires careful attention to detail. To achieve this goal, we integrated data that quantify:

1. The composition of timber harvests by species for each forest type (U.S. Forest Service, 2005a).
2. The mix of products (principally pulp wood, fuel wood, saw logs, and veneer) generated by each species for pole- and sawtimber (U.S. Forest Service, 2005b).
3. The average stumpage price of each product class. These data were provided by Paul Sendak of the U.S. Forest Service (personal communication, 2005) based on surveys conducted by the New Hampshire Timberland Owners Association.[3]

Since the stumpage price data were expressed in a variety of different units, it was necessary to convert them to a standardized measure of dollars per cubic meter of timber. Our calculations assumed conversion factors of 4.5 m^3 per thousand board feet for saw and veneer logs and 2.25 m^3 per cord for pulp and fuel wood (Irland Group Forestry Consultants, 1999).

Based on data from the U.S. Forest Service (2005a), we parameterized the relationship between stand age and the proportion of sawtimber as a function of total timber volume according to the equation:

$$f_{\mathrm{saw}}(s) = \begin{cases} 0 & \beta_0 s/(s+\beta_1) - \beta_2 < 0 \\ \beta_0 s/(s+\beta_1) - \beta_2 & \beta_0 s/(s+\beta_1) - \beta_2 \in [0,1] \\ 1 & \beta_0 s/(s+\beta_1) - \beta_2 > 1. \end{cases} \tag{3}$$

This relationship implies that $f_{\mathrm{saw}}(s)$ follows a curvilinear trend with a minimum value of zero and a maximum value of unity. For young timber stands – i.e. those with stand ages below roughly 15 years – timber consists entirely of poletimber trees with low market value. For mature stands – with stand ages on the order of 100 years – sawtimber accounts for between 46% and 79% of harvestable volume depending on the particular forest type under consideration.

In the absence of concerns about carbon sequestration and other environmental issues (such as nutrient removal, soil erosion, and habitat alteration), a rational land owner would manage timber stands to maximize the net present value of the revenue stream provided by sequential timber harvests:

$$\mathrm{NPV}_{\mathrm{timber}} = \sum_{i=1}^{\infty} P(s_h, s_h{*}i)V(S_h) \prod_{t=1}^{S_h{*}i} \frac{1}{1+r(t)}. \tag{4}$$

In this expression, the discount rate $r(t)$ follows a path that is calibrated to conform to the numerical values reported in Howarth's (2001) analysis of climate change mitigation policy:

$$r(t) = 0.0268 + (0.0434 - 0.0268)0.992^t. \tag{5}$$

According to Eq. (5), the discount rate falls gradually from a value of 4.3% per year in the present to a long-run value of 2.7%. Although the use of a time-varying discount rate may be unfamiliar to some readers, it is consistent with the view that returns to capital investment will fall slowly over time as the capital stock grows and as the rate of economic growth declines (see Nordhaus and Boyer, 2000). Over the course of the next century, this specification implies an average discount rate of 3.7% per year — a figure that is generally consistent with the market rate of return paid by a balanced portfolio of private-sector investments (see Howarth, 2003).

2.1. *Accounting for carbon storage*

The central focus of our analysis concerns how incorporating the value of net carbon sequestration alters the relatively conventional forest economics model outlined above. As noted in the introduction, our approach builds on the framework considered by van Kooten et al. (1995), although the current analysis provides for a greater degree of economic and ecological realism. For related but conceptually distinct approaches in different geographical contexts, see Krcmar et al. (2005) and Nijnik (2005).

To gauge the net social benefits associated with carbon sequestration, we begin by calculating the impacts of various timber management strategies on net carbon uptake at each point in time. For the purposes of analysis, we disaggregate net carbon storage at date t [$C(t)$, measured in metric tons per hectare]into four underlying components:

$$C(t) = C_{\mathrm{live}}(t) + C_{\mathrm{dead}}(t) + C_{\mathrm{soil}}(t) + \sum_{i=1}^{4} C_{\mathrm{prod}}(i,t). \tag{6}$$

[3] As discussed in Wagner and Sendak (2005), the New Hampshire Timberland Owners Association gathers quarterly data on stumpage prices. In addition, biennial data are collected by the University of New Hampshire Cooperative Extension Service (see Smith, 2001).

In this formulation, $C_{live}(t)$ is the total storage of carbon in live biomass; $C_{dead}(t)$ measures the storage of carbon in dead and downed wood; $C_{soil}(t)$ gauges soil carbon storage; and $C_{prod}(i,t)$ represents the carbon stored in four categories of long-lived wood products — softwood pulp products ($i=1$), softwood sawtimber products ($i=2$), hardwood pulp products ($i=3$), and hardwood sawtimber products ($i=4$).

Our assumptions concerning carbon storage in live biomass and dead wood are calibrated based on the carbon yield tables that the U.S. Department of Energy (2004) provides for typical forest stands in the Northeastern United States:

$$C_{live}(t) = \gamma_0(1-(1-\gamma_1)^s) \tag{7}$$

$$C_{dead}(t) = (1-\delta_0)[C_{dead}(t-1) + \delta_1 C_{live}(t-1)^{\delta_2} + D(t-1)]. \tag{8}$$

These estimates are in turn based on the FORCARB model developed and maintained by the U.S. Forest Service (Heath et al., 2003), which provides a detailed description of forest stand dynamics that is structured around a careful analysis of field measurements and empirical generalizations drawn from the FIA database and the peer-reviewed literature. According to these sources, carbon storage in forest soils is effectively independent of stand age and timber management practices. Thus we assume that $C_{soil}(t)$ is a fixed parameter that assumes a unique value for each forest type.

In Eq. (7), the carbon stored in live biomass is a simple function of stand age, reflecting the accumulation of biomass as the forest ecosystem matures. Eq. (8), in contrast, is based on a simple box model in which dead and downed wood decays at the annual rate δ_0, with additions to this stock determined by two factors. First, the term $\delta_1 C_{live}(t-1)^{\delta_2}$ captures the rate at which live biomass dies and is hence added to the stock of dead and downed wood. Second, the variable $D(t-1)$ represents logging debris (or slash) that is left on the forest floor following a timber harvest. In the absence of a timber harvest, this variable assumes a value of zero. When a harvest occurs, however, logging debris may be calculated as the difference between the pre-harvest stock of carbon in live biomass and the carbon that is removed from the forest in the form of harvested wood. Hence:

$$D(t) = \begin{cases} 0 & H(t) = 0 \\ C_{live}(t) - \varepsilon H(t) & H(t) > 0. \end{cases} \tag{9}$$

In this expression, ε is a coefficient that represents the average carbon content of harvested wood, measured in metric tons per cubic meter.

To track changes in the carbon that is stored in long-lived wood products, we make use of the following reduced-form equation that is calibrated based on the tabular estimates developed by Birdsey (1996; see also Row and Phelps, 1991) and reported by the U.S. Department of Energy (2004):

$$C_{prod}(i,t) = (1-\phi_{0i})[C_{prod}(i,t-1) + \phi_{1i}\varepsilon_i h_i H(t-1)]. \tag{10}$$

Birdsey's estimates are based on a careful analysis of the disposition of harvested wood and the disposal and decomposition of wood products. The empirical generalizations used to calibrate Eq. (10) are based on data that are specific to timber harvests in the Northeastern United States.

In Eq. (10), h_i represents the share of the timber harvest that is allocated to product category i, while ε_i represents the carbon content per unit of harvested wood for each classification. The parameter ϕ_{0i} measures the rate at which stored carbon is released to the atmosphere through the decay of wood products (including decomposition in landfills), while ϕ_{1i} represents the proportion of harvested carbon that is embodied in long-lived wood products.

Significantly, Birdsey's analysis found that over 70% of the carbon contained in harvested wood is emitted to the atmosphere in the form of carbon dioxide shortly after a timber harvest. These emissions are dominated by the large net losses that occur in wood processing and manufacturing, though they also include a small fraction of the carbon stored in harvested wood (typically 3–6%) that is embodied in short-lived products that decay fully in the course of a few months or years. To simplify the analysis, we assume that the carbon embodied in short-lived products is emitted to the atmosphere during the same year that each timber harvest occurs. While long-lived wood products effectively store carbon over extended time spans with annual decay rates on the order of 0.4–0.6% or less, only 19–24% of harvested wood winds up in long-lived products in the Northeastern United States.

2.2. Valuing carbon sequestration

Given the model of forest dynamics, timber harvesting, and wood products use that is outlined above, the net uptake of carbon at date t may be calculated using the equation:

$$\Delta C(t) = C(t+1) - C(t) \tag{11}$$

that measures the change in the total carbon stored in live biomass, dead and downed wood, soils, and long-lived wood products between dates t and $t+1$, measured in metric tons per hectare. Under the assumption that carbon uptake yields a marginal benefit of $MB(t)$ dollars per tonne at each date $t=0,1,2,\ldots$ the carbon sequestered over time by a given timber management regime yields discounted benefits that attain a net present value of:

$$NPV_{carbon} = \sum_{t=0}^{\infty} MB(t)\Delta C(t) \prod_{i=1}^{t} \frac{1}{1+r(t)}, \tag{12}$$

denominated in dollars per hectare of forested land.

Under current public policies, land owners have little incentive to optimize timber management regimes to account for the net social benefits of carbon sequestration since these benefits are not reflected in the market price of harvested wood. A rational policy-maker who aimed to optimize the overall discounted net benefits provided by forest ecosystems, however, would choose timber management practices to maximize the net present value of both timber harvests and carbon sequestration:

$$\mathrm{NPV}_{\mathrm{social}} = \mathrm{NPV}_{\mathrm{timber}} + \mathrm{NPV}_{\mathrm{carbon}}. \tag{13}$$

In the context of a market economy, the resulting optimum could then be implemented through policies that either:

1. Subsidized land owners for activities that led to net carbon uptake while taxing activities that generated net carbon emissions.
2. Imposed timber management rules that required land owners to adopt desired land-use practices via regulatory mandate.

Of course, forest resource management yields important benefits such as outdoor recreation and the sustenance of soils, streams, wildlife, and biodiversity that are beyond the scope of the present analysis. As we shall see, however, limiting the analysis to the tradeoff between the economic value of timber harvesting and carbon sequestration yields rather striking results even when these additional benefits are omitted. There are good reasons to explicitly consider these issues in the context of future research.

How can the marginal social benefit of carbon sequestration be quantified for the purposes of this analysis? In answering this question, we assume a setting in which policy-makers aim to achieve set targets for the net carbon emissions generated by fossil fuel combustion and industrial production at the overall regional or national scale. We assume the existence of policies in which carbon sequestration in forests and wood products can be used to offset carbon emissions on a one-to-one basis. Although such measures are not currently in place in New Hampshire, the state is actively developing policies to reduce net carbon dioxide emissions (RGGI, 2005). In this context, the potential benefits of carbon sequestration strategies are a matter of direct practical relevance.

As demonstrated by Howarth et al. (1993), the marginal benefit of carbon sequestration may be calculated in terms of the marginal cost of achieving the net emissions targets specified by a given climate policy regime. This rests on the assumption that the portfolio of mitigation measures, including both emissions reductions and carbon sequestration options, is chosen to minimize net compliance costs. In effect, carbon sequestration provides social benefits by allowing incremental increases in carbon dioxide emissions, thereby reducing emissions abatement costs. This approach is related to the specific mechanisms that are now being implemented under the Kyoto Protocol. The Kyoto agreement, however, places bounds on countries' ability to offset carbon dioxide emissions through carbon sequestration. Here we envision a more expansive approach that does not involve such restrictions.

Based on the work of Howarth (2001), we consider two potential climate change policy regimes that differ significantly in terms of the marginal cost of emissions abatement and hence the marginal benefit of carbon sequestration. Howarth's analysis is based on a numerical model of interactions between climate change and the world economy that is calibrated to reflect mainstream assumptions concerning the costs and benefits of climate change response strategies. The resulting marginal benefit estimates are broadly consistent with the work of other authors (see Nordhaus and Boyer, 2000; IPCC, 2001).[4]

In the first policy regime considered (the "low marginal benefit" scenario), carbon dioxide emissions policies are designed to maximize the present-value net benefits of net emissions reductions. In this scenario, only modest steps towards emissions abatement are undertaken. As a result, the concentration of carbon dioxide in the atmosphere increases by 250% over the long run relative to current levels, with an accompanying increase of 5.8 °C in mean global temperature. This outcome is in one sense extreme, involving a rapid shift towards a climate that scientists believe "is very likely to be without precedent during at least the last 10,000 years" (IPCC, 2001, p. 13). In this case, the marginal benefit of carbon sequestration follows a path that may be represented by the function:

$$\mathrm{MB}_{\mathrm{low}}(t) = 99.69\text{–}(99.69\text{–}24.63)0.989^{t}, \tag{14}$$

rising from \$25 to \$75/metric ton over the course of the next century with a growth rate that falls gradually over time.[5]

In the second climate change policy regime that Howarth considers (the "high marginal benefit" scenario), policy-makers aim to achieve the stated goal of Framework Convention on Climate Change, which calls for the "stabilization of greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system". Although the precise implications of this language are the subject of ongoing negotiations, the central thrust is that aggressive actions to reduce the rate and magnitude of climate change are warranted based on the potential risks that climate change poses to the welfare of future generations and the functioning and resilience of ecosystems. Most discussions have centered on stabilizing carbon dioxide concentrations at a level between 450 and 650 ppm by volume. In Howarth's analysis, a stabilization target of 560 ppm (roughly 50% above current levels) is achieved through the design of policies that minimize the present-value cost of achieving this objective. In this scenario, the long-term increase in mean global temperature is limited to 1.1 °C, and the marginal benefit of carbon sequestration follows a path that may be represented by the equation:

$$\mathrm{MB}_{\mathrm{high}}(t) = 986.8\text{–}(986.8\text{–}226.5)0.994^{t}, \tag{15}$$

increasing from \$227 to \$570/metric ton.

[4] An anonymous reviewer noted that the "marginal benefit analyses reported by Nordhaus and Boyer (2000) and the IPCC (2001) are highly contestable, for reasons ranging from their hidden ethical assumptions to mathematical difficulties that are either ignored or ruled out of the 'mainstream' models by assumption". This point is well-taken and provides some justification for reliance on the "high marginal benefit" scenario described below.

[5] Howarth's (2001) underlying model provides numerical estimates of the marginal benefits of carbon sequestration at discrete points in time. Eqs. (14) and (15) replicate the results of this study with R^2 statistics exceeding 0.99.

Why focus on the results from Howarth's global model of climate-economy interactions in gauging the specific benefits of carbon sequestration in the state of New Hampshire? In answering this question, it is important to observe that the emerging global climate policy regime explicitly embodies flexibility mechanisms through which nations may buy and sell emissions allowances to achieve their net emissions targets. If and as emissions caps are accepted by nations such as the United States, China, and India that do not currently face such limits under the Kyoto Protocol, a global market in carbon emissions and offset allowances is likely to emerge that achieves global net emissions targets at the lowest achievable economic cost. In this event, the marginal cost of net emissions reductions would be equated across participating nations. Since forest management practices must be evaluated based on a framework that extends many decades into the future, envisioning the long-term structure of climate change policies is a necessary undertaking.

2.3. Partial harvesting

The discussion thus far has focused on clear-cut timber management, extending a relatively standard optimal rotation model to consider the economic benefits of net carbon sequestration. This approach is justified by the fact that clear-cutting and related heavy-harvesting methods are widely practiced in New Hampshire and (more generally) the New England region. In Maine, for example, such techniques accounted for roughly half of the timber harvested in 1995 (Gadzik et al., 1998). That said, many land owners in the region choose to manage timber through the use of relatively light sequential partial harvests (Beattie et al., 1993; Thorne and Sunquist, 2001). Partial harvesting provides a sustained stream of timber revenues while also supports non-harvest benefits such as enhanced wildlife habitat and aesthetic values.

To explore the economics of partial harvesting, we consider a specific harvesting regime described by Rowland (2001), who conducted interviews with New Hampshire forest experts regarding representative timber management practices in the state. In this scenario, approximately 35% of a timber stand is harvested when the stand reaches an initial stand age of 45 years, with subsequent harvests of equal intensity every 15 years thereafter. Based on field observations from New Hampshire forests, Rowland assumes that volume growth exhibits simple density dependence. Thus each partial harvest may be modeled as if it reduced the effective stand age from 45 to 30 years, with a net harvest of $H = V(45) - V(30) \approx 0.35V(45)$ given rates of timber growth in the region. A similar approach is used by Gadzik et al. (1998) and Turner and Caldwell (2001) to project future timber supplies in (respectively) Maine and the forests of New York and New England.

In gauging the net economic benefits of partial harvesting, we assume that the mix of forest products (e.g. poletimber and sawtimber) obtained in each successive harvest is equivalent to the mix obtained in the initial harvest when the stand age reaches 45 years. This may understate long-run timber harvest revenues since partial harvest techniques can enhance stand quality by promoting the growth of high-value sawlogs over a period of time (Beattie et al., 1993). This issue is not easily sorted out based on currently available data and would be an appropriate topic for future research. As we shall see, however, the results of the analysis tend to support the adoption of partial harvesting regimes despite the use of this simplifying and conservative assumption.

Allowing for partial harvests does not require structural changes in our carbon accounting model aside from an adjustment in Eq. (9). In the base version of the model, logging debris is calculated as the difference between carbon storage in live biomass and harvested wood according to $D(t) = C_{\text{live}}(t) - \varepsilon H(t)$. This equation rests on the assumption that all live biomass is killed in the context of a clear-cut harvest. In the case of a partial harvest, the fraction of biomass that is killed is limited to $H(t)/V(t) \approx 35\%$, yielding the revised equation:

$$D(t) = \frac{H(t)}{V(t)} C_{\text{live}}(t) - \varepsilon H(t). \tag{9'}$$

Aside from this adjustment, our analysis of partial harvests follows the core structure of the model outlined above.

3. Results

The results of this analysis are described in Table 2. These results were derived by solving the model described by Eqs. (1)–(15) using Microsoft Excel. In the clear-cut harvest scenarios, optimal rotation periods were established by conducting a grid search over values of the rotation period s_h ranging from 15 to 500 years with one-year time steps.

In the absence of carbon storage benefits, the optimal rotation period that arises under clear-cut timber management ranges from 34 to 44 years depending on the forest type. If one assumes that the initial condition of the forest ecosystem involves the first stages of forest regrowth following a clear-cut harvest, then the net present value of future harvests ranges from \$213/ha for spruce-fir forests to \$1326/ha for oak-hickory forests. In general, these figures are in line with the market value of actual forestlands, although they are, in some cases, much lower than the typical values associated with land uses such as residential and commercial development. The highest values are associated with forest types that provide the largest fraction of high-quality sawtimber.

Accounting for the value of carbon sequestration changes these results in significant respects. When the marginal benefits of net carbon uptake are low, the optimal rotation period increases to 53–58 years for the white–red-jack pine, oak-hickory, and oak-pine forest types. For these forest types, increasing the rotation period yields net economic benefits of \$59–157/ha. In each case, a relatively small reduction in timber revenues is offset by the benefits of increased carbon storage.

More striking results arise for the spruce-fir forest type, in which the optimal rotation period increases to a full 177 years when the value of carbon sequestration is factored into the analysis. In a similar but less dramatic vein, an optimal rotation period of 92 years holds for the maple-beech-birch forest type when the marginal benefit of net carbon storage is low. In these two cases, the value of timber harvesting is comparatively low since these forest types yield relatively low volumes of saw logs with a higher fraction of low-value products such as pulp and fuel wood. It is worth noting that spruce-fir and maple-beech-

Table 2 – Stand age at harvest (years) and net present value ($/ha) under alternative timber management regimes

	Private optimum	Social optimum (low MB)	Social optimum (high MB)	Partial harvest
White–red-jack pine				
Stand age at harvest	37	53	237	*
NPVtimber	736	662	31	537
NPV_{social} (low MB)	1630	1689	1363	1704
NPV_{social} (high MB)	8084	9033	10,692	9954
Spruce-fir				
Stand age at harvest	44	177	391	*
NPV_{timber}	213	35	1	194
NPV_{social} (low MB)	723	1091	1079	1006
NPV_{social} (high MB)	4181	8108	8246	6435
Oak-pine				
Stand age at harvest	42	58	222	*
NPV_{timber}	1154	1050	64	867
NPV_{social} (low MB)	2255	2357	1807	2338
NPV_{social} (high MB)	10,099	11,566	13,845	12,611
Oak-hickory				
Stand age at harvest	34	55	271	*
NPV_{timber}	1326	1124	31	896
NPV_{social} (low MB)	2772	2929	2464	2890
NPV_{social} (high MB)	13,288	15,844	19,475	17,031
Maple-beech-birch				
Stand age at harvest	39	92	317	*
NPV_{timber}	605	325	6	475
NPV_{social} (low MB)	1590	1860	1747	1910
NPV_{social} (high MB)	8626	12,493	13,740	11,899

* In the partial harvest case, approximately 35% of marketable timber is harvested at 15-year intervals after the timber stand achieves an initial stand age of 45 years.

birch forests together account for nearly two-thirds of New Hampshire forests by land area (U.S. Forest Service, 2005a). Accordingly, the results that hold for these forest types are of particular significance.

The results suggest that net carbon sequestration provides present-value benefits ranging from $1027 to $1805/ha when the shadow price of carbon is low and when forests are managed under a clear-cut harvest regime in which the rotation period is chosen to maximize net social benefits. These figures are larger than the maximum present-value net revenues that are available from timber harvesting for each and every forest type. Accordingly, one may conclude that policy instruments that rewarded land owners for undertaking land-use practices that emphasize carbon storage could generate substantial cash flows.

Thus far, our discussion of the results has focused on the case where the shadow price of net carbon sequestration is comparatively low. This scenario assumes that climate change policies are based on the use of cost–benefit analysis, with a shadow price of net carbon emissions that increases from $25 to $75/metric ton between 2005 and 2105 (Howarth, 2001). As described above, however, there are reasons to believe that decision-makers may implement considerably more aggressive policies that cap atmospheric concentrations of carbon dioxide at a level that is twice the pre-industrial norm (IPCC, 2001). In this "high marginal benefit" scenario, the shadow price of net carbon sequestration rises from $227 to $570/metric ton over the next 100 years.

It should come as no surprise that the high marginal benefit scenario leads to significantly longer optimal rotation periods under clear-cut harvesting. As Table 2 suggests, the numerical scale of this effect turns out to be quite large. In this scenario, the optimal rotation period ranges from 222 years for oak-pine forests to 391 years for spruce-fir forests. In comparison with the private optimum – i.e., the management strategy that maximizes the present value of net timber revenues – this harvesting regime reduces the economic benefits of timber harvesting by 94–99%. Just as important is the magnitude of the economic benefits provided by net carbon uptake, which ranges from $8245/ha for spruce-fir forests to $19,444/ha for oak-hickory forests. These very substantial figures are much larger than the potential revenues that can be garnered from harvesting timber. In the face of stringent climate change policies, these results suggest that carbon sequestration should effectively trump resource extraction in the design of forest management regimes.

Finally, it is worthwhile to evaluate the relative benefits of the partial harvesting regime described by Rowland (2001), in which approximately 35% of standing timber is removed at 15-year intervals once the timber stand reaches an initial age of 45 years. A first point to note is that partial harvesting provides net timber revenues that are only 9–32% below those achieved under aggressive clear-cut management. Since partial harvesting provides wildlife, aesthetic, and ecological values that are not considered in this analysis, and since (as noted above) the model under discussion may understate the long-term net revenues generated by sequential partial harvests, it is easy to understand why many land owners regard this approach as an attractive management option.

A further point is that partial harvesting outperforms the private optimum with short-rotation clear-cuts in terms of carbon sequestration. And when the marginal benefit of carbon sequestration is low, the partial harvesting regime yields net social benefits that are closely comparable to those achieved under clear-cut timber management with a rotation period that is optimized to balance the benefits of timber harvesting and carbon storage. Even when the marginal benefit of carbon sequestration is high, partial harvesting yields net benefits that are only 7–21% lower than those that hold in the socially optimal clear-cut regime with its notably long rotation periods. This implies that the partial harvesting approach is robust in the sense that it performs well under a variety of conditions. This point is relevant because the stringency and cost of future climate change policies is and is likely to remain uncertain. It is interesting that a resource management regime that is already in widespread practice appears to constitute an appropriate mechanism for promoting enhanced carbon sequestration.

4. Conclusions

This paper has explored the implications of carbon dioxide sequestration for the optimal management of representative timber stands in the state of New Hampshire. The analysis is based on a relatively simple forest economics model that integrates the net revenues generated by timber harvests and the economic benefits of carbon sequestration in forest ecosystems and wood products. The benefits of carbon sequestration are calculated based on the assumption that carbon sequestration can be used to offset carbon dioxide emissions from fossil fuel combustion and industrial production in a setting where policy-makers aim to achieve specified net emissions targets at the lowest possible cost.

When net emissions targets are chosen based on the application of cost–benefit analysis and when timber stands are managed according to a conventional clear-cut harvesting regime, accounting for the benefits of carbon sequestration extends the optimal rotation period by between 16 and 133 years depending on the forest type. The smallest effects are observed for the white–red-jack pine, oak-pine, and oak-hickory forest types, which generate relatively large timber revenues at the time of harvest. The largest effects arise for the spruce-fir and maple-beech-birch forest types, which generate lower-quality timber of comparatively low economic value.

When net emissions targets are chosen to stabilize atmospheric carbon dioxide concentrations at twice the pre-industrial norm using cost-effective implementation policies, optimal rotation periods range from 222 to 391 years for the forest types considered in this analysis. According to the IPCC (2001), pursuing this policy scenario may be necessary to achieve the stated objective of the Framework Convention on Climate Change, which calls for the "stabilization of greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system".

As noted by Thorne and Sunquist (2001), many New Hampshire land owners favor relatively light partial harvesting regimes over the conventional clear-cut harvesting practices that are emphasized in the forest economics literature. To explore the costs and benefits of this approach, we considered a representative scheme in which approximately 35% of standing timber is removed from the forest with sequential harvests every 15 years (Rowland, 2001). Our analysis suggests that partial harvesting performs well in balancing the benefits derived from resource extraction and carbon sequestration.

There are many ways in which the model reported in this paper might be extended and improved. First, we have considered optimal management practices at the timber stand level, abstracting away from the impact that changing management practices might have on equilibrium prices at higher levels of scale. There are good reasons to embed the benefits of carbon sequestration in a regional forest economics model such as the framework developed by Sendak et al. (2003). Such a model could shed considerable light on the overall potential for carbon storage in New Hampshire forests, along with the total costs and benefits of alternative policy options.

Second, the model itself involves certain simplifications that could profitably be explored in future research. Our model, for example, accounts for the transition from low-value poletimber to high-value sawtimber as forests regenerate following each harvest. It does not, however, account for the maturation of timber within each of these categories, which of course should affect the net value of a timber stand as a function of stand age. In a similar vein, our model assumes that partial harvests yield average stumpage values that are equal to those that would be generated by a clear-cut harvest of a 45-year-old timber stand. While an assumption like this is necessary in absence of better quality data, we suspect that this assumption may lead our model to undervalue the long-run revenues derived from partial harvesting. This is true because careful harvesting practices can improve stand quality and thus presumably stumpage values (Beattie et al., 1993).

Finally, it is important to note that our analysis has focused on representative timber stands based on empirical generalizations that describe New Hampshire forests in broad terms. This does not, however, imply that our results could be applied directly to individual timber stands which differ in terms of factors such as species composition, forest productivity, and access to roads and markets, each of which affect the stumpage price of timber at the point of sale. We believe that the qualitative findings of our analysis are robust — namely, that accounting for the value of carbon sequestration favors longer (in some cases *much* longer) optimal rotation periods and/or the adoption of partial harvesting regimes. There is ample scope, however, for further research that explores these issues in greater detail and at varying levels of scale.

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