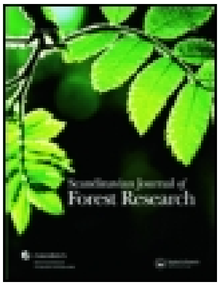

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Joseph Buongiorno [a], Espen Andreas Halvorsen [b], Ole Martin Bollandsås [b], Terje Gobakken [b] & Ole Hofstad [b]

[a] Department of Forest and Wildlife Ecology, University of Wisconsin-Madison, 1630 Linden Drive, Madison, WI, 53706, USA

[b] Department of Ecology and Natural Resource Management, Norwegian University of Life Sciences, P.O. Box 5003, N-1432, Ås, Norway

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ORIGINAL ARTICLE

Optimizing management regimes for carbon storage and other benefits in uneven-aged stands dominated by Norway spruce, with a derivation of the economic supply of carbon storage

JOSEPH BUONGIORNO[1], ESPEN ANDREAS HALVORSEN[2], OLE MARTIN BOLLANDSÅS[2], TERJE GOBAKKEN[2] & OLE HOFSTAD[2]

[1]*Department of Forest and Wildlife Ecology, University of Wisconsin-Madison, 1630 Linden Drive, Madison, WI 53706, USA, and* [2]*Department of Ecology and Natural Resource Management, Norwegian University of Life Sciences, P.O. Box 5003, N-1432 Ås, Norway*

Abstract
This study sought optimal sustainable management regimes of uneven-aged Norway spruce-dominated stands with multiple objectives. The criteria were financial returns, CO_2 sequestration and diversity of tree size and species. At prevailing timber prices, harvest and transport costs, and interest rates, uneven-aged management for timber alone was most profitable with a 5-year cutting cycle. Lengthening the cutting cycle to 20 years decreased the net present value from timber by 10%, but raised the carbon storage by 21%, the tree species diversity by 32%, and the tree size diversity by 24%. Maximizing CO_2 sequestration induced an almost pure spruce stand. A compromise policy maximized CO_2 storage, while maintaining a rate of return on the capital of standing trees equal to the interest rate. A supply curve for CO_2 storage was derived, showing how much forest owners would be willing to sequester as a function of the price of CO_2. Maximizing the NPV from combined CO_2 storage and timber production showed complementarity of CO_2 storage and timber production for up to NOK 300 Mg^{-1} of CO_2, and sustained, though lower, timber production at higher CO_2 prices.

Keywords: *Management, economics, optimization, carbon storage, supply, diversity, Norway.*

Introduction

Carbon sequestration is an increasingly important goal of forest management because of the current focus on reducing the CO_2 levels in the atmosphere to counter global warming (IPCC, 2001). In terrestrial ecosystems, forests are the largest carbon sink and the world's forest account for 90% of the carbon flux between the atmosphere and the surface of the earth (Winjum et al., 1993).

The potential for reducing the atmospheric CO_2 levels through forest management is therefore evident. However, more knowledge is needed to achieve this potential. Long-term carbon storage in forests varies with several factors (Foley et al., 2009) which can be influenced by silvicultural practices in stand establishment (Harmond & Marks, 2002), species composition (Gutrich & Howarth, 2007; Liski et al., 2001), and harvest frequency and intensity (Foley et al., 2009; Gutrich & Howarth, 2007).

Modern forestry is also facing challenges regarding biodiversity. In Norway, where this study was conducted, even-aged management has dominated since the 1950s, creating large areas of stands with few tree species and with trees of similar age and size. While being economically effective by reducing costs and promoting certain timber qualities, this practice is criticized (Andersen, 2007) because it fails to preserve the ecological qualities of the forest (Doyon et al., 2005; Xabadia & Goetz, 2010).

Consequently, systems that maintain a more diverse stand structure are now returning in favor. Continuous cover forestry (CCF), for example, is a silvicultural system designed to maintain uneven-aged and multi-species forest stands. The main idea

Correspondence: Ole Martin Bollandsås, Department of Ecology and Natural Resource Management, Norwegian University of Life Sciences, P.O. Box 5003, N-1432 Ås, Norway. E-mail: olebo@umb.no

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of CCF is to maintain a continuous canopy cover so that the forest floor is minimally exposed. This and other silvicultural systems that promote a diverse canopy structure are important to conserve biodiversity (Brokaw & Lent, 1999; Hunter, 1990; Lin & Buongiorno, 1998; Whittam et al., 2002). As a result, it is expected that the area comprising uneven-aged forest stands will increase in Norway.

Goals of increased CO_2 sequestration and increased biodiversity are mostly put forward by the public and they often conflict with the financial goals of many forest owners. Several studies have shown that the opportunity cost of stand diversity and CO_2 sequestration, in terms of foregone timber harvest, increases with the tightening of constraints on diversity and carbon sequestration. For example, Buongiorno et al. (1994, 1995) and Boscolo et al. (1997) discuss the case of uneven-aged management in tropical forests, and Díaz-Balteiro and Romero (2003), Díaz-Balteiro and Rodriguez (2006), and Pohjola and Valsta (2007) address even-aged management for a variety of species and countries. Pukkala et al. (2011) consider both even-aged and uneven-aged management in boreal forests managed for timber, carbon storage, and bilberry benefits.

Given the observed trade-off between objectives, incentives are needed to change forest owners' decisions regarding forest management in favor of increased forest diversity and CO_2 sequestration. For example, certification systems such as the Forest Stewardship Council (FSC) or the Programme for Endorsement of Forest Certification schemes (PEFC) give forest owners better market access if management is conducted according to specific standards. Managerial changes can also be induced with direct economic incentives (e.g. payment for carbon storage or tax on CO_2 emissions at the time of cutting) or laws that prohibit certain actions (e.g. logging of stands essential for biodiversity). The effectiveness of such measures varies with the biological and social context, and combinations of measures must be considered depending on the situation.

The European Union has established a cap and trade system for greenhouse gases. This is based on the Kyoto Protocol. Emission Reduction Units (ERU = 1 $MgCO_2e$) are traded daily on this market. But because of the formulations in the Kyoto Protocol (Article 3.3) the potential for sale of ERU from Scandinavian forests is limited. While industrial companies may buy carbon sequestration from forest owners on a voluntary basis outside the cap and trade system, there are still few examples of such trade in Scandinavia. Still, the markets are likely to improve as the carbon price could rise from 10 to 15 USD Mg^{-1} CO_2e to 50 USD Mg^{-1} CO_2e in 2020 and 110 USD Mg^{-1} CO_2e in 2030 (IEA, 2009, 2010, scenario 450).

Regardless of the policy being considered, it is useful to know how best to achieve specific goals, be it to store carbon, to maintain tree diversity in the forest, to generate income, or a combination thereof. Needed to acquire this knowledge are forest growth models with enough detail to represent accurately multi-species, uneven-aged forest stands. Tree size-distribution models (e.g. Bollandsås et al., 2008; Buongiorno & Michie, 1980; Tahvonen, 2009; Tahvonen et al., 2010) are well suited for this purpose. In them, the stand state is represented by a vector of the number of trees by species and size classes, and a linear or non-linear transition matrix represents changes over time.

Such matrix models have been used extensively to study the management of uneven-aged stands with economic and ecological objectives, in northern hardwoods (Adams & Ek, 1974; Buongiorno et al., 1994; Haight et al., 1985), mixed loblolly pine stands (Schulte & Buongiorno, 1998), and tropical forests (Boscolo et al., 1998; Ingram & Buongiorno, 1996). The EFISCEN (EFI, 2010; Karjalainen et al., 2002) is another matrix-based model which has been used operationally on large areas dominated by even-aged forests (EFI, 2010). However, different growth models have also been found useful. For example, Garcia-Gonzalo et al. (2007) used the process-based FinnFor model developed by Kellomäki and Väisänen (1997) to study forest management under climate change.

For Norway, Bollandsås et al. (2008) developed a non-linear matrix model to simulate the long-term growth of uneven-aged, multi-species forests. This paper continues the work of Bollandsås et al. (2008) by seeking optimum management regimes with mathematical programming. The main objective was to assess tradeoffs between financial returns and CO_2 storage, and attendant effects on the diversity of tree species and tree size. Special attention was given to optimization of net present value without restriction on carbon sequestration, maximization of carbon sequestration without restriction on net present value, and maximization of carbon sequestration with a specific rate of return on timber capital. A supply curve was also derived showing how much CO_2 would be stored as a function of the price of CO_2.

Materials and methods

Forest growth model

This study used the matrix stand growth model of Bollandsås et al. (2008). The model had its origin in the linear matrix population models of Leslie (1945) and Usher (1966, 1969), extended to reflect the dependence of recruitment on stand state (Buongiorno & Michie, 1980), and the dependence of individual tree growth and mortality on stand state (Buongiorno et al., 1995). The general model form was:

$$\mathbf{y}_{t+5} = \mathbf{G}_t(\mathbf{y}_t - \mathbf{h}_t) + \mathbf{R}_t \quad (1)$$

where $\mathbf{y}_t = [y_{ijt}]$ is a vector of the number of live trees in year t, of species group i, and diameter class j. There were four species groups: Norway spruce (*Picea abies* (L.) Karst.), Scots pine (*Pinus sylvestris* L.), birch (*Betula pubescens* Ehrh. and *Betula pendula* Roth), and other broadleaves which consisted of, in alphabetical order: alder (*Alnus* spp.), ash (*Fraxinus excelsior* L.), aspen (*Populus tremula* L.), beech (*Fagus sylvatica* L.), Bird cherry (*Prunus padus* L.), linden (*Tilia cordata* L.), maple (*Acer* spp.), oak (*Quercus* spp.), rowan (*Sorbus aucuparia* Stell.), sallow (*Salix caprea* L.), and Wych elm (*Ulmus glabra* Huds.). There were 13 diameter classes, from 75 mm dbh to 675 mm dbh. $\mathbf{h}_t = [h_{ijt}]$, is the corresponding harvest. The growth matrix $\mathbf{G}_t$ and the recruitment vector, $\mathbf{R}_t$, depend on the state of the residual stand, $\mathbf{y}_t$–$\mathbf{h}_t$, so that the growth model is non linear. The non-linear tree growth, mortality, and recruitment equations that define $\mathbf{G_t}$ and $\mathbf{R}_t$ were developed with data from more than 170,000 individual trees on 7241 plots. The model was thoroughly tested on post-sample plots for both short-term and long-term projections (Bollandsås et al., 2008).

Models of biomass, volume, diversity, log grade, and tree height

The weight of above- and below-ground tree biomass down to 2 mm roots was computed as in Marklund (1988) and Petersson and Ståhl (2006). The volume per tree in a diameter class was obtained with the models of Vestjordet (1967) for spruce, Brantseg (1967) for pine, and Braastad (1966) for birch and other broadleaves. Volume and biomass depend on tree height, predicted with the diameter-height models of Bollandsås (2007).

The mass of CO_2 was estimated from the biomass with the carbon to CO_2 ratio 44/12 based on the atomic weights of C (12) and O (16), and assuming that the carbon mass was half of the biomass Penman et al. (2003).

The diversity of tree species and tree size was measured with Shannon index (Pielou, 1977; Shannon & Weaver, 1963), relative to its maximum value, the logarithm of the number of categories. Species frequency was expressed by the relative basal area of each species, thus giving more weight to large trees:

$$H_{\text{species}} = \frac{\sum_{i=1}^{4} \frac{BA_i}{BA} \ln\left(\frac{BA_i}{BA}\right)}{\ln(4)} \quad (2)$$

where BA_i was the basal area of trees of species i, and BA was the total stand basal area. The tree species diversity reached a maximum value of 1 when basal area was equally distributed in all four species groups, and a minimum value of 0 when all trees were in the same species group. Similarly, tree size diversity was defined as:

$$H_{\text{size}} = \frac{\sum_{j=1}^{13} \frac{BA_j}{BA} \ln\left(\frac{BA_j}{BA}\right)}{\ln(13)} \quad (3)$$

where, BA_j was the basal area of trees in diameter class j.

The effect of tree size on the expected value of harvest was determined as in Blingsmo and Veidahl (1992). The harvesting cost was estimated as in Dale et al. (1993) for harvester productivity, and with the formulae of Dale and Stamm (1994) for forwarder productivity. These were slightly modified by setting harvest cost for the smallest diameter class (50–100 mm dbh) equal to what they would be in a tending operation, and harvest productivity was constant for trees of at least 375 mm in diameter.

Maximizing timber revenues with constraints on CO_2 sequestration

The optimization dealt with steady-state regimes, in which the growth over the cutting cycle compensated exactly for the harvest, so that the harvest could be continued in perpetuity.

The harvest, $\mathbf{h}_t$, and the corresponding growing stock, $\mathbf{y}_t$, that maximized the net present value from timber revenues only, in the steady state, subject to carbon storage limitations, were found by solving the following non-linear optimization problem:

$$\max_{\mathbf{h}_t, \mathbf{y}_t} NPV_h = \mathbf{v}\mathbf{h}_t + \frac{\mathbf{v}\mathbf{h}_t}{(1+r)^{5n} - 1} - \mathbf{v}\mathbf{y}_t \quad (4)$$

Subject to:

$$\mathbf{y}_{t+5} = \mathbf{G}_t(\mathbf{y}_t - \mathbf{h}_t) + \mathbf{R}_t \quad (5)$$

$$\mathbf{y}_{t+10} = \mathbf{G}_{t+5}(\mathbf{y}_{t+5}) + \mathbf{R}_{t+5} \quad (6)$$

...

$$\mathbf{y}_{t+5n} = \mathbf{G}_{t+5(n-1)}\left(\mathbf{y}_{t+5(n-1)}\right) + \mathbf{R}_{t+5(n-1)} \quad (7)$$

$$\mathbf{y}_{t+5n} = \mathbf{y}_t \quad (8)$$

$$\mathbf{h}_t \geq 0 \quad (9)$$

$$\mathbf{y}_t - \mathbf{h}_t \geq 0 \quad (10)$$

$$\mathbf{c}(\mathbf{y}_t - \mathbf{h}_t/2) \geq C_{\min} \quad (11)$$

where $\mathbf{v}$ was the row vector of tree value for timber alone, by species and size, and NPV_h was the net present value of the timber harvests, in a steady-state regime over an infinite horizon, given the net value of the periodic timber harvest, $\mathbf{vh}_t$, occurring every $5n$ years, and the initial investment in the growing stock valued as timber only, $\mathbf{vy}_t$ (Buongiorno & Gilless, 2003, p. 161). The real interest rate, r, was set at 3% per year (Bernhardsen & Gerdrup, 2006). Given a particular cutting cycle and interest rate, NPV_h was a linear function of $\mathbf{h}_t$ and $\mathbf{y}_t$. Table I shows the data for volume, value, and CO_2 content per tree, by species and diameter class. These values reflect current prices and were maintained fixed throughout the analysis.

The Equations (5) to (7) defined the stand growth over a cutting cycle of $5n$ years. Equation (8) specified a steady state: the stock must be the same at the end of the cutting cycle as at the beginning. Constraint (9) ensured a non-negative harvest. Constraint (10) stated that the harvest must be less than the stock, and given (9), the stock could not be negative. Constraint (11) set a lower bound on carbon storage. The row vector $\mathbf{c}$, defines the carbon stored in every tree of a particular species and diameter class, and $C_{\min}$ is the lower bound on the amount of stored carbon per unit area, on average over the cutting cycle. The remainder of the analysis focuses on this amount of carbon stored, as it is clear that in steady state the system is carbon neutral, the carbon removed by the harvest being just replaced by the stand growth.

Given the non-linearity of the growth model (1), the relationship between $\mathbf{y}_{t+5n}$, $\mathbf{y}_t$, and $\mathbf{h}_t$ defined by Equations (5) to (7) became more and more highly nonlinear with longer cutting cycles, n. To make computations manageable the maximum cutting cycle was set at n=4, or 20 years. The optimizations were done with the program What's Best (LINDO Systems Inc., 2003). Multiple starting points and alternative optimization paths were used to avoid local optima.

Maximizing CO_2 storage with or without constraints on timber revenues

A symmetric form of the model was used to find the management regimes that would maximize carbon sequestration, with or without constraint on NPV. In that case, Equations (5) to (10) stayed the same, while the objective function was changed to the average of the CO_2 stored over the cutting cycle, which given the steady state condition (8) is equal to:

$$\max_{\mathbf{h}_t, \mathbf{y}_t} C = \mathbf{c}(\mathbf{y}_t - \mathbf{h}_t + \mathbf{y}_{t+5n})/2 = \mathbf{c}(\mathbf{y}_t - \mathbf{h}_t/2) \quad (12)$$

And constraint (11) was replaced by:

$$\mathbf{vh}_t + \frac{\mathbf{vh}_t}{(1+r)^{5n} - 1} - \mathbf{vy}_t \geq NPV_{\min} \quad (13)$$

where $NPV_{\min}$ was the lower bound on net present value coming from timber alone.

Economic supply schedule for stored CO_2

The dual solution of the program described earlier with Equations (4) to (11), which maximized the NPV from timber harvest only, subject to a

Table I. Volume, gross value and CO_2 content per tree, by species and diameter class.

	Diameter class (mm)												
	75	125	175	225	275	325	375	425	475	525	575	625	675
Volume (m^3)													
Spruce	0.02	0.08	0.18	0.34	0.55	0.80	1.10	1.44	1.81	2.22	2.67	3.15	3.67
Pine	0.02	0.08	0.18	0.33	0.53	0.78	1.08	1.43	1.82	2.27	2.76	3.31	3.90
Birch	0.02	0.08	0.18	0.33	0.52	0.76	1.05	1.39	1.78	2.21	2.70	3.23	3.82
Other	0.02	0.08	0.18	0.32	0.51	0.75	1.03	1.37	1.75	2.19	2.67	3.21	3.80
CO_2 content (kg)													
Spruce	40	120	290	530	840	1210	1620	2070	2540	3020	3500	3990	4480
Pine	20	90	210	380	600	860	1130	1420	1710	2000	2290	2580	2860
Birch	30	120	260	480	740	1050	1400	1770	2170	2580	2990	3410	3840
Other	40	120	280	510	790	1130	1500	1910	2330	2770	3220	3680	4130
Gross value (NOK)													
Spruce	7	31	65	127	210	310	427	559	704	860	1026	1201	1385
Pine	5	20	44	128	208	307	426	562	718	894	1088	1303	1536
Birch	7	24	54	98	156	228	315	417	533	664	810	970	1146
Other	6	23	53	96	152	224	309	410	526	656	802	963	1139

constraint on CO_2 storage gave the Lagrange multiplier, or shadow price of constraint (11). This is the marginal cost (NOK Mg^{-1}) of raising CO_2 storage, in terms of foregone net present value of timber harvest. A plot of this shadow price of CO_2 (NOK Mg^{-1}) against the amount stored CO_2 (Mg ha^{-1}) gives the supply schedule of CO_2 in an environment where the owners would be paid both to produce timber and to store carbon.

Maximizing returns from timber and stored CO_2

The following model was used to determine for any point along the supply curve the actual management, in terms of harvest and growing stock that would maximize total net present value, inclusive of timber revenues and income from CO_2 sequestration when stored CO_2 had a price.

Let q be the price of stored CO_2 (NOK Mg^{-1}). Then, the optimum management was the solution of a model expressed by Equations (4) to (10), with the objective function (4) changed to:

$$\max_{\mathbf{h}_t,\mathbf{y}_t} NPV = \mathbf{v}\mathbf{h}_t + \frac{\mathbf{v}\mathbf{h}_t}{(1+r)^{5n}-1} - \mathbf{v}\mathbf{y}_t + q\mathbf{c}(\mathbf{y}_t - \mathbf{h}_t/2) \quad (14)$$

where NPV was the combined net present value from timber production and CO_2 sequestration, and $q\mathbf{c}(\mathbf{y}_t–\mathbf{h}_t/2)$ was the value of the CO_2 equivalent of the average growing stock being held over the cutting cycle.

Results

Effects of maximizing timber revenues with constraints on CO_2 sequestration

Figure 1 shows the maximum NPV (1), and the corresponding value of growing stock (2), annual harvest volume (3), and tree species diversity (4), for management regimes that maximized net present value of timber only, in steady state, with cutting

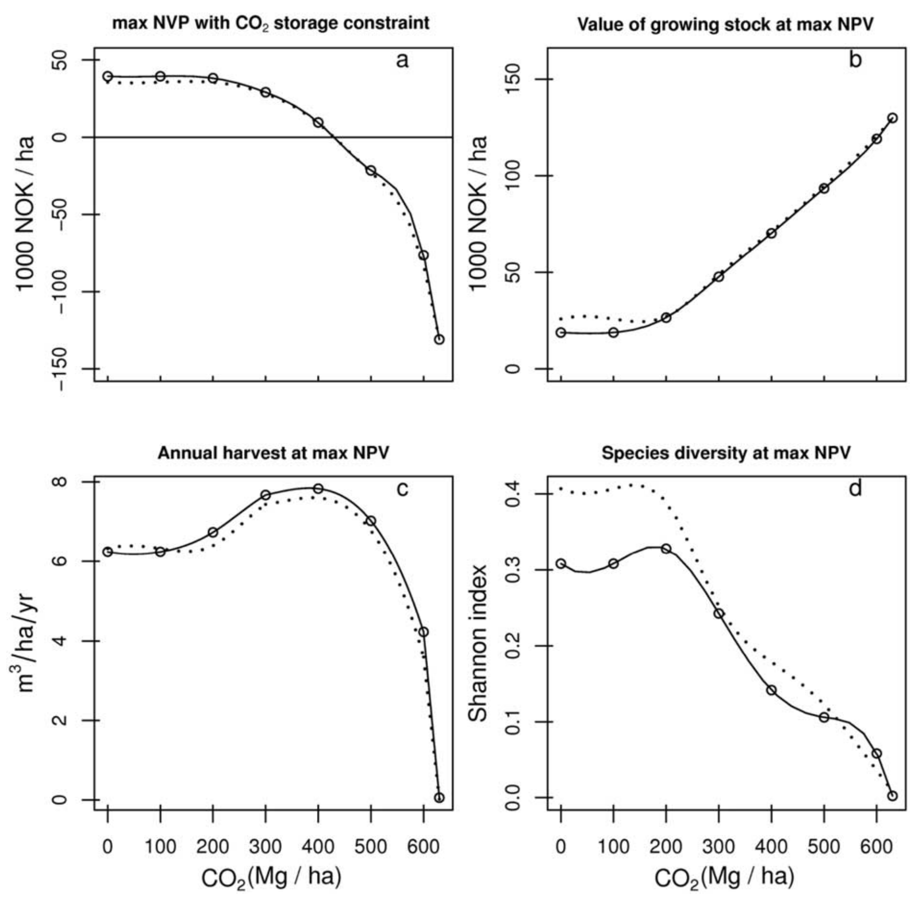

Figure 1. Effects of constraints on carbon storage on (a) net present value, (b) value of growing stock, (c) harvest volume, and (d) tree species diversity, for management regimes that maximized net present value in steady state for cutting cycles of 5 years (–– ○ ––), and 20 years (----).

cycles of 5 and 20 years, with carbon sequestration constraints varying from 0 to the highest possible CO_2 storage level. Like the stored carbon [Equation (12)], the other data pertaining to growing stock are the mean of pre- and post-harvest levels, to reflect the average condition over the cutting cycle.

According to Figure 1a the maximum NPV conditional on a CO_2 level was higher for the 5-year cycle than for the 20-year cycle, for up to 300 Mg ha^{-1} of CO_2 storage. Furthermore, NPV was almost unaffected by constraints on CO_2 storage for up to 200 Mg ha^{-1}. For both cutting cycles the NPV became 0 at about 450 Mg ha^{-1} of stored CO_2. At that point the present value of future harvests just balanced the initial value of the growing stock, and the same present value of income could be realized by liquidating the stock immediately or waiting for all future harvests. Beyond 450 Mg ha^{-1} the NPV decreased rapidly with increasing restrictions on CO_2 storage.

As expected, the value of growing stock increased with increasing CO_2 constraints (Figure 1b). However, as in Figure 1a, the curves were almost flat for CO_2 restrictions up to 200 Mg ha^{-1}. The investment in growing stock was higher with the 20-year cutting cycle for up to 300 Mg ha^{-1}. Beyond that level of CO_2 storage, the value of the growing stock was practically the same for the two cutting cycles.

Figure 1c shows that there was little difference in the volume of annual harvest at maximum NPV according to the cutting cycle. With constraints between 200 Mg ha^{-1} and 600 Mg ha^{-1} of stored CO_2, the annual harvest volume was only slightly lower with the 20-year cutting cycle. For both cutting cycles, below 200 Mg ha^{-1} of stored CO_2, the annual harvest volume was almost independent of the CO_2 constraint. The annual harvest increased for restrictions between approximately 200 and 400 Mg ha^{-1}, at which point the NPV approached zero for both cutting cycles (Figure 1a) and the harvest was near 8 m^3 ha^{-1} yr^{-1}. For CO_2 storage exceeding 500 Mg ha^{-1}, the average annual harvest declined rapidly.

The graph of tree species diversity at maximum NPV shows that the tree species diversity with the 5-year cycle was substantially higher than for the 20-year cycle for up to 200 Mg ha^{-1} of stored carbon (Figure 1d). But at 300 Mg ha^{-1} of CO_2 storage and beyond the two cutting cycles gave similar species diversity.

When maximizing NPV without restriction on CO_2 storage, a mixed-species stand was maintained, with both cutting cycles (Table II). Many more large trees were present with a 20-year cycle which kept trees of up to 425 mm in diameter, while with a 5-year cycle the maximum tree size was 275 mm. The NPV was 10% lower with a 20-year than with a 5-year cutting cycle, due to the high opportunity cost of the growing stock, which was 37% higher with the 20-year cycle (Table III). All the other stand characteristics considered here, stand basal area, volume, CO_2 storage, and tree species and size diversity were substantially higher with the 20-year cycle. Only the annual harvest volume was approximately the same.

Table II. Growing stock and harvest per hectare in steady state for a management that maximized the net present value of timber, without constraint on CO_2 storage.

		Diameter class (mm)										
		75	125	175	225	275	325	375	425	475	525	575
5-year cutting cycle		Trees ha^{-1}										
Spruce	Stock	172	148	132	121	51						
	Harvest					51						
Pine	Stock	2	2	2	1							
	Harvest				1							
Birch	Stock	64	12									
	Harvest		12									
Other broadleaves	Stock	73	46	12								
	Harvest			12								
20-year cutting cycle												
Spruce	Stock	164	138	123	106	77	40	12	1			
	Harvest				52	77	40	12	1			
Pine	Stock	2	2	2	1	1	0	0				
	Harvest				1	1						
Birch	Stock	61	33	10	2	0						
	Harvest		33	10	2							
Other	Stock	84	54	32	14	4	0					
	Harvest			32	14	4						

Table III. Net present value and stand characteristics in steady state for a management that maximized net present value of timber without constraint on CO_2 storage.

	Cutting cycle		
	5 year	20 year	Difference (%)
NPV (1000 NOK ha^{-1})	39.4	35.6	−10
CO_2 stored (Mg ha^{-1})[a]	162.1	195.5	21
Stock value (1000 NOK ha^{-1})[a]	18.9	26.0	37
Stock BA (m^3 ha^{-1})[a]	13.6	15.9	17
Stock vol (m^3 ha^{-1})[a]	102.7	125.4	22
Harvest vol (m^3 ha^{-1} yr^{-1})[a]	6.2	6.3	1
Tree species diversity[a]	0.3	0.4	32
Tree size diversity[a]	0.6	0.7	24

[a]Average over the cutting cycle.

Maximizing CO_2 storage with or without constraints on timber revenues

The management with the purely environmental objective of maximizing unconstrained CO_2 storage led to an almost pure spruce stand (Table IV). The harvest was very small, limited to removing a few hardwoods as soon as they appeared in the smallest size class. The NPV was negative, practically the same for both cutting cycles, and about 170,000 NOK ha^{-1} less than the maximum NPV without CO_2 constraint. When stored CO_2 was maximized in this manner, all the other stand characteristics were also nearly the same with a 5- and 20-year cutting cycle, since the harvest was small and the same in both cases (Table V).

Maximizing CO_2 storage, while maintaining a non-negative NPV led to NPV = 0, due to the direct conflict between NPV and CO_2 storage shown in Figure 1(a). With this management, the internal rate of return of the growing-stock capital was just equal to the guiding rate of interest of 3% per year used in calculating NPV. It caused a loss of NOK 35,000 ha^{-1} to NOK 39,000 ha^{-1} in net present value. However, this option led to a much more varied stand in terms of tree species and size than maximizing unconstrained CO_2 (Table VI). With a 5-year cutting cycle, a larger number and bigger hardwood trees were being maintained than with a 20-year cycle, while there were fewer large spruce trees. Accordingly, the tree species diversity was higher with the 5-year cycle than with the 20-year cycle, while the tree size diversity was the same. The amount of CO_2 stored was similar for the two cutting cycles, 30% less than the maximum unconstrained CO_2 storage (Table VII).

Maximizing returns from timber and stored CO_2

The data in Figure 1 have been recast in Figure 2 to plot the amount of CO_2 stored per ha against the negative of the marginal change in maximum NPV per ha. This is the supply schedule for CO_2 storage, showing how much would be stored per unit area at different prices of CO_2. A positive price of CO_2 is needed to induce more than 200 Mg ha^{-1} of CO_2 storage. Beyond that point, the amount of stored CO_2 rises linearly with the price of CO_2, amounting to about 500 Mg ha^{-1} at a price of NOK 400 Mg^{-1}. Beyond that, the supply curve is almost vertical as the amount of stored carbon approaches its biological limit, and no more storage can be induced regardless of price.

Table IV. Growing stock and harvest in steady state for a management that maximized CO_2 storage without constraint on net present value.

		Diameter class (mm)											
		75	125	175	225	275	325	375	425	475	525	575	625
5-year or 20-year cutting		Trees ha^{-1}											
Spruce	Stock	264	127	85	67	57	51	47	43	38	30	18	5
	Harvest												
Pine	Stock												
	Harvest												
Birch	Stock	4											
	Harvest	4											
Other	Stock	4											
	Harvest	4											

Table V. Net present value and stand characteristics in steady state for a management that maximized CO_2 storage without constraint on net present value, with a 20-year cutting cycle (the results were nearly the same with a 5-year cycle).

NPV (1000 NOK ha^{-1})	−130.5
CO_2 stored (Mg ha^{-1})[a]	629.8
Stock value (1000 NOK ha^{-1})[a]	129.8
Stock BA (m^3 ha^{-1})[a]	45.8
Stock vol (m^3 ha^{-1})[a]	437.8
Harvest vol (m^3 ha^{-1} yr^{-1})[a]	0.04
Tree species diversity[a]	0.01
Tree size diversity[a]	0.92

[a]Average over the cutting cycle.

Figure 3 shows the effects on carbon storage and timber production of managements that maximized the net present value of both, at different carbon prices. Additional stand characteristics are in Table VIII. The data correspond to the conditions at four price levels on the supply curve in Figure 2. The current carbon price is 10–15 USD Mg^{-1} CO_2e (Turner, 2011) or approximately 85 NOK Mg^{-1} at current exchange rates, and the IEA (2009) estimates that in OECD countries the carbon price reaches 50 USD (NOK 285) Mg^{-1} CO_2e in 2020 and 110 USD (NOK 625) Mg^{-1} CO_2e in 2030 if the so-called 450 Scenario is followed (IEA, 2010).

The data in Figure 3 and Table VIII come from solving the optimization problem with objective function (14) subject to constraints (5) to (10), with q=0, 85, 285, or 625 (NOK Mg^{-1} CO_2), other things being held constant. As the price of CO_2 increases from 0 to about 300 NOK Mg^{-1}, the CO_2 stored increases and the annual harvest volume and value also increases (Figure 3). Within that range, there was no conflict, in fact complementarity of carbon storage and timber production. Beyond a CO_2 price of 300 NOK Mg^{-1}, however, the annual harvest decreased as the stored CO_2 continued to increase, although at a decreasing rate. The pattern was similar for 5-year or 20-year cutting cycle, and for both cutting cycles, at the highest CO_2 price of NOK 625 Mg^{-1}, the amount of stored CO_2 was still lower than the maximum amount of CO_2 that could be stored without other constraints (Table VII).

At zero CO_2 price all the NPV comes from timber production (Table VIII). At NOK 85 Mg^{-1} about 60% of the NPV still comes from timber production, but at NOK 285 Mg^{-1} timber production begins to decrease NPV, and even more so at NOK 625 Mg^{-1}, yet the harvest is necessary to maintain the best growing stock and to compensate for the rising cost of capital in growing stock as it rises with carbon storage.

The growing stock and the harvest that maximized NPV from timber and CO_2 at NOK 625 Mg^{-1} of

Table VI. Growing stock and harvest in steady state for a management that maximized CO_2 storage while maintaining a 3% annual rate of return on the timber capital.

		Diameter class (mm)									
		75	125	175	225	275	325	375	425	475	525
5-year cutting cycle		Trees ha^{-1}									
Spruce	Stock	86	61	49	42	37	33	14	1		
	Harvest							10	1		
Pine	Stock	1									
	Harvest										
Birch	Stock	30	19	3							
	Harvest			3							
Other	Stock	372	182	114	82	65	55	40	10		
	Harvest							4	10		
20-year cutting cycle											
Spruce	Stock	205	147	121	105	94	85	67	38	12	2
	Harvest							56	38	12	2
Pine	Stock	1	1								
	Harvest										
Birch	Stock	32	21	9	3						
	Harvest			9	3						
Other	Stock	28	14	9	5	2					
	Harvest				5	2					

Table VII. Net present value and stand characteristics in steady state for a management regime that maximized CO_2 storage while maintaining a 3% annual rate of return on the timber capital.

	Cutting cycle		
	5 year	20 year	Difference (%)
NPV (1000 NOK ha^{-1})	0.0	0.0	
CO_2 stored (Mg ha^{-1})[a]	426.8	434.1	2
Stock value (1000 NOK ha^{-1})[a]	54.1	79.2	46
Stock BA (m^3 ha^{-1})[a]	33.6	32.1	−4
Stock vol (m^3 ha^{-1})[a]	277.4	285.9	3
Harvest vol (m^3 ha^{-1} yr^{-1})[a]	6.3	7.5	18
Tree species diversity[a]	0.5	0.1	−70
Tree size diversity[a]	0.8	0.8	6

[a]Average over the cutting cycle.

CO_2 are shown in Table IX. Compared with the management that maximized NPV from timber alone (Table II), the growing stock had many more spruce trees in the 325 mm to 525 mm diameter classes, while there were fewer trees of other species in most diameter classes. As expected, the stand structure approached that of the stand that maximized CO_2 storage (Table VII), although there were fewer large spruce trees and more trees of other species.

Accordingly, the tree species diversity of the stand tended to decrease as the price of CO_2 increased (Table VIII), which suggests a conflict between carbon storage and some ecological policies. On the other hand, the tree size diversity increased with the price of CO_2 as it led to maintain more large

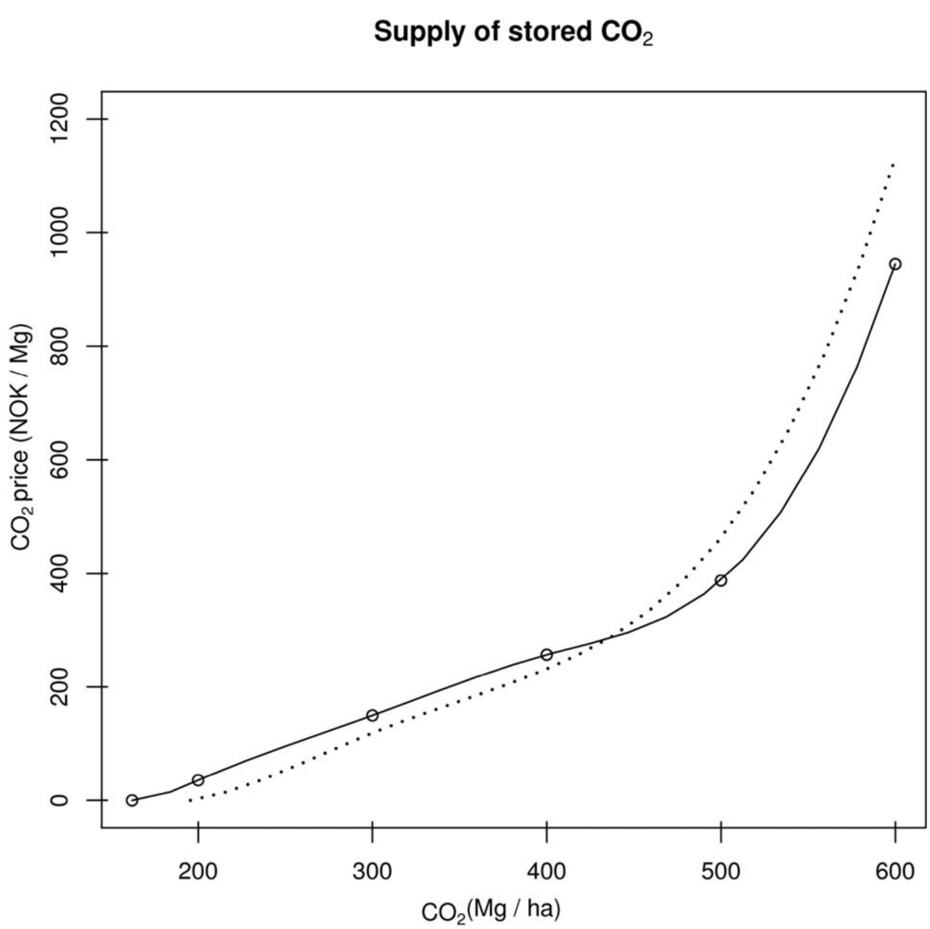

Figure 2. Economic supply curves for CO_2 storage for cutting cycles of 5 years (— ○ —), and 20 years (----).

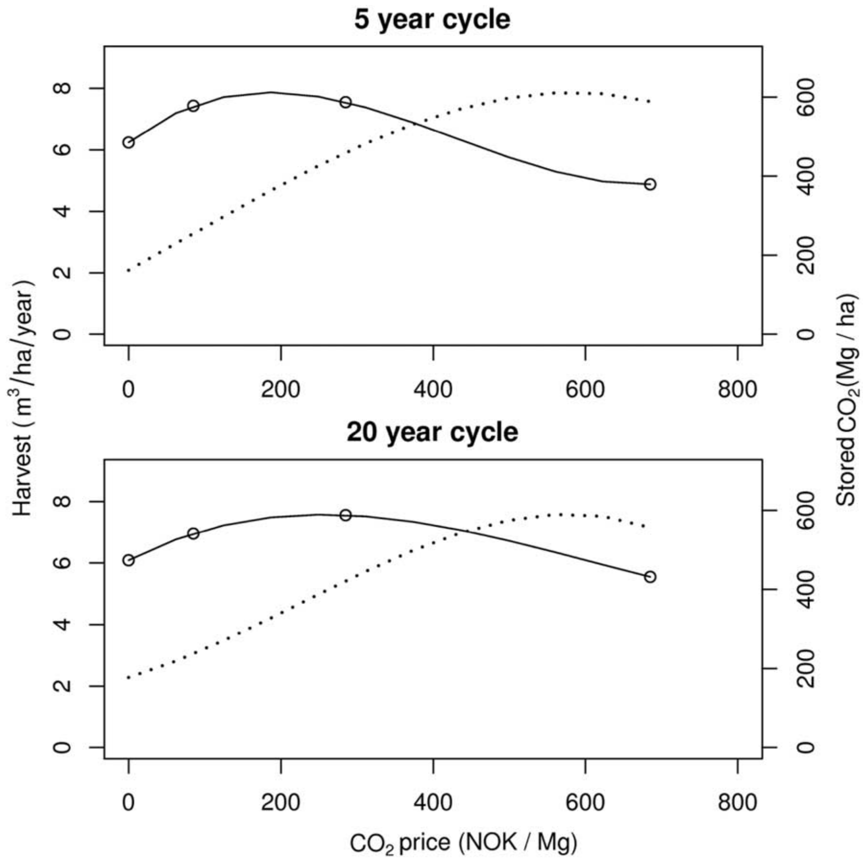

Figure 3. Levels of harvest (–– ○ ––) and stored CO_2 (----) for five and 20-year cutting cycles with management that maximized the net present value of timber production and stored carbon at varying CO_2 prices.

trees. The pattern of the results was similar with the 5- and 20-year cutting cycle. In particular the NPV from timber and CO_2 storage was only marginally higher with the 5-year cutting cycles.

Discussion

A mathematical programming method, coupled with an existing non-linear growth model has been presented to optimize the management of stands dominated by Norway spruce with uneven-aged silviculture. The model was used to obtain sustainable (steady-state) management regimes that maximized selected objectives. The two main criteria were financial returns, measured by net present value, and CO_2 storage, supplemented with measures of stand stocking and diversity of tree size and species.

One main finding was that in this forest type, under prevailing conditions of timber prices, harvest and transport costs, and interest rates, uneven-aged management was profitable. However, the profitability would be lower if timber prices decreased or/and interest rates increased. Also, the economically optimum composition of the stand depends critically on the relative value of the trees of different species. Optimum decision-making under economic or catastrophic risk for this forest type and location should be a subject for further research. One promising approach is to use Markov Decision Process Models to integrate the data used in this study and add the uncertainty stemming from economic, biological, and catastrophic events (Zhou & Buongiorno 2006; Zhou et al., 2008). It has also been suggested that uneven-aged (a.k.a. continuous cover) forestry is more efficient than even aged forestry in storing carbon in boreal forests (e.g. Seidl et al., 2008). Much of this proposition is based on arguments about carbon stored in soil humus and its release after clear felling (Jandl et al., 2007), while the present study dealt only with the woody biomass in trees above and below ground.

Without CO_2 constraint the net present value reached NOK 39,000 ha^{-1} with a 5-year cutting cycle. This differs from Pukkala et al. (2010) who found that a 20-year cutting cycle was optimal. Here, lengthening the cutting cycle to 20 years raised the average carbon storage by 21% and the tree species diversity by 32%, but decreased the NPV by 10%. The opportunity cost of the longer cutting cycle in term of foregone timber revenues was NOK 3800 ha^{-1}. However, the cost may be underestimated, as

Table VIII. Effects of the price of CO_2 on stand characteristics when maximizing the net present value of timber and stored CO_2.

CO_2 price (NOK Mg^{-1})	CO_2 stored (Mg ha^{-1})	Stock value (10^3 NOK ha^{-1})	Stock basal area (m^2 ha^{-1})	Stock volume (m^3 ha^{-1})	Harvest volume (m^3 ha^{-1} yr^{-1})	Harvest value (NOK yr^{-1})	Species diversity	Size diversity	max NPV (10^3 NOK ha^{-1})	NPV from timber (10^3 NOK ha^{-1})
5-year cycle										
0	162.1	18.9	13.6	102.7	6.2	1722	0.31	0.58	39.4	39.4
85	254.7	38.3	20.0	163.7	7.4	2184	0.23	0.65	57.4	35.7
285	459.5	83.7	33.8	302.1	7.5	2282	0.13	0.74	124.6	−6.4
625	588.8	115.7	42.6	397.8	4.9	1466	0.09	0.83	301.9	−66.0
20-year cycle										
0	177.4	23.6	14.4	113.6	6.1	1701.8	0.30	0.72	35.6	35.6
85	236.8	35.3	18.7	152.5	7.0	2027	0.29	0.73	55.4	35.3
285	421.3	76.2	31.2	276.9	7.6	2307.9	0.16	0.80	124.2	4.2
625	555.8	108.4	40.3	373.4	5.6	1689.4	0.10	0.85	297.8	−49.6

[a]Average over the cutting cycle.

the a 20-year cutting cycle of maximum NPV requires a 22% higher volume of growing stock, which would increase the risk of losses due to storms and other catastrophic events.

Seeking maximum CO_2 storage came at high cost in terms of foregone timber revenues. Maximum carbon storage was consistent with very low timber harvest, leading to an opportunity cost of approximately NOK 82,000 ha^{-1} and NOK 97,000 ha^{-1} for the 5- and 20-year cutting cycles, respectively. Furthermore, when NPV was maximized instead of CO_2 storage, the stands contained more birch and other hardwood trees, and more large trees of all species, thus improving the species and size diversity of the stands.

A compromise strategy was illustrated by maximizing CO_2 storage with zero NPV, i.e. with a rate of return on the growing stock investment just equal to the interest rate, set at 3% per year in this case. By using a suitable social rate of interest (Caplin & Leahy, 2004) this approach gives a way of determining management on public lands aimed at carbon storage, while recognizing other social needs. The results suggest that maximizing CO_2 storage would, with an interest rate of 3%, lead to stands of higher species diversity than maximizing unconstrained CO_2 storage, although tree size diversity would be lower.

Still, it is likely that practical management on private as well as public lands would call for objectives that fall between the extremes of maximizing either NPV or CO_2 storage. The maximization of NPV showed that up to about 200 Mg ha^{-1} of CO_2 could be stored at almost no cost in terms of timber revenue foregone. Higher CO_2 stocks reduced revenue from sale of timber substantially. Thus, if society demands more storage, forest owners need to be compensated for this loss, e.g. through the sale of carbon storage to private or public customers.

In that spirit we explored managements that maximized the combined net present value of timber and stored CO_2. The results showed that, other things being equal, the supply of carbon storage, expressed as the amount of CO_2 equivalent stored per ha, increased linearly from 200 Mg ha^{-1} at zero price of CO_2 to 500 Mg ha^{-1} at NOK 400 Mg^{-1} CO_2, and then rose very steeply. Concurrently, the timber supply, in volume per ha per year, also increased initially, so that for CO_2 prices between zero and 300 NOK Mg^{-1} timber supply and CO_2 storage were complementary. Although the harvest declined beyond that price while stored CO_2 increased, timber was still harvested at a price as high as 625 NOK Mg^{-1} in order to maintain the stand structure of highest CO_2 storage, despite the

Table IX. Growing stock and harvest for a management that maximized net present value from timber and CO_2 storage, at NOK 625 Mg^{-1} CO_2.

		Diameter class (mm)										
		75	125	175	225	275	325	375	425	475	525	575
5-year cutting cycle		Trees ha^{-1}										
Spruce	Stock	238	139	102	83	72	64	58	53	47	11	
	Harvest	0	0	0	0	0	0	0	0	0	11	
Pine	Stock	0	0									
	Harvest	0	0									
Birch	Stock	20	11	1								
	Harvest	0	0	1								
Other	Stock	21	8	5	3	2	2	0.5				
	Harvest	0	0	0	0	0	0	0.5				
20-year cutting												
Spruce	Stock	232	140	106	88	76	69	62	57	38	14	2
	Harvest	0	0	0	0	0	0	0	0	38	14	2
Pine	Stock	0	0									
	Harvest	0	0									
Birch	Stock	22	12	5	1							
	Harvest	0	0	5	1							
Other	Stock	22	9	5	4	3	2	1				
	Harvest	0	0	0	0	0	2	1				

net loss of the timber operation alone at that CO_2 price. This is different from Díaz-Balteiro and Romero (2003) finding of "marked difficulty in obtaining from an economic and forestry viewpoint good harvest schedules compatible with high levels of carbon captured."

There are still few instances of concrete payments to timber owners for carbon storage. The Cancun conference gave a better role to forestry to reduce emissions from deforestation and forest degradation (REDD), and the REDD+ extended this to sustainable forest management and afforestation (World Bank, 2011). Australia's Carbon Farming Initiative (CFI) is meant to give new economic opportunities to forest growers. The greenhouse gas Emissions Trading Scheme in New Zealand (NZ ETS), retrospectively covers forestry from January 2008. In California, Assembly Bill 32 allows even the possibility of importing international forest offsets. In Scandinavia, the mining company LKAB had offered to purchase carbon sequestration in northern Sweden (Esping, 2011), but the procedure was not accepted by the European Union. Indeed, the conditions and modalities of offset payments are still being worked out. In this context, the methods and data presented in this paper should be useful to clarify some of the economic issues and opportunities in treating CO_2 storage on a par with timber supply.

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