Economics of forest carbon storage and the additionality principle

Olli Tahvonen and Aapo Rautiainen

CREE – Working Paper 13/2016

The CREE Centre acknowledges financial support from The Research Council of Norway, University of Oslo and user partners.

ISBN: 978-82-7988-236-7
ISSN: 1892-9680
http://www.cree.uio.no

Economics of forest carbon storage and the additionality principle

Olli Tahvonen* and Aapo Rautiainen**

*University of Helsinki, Department of Forest Sciences, Department of Economics and Management, olli.tahvonen@helsinki.fi
**Corresponding author. University of Helsinki, Department of Environmental Sciences, aapo.rautiainen@helsinki.fi

Abstract

The ability of forests to store carbon is vital in maintaining the preset climate conditions, but is not systematically included in forest management or land-use decisions. Economic reasoning suggests subsidizing carbon storage, but empirical models show that this may easily more than double stand-level bare land values. Subsidization may thus be expensive, as it requires paying for all storage, including what would otherwise be obtained for free. To limit the consumption of public funds, the regulator may apply an additionality principle and solely subsidize storage exceeding a baseline level. We show that within a stand-level analysis the additionality principle can be applied without distortions on optimal rotation decisions. However, applying a forest vintage model with endogenous prices and land allocation decisions show that similar application of the additionality principle causes distortions on both land allocation and optimal forest rotation. However, subsidizing carbon storage with forest site productivity tax may still be preferable among the second-best policies. The distortions can be avoided by eliminating excessive subsidies by general land taxation irrespective of whether the land is used for forestry or agriculture.

Keywords: Carbon sequestration, optimal rotation, forest vintages, additionality, afforestation

JEL classification: Q15,Q23,Q54

1 Introduction

Terrestrial ecosystems and forests play a major role in the global carbon cycle and 30% of human-caused carbon emissions are removed from the atmosphere by forests and other vegetation (Pan et al. 2011). This major ecosystem service is not systematically included in natural resources and land-use decisions. The ability of forests to serve as a carbon sink can be viewed as a positive externality that is lost if forestland is converted to other forms, for example industrial or agricultural use. Forest management choices have additionally a major impact on the carbon content per unit of forestland. The aim of our study is to analyze the problems faced in the subsidization of carbon storage at both the levels of a single forest stand and the markets for wood and land.

Van Kooten et al. (1995) suggest that carbon storage can be added to the generic single-stand optimal rotation model by subsidizing carbon flow from the atmosphere to trees. This and many other typically numerical studies suggest that carbon storage lengthens the rotation period. These models are in line with general equilibrium analysis and the first-best policy for subsidizing carbon storage and taxing carbon emissions (Tahvonen 1995). Other suggestions to create incentives for carbon storage and afforestation include subsidizing wood bioenergy (Favero and Mendelsohn 2015) and afforestation (Mason and Plantinga 2013). All these schemas face the question of additionality; both baseline land allocation and forest management also offer carbon storage services, and because using public funds has an opportunity cost, governments may prefer not to pay for non-additional carbon storage. Detailed empirical stand-level studies suggests that paying subsidies for gross carbon storage calls for subsidies that may increase the value of bare forest land to two- or even four fold (Niinimäki et al. 2013). Country-level econometric studies on subsidizing afforestation show a huge cost burden for public funds as well (Mason and Plantinga 2013).

Carbon markets where forest owners can sell carbon offset credits to emitters through voluntary markets has been implemented in Alberta, Canada (Asante and Armstrong 2016). The credibility of this offsetting system is based on additionality: only carbon excess of a predetermined baseline is accounted as additional carbon stored. One possibility of defining the baseline is to compute additionality by subtracting periodic changes in the baseline's carbon stock from periodic changes along the actual development of carbon storage. This procedure may be suitable in the light of stand-level optimal rotation model, as subsidizing solely for additional carbon storage should be possible to implement without distorting the decisions for optimal forest rotations. However, the market and land allocation implications of this application of the additionality principle are open.

While most of the existing economic studies for carbon storage are numerical, we analytically study the stand-level forest management (Section 2), and prove the existence and uniqueness of optimal rotation in the presence of carbon storage. We additionally show that optimal carbon storage may increase or decrease the rotation length. A straightforward option to apply the additionality principle at the stand level without distorting the optimal rotation decision is to use profit or site productivity taxation for eliminating the subsidies for the baseline carbon storage.

Albeit profit and site productivity taxation are typically taken as neutral in forest economic literature, they change decisions between forestry and other land-use forms such as agriculture. To understand the land allocation decisions we include carbon sequestration into a market-level "forest vintage" model (Section 3). This model, originally introduced in economics by Mitra and Wan (1985, 1986), and later extended to cover land allocation between forestry and agriculture by Salo and Tahvonen (2002, 2004) and Piazza and Roy (2015), includes optimal rotation decisions with endogenous timber and land prices. The model is used for carbon storage by Akao (2011) but without land allocation, and by Cunha-e-Sá (2013) for analyzing the IPCC carbon accounting principles. We first develop equations for an optimal steady-state forest rotation period, age-class structure, and land allocation between forestry and agriculture. It is shown that it may be optimal to use a portion of forestland purely for carbon storage. By decentralizing the social planning problem it is shown how applying the additionality principle in the form of a forest site productivity tax causes distortions to land allocation and also potentially for optimal rotation. We present a numerical example for comparing the optimal solution with the other second-best proposals. The comparison clarifies that the problem in subsidizing timber production (Favero and Mendelsohn 2014) or afforestation (Mason and Plantinga 2013) is that these proposals neglect the stand-level possibilities of increasing carbon storage per unit of forestland. As a consequence, the proposals lead to excessive afforestation, increases in agricultural land prices, and consequently decreases in agricultural land area and production. Our proposal for applying the additionality principle is, despite the distortions, a site productivity tax on forestland or, if the aim is to avoid distortions completely, a general tax on land independently of whether land is used for forestry or agriculture.

2 Carbon storage at stand level

Let t denote stand age. Assume that the volume of wood (per ha) is given as a function F of stand age t and that the function satisfies

$$\begin{aligned} &F \in \mathbb{C}^3,\ F(0) \geq 0,\ F\left(0\right) = 0, F(t) > 0 \ for \ t > 0, F'(t) \to 0 \ and \ F \to \hat{F} \\ &as\, t \to \infty,\ F'' > 0 \ \ for \ 0 < \hat{t},\ F'' < 0 \ \ for \ t > \hat{t} \ \ and \ \ F''/F' \, is \ decreasing \ in \ t. \end{aligned} \tag{A1}$$

Thus the function is convex for young stands and concave after stand age has reach the culmination age denoted by $\hat{t}.$ This specification and the assumption that F''/F' is decreasing in t covers several s-shaped functions[1] suitable in this context. Let τ denote the social price of carbon per m^3 of wood and $w \geq 0$ the stand regeneration cost (per ha). The parameters $r \geq 0$ and $p \geq 0$ denote the interest rate and stumpage price (€ per m^3), respectively. The term β $(0 \leq \beta \leq 1)$ is the release of CO_2 from harvested wood products. If $\beta = 1$, all carbon is released immediately (cf the IPCC (2006) "instantaneous oxidation"). If $\beta = 0,$ carbon is stored forever in wood products.

[1] Examples include: $f = \alpha_1(1 - e^{-\alpha_2 t})^{\alpha_3}, \alpha_3 > 1,$ $f = \alpha_1 / [1 + e^{-(t-\alpha_2)/\alpha_3}] - \alpha_4,$ and $f = K / \left[1 + \left(K / f_o\right) - 1)\ e^{-rt}\right] - f_0,$ where all the parameters are positive.

The objective is to maximize Bare Land Value (BLV) by optimizing the rotation length, i.e. the problem is to solve

$$\max_{\{t\geq 0\}} J(t) = \frac{-w + \tau\int_0^t F'(s)e^{-rs}ds + e^{-rt}(p-\tau\beta)F(t)}{1-e^{-rt}}, \tag{1}$$

where the BLV is denoted by J. Differentiating (1) with respect to t and rearranging, leads to the optimality condition

$$J' = \left[p + (1-\beta)\tau\right]F'(t) - r\left[(p-\tau\beta)F(t) + J(t)\right] = 0. \tag{2}$$

It is thus optimal to harvest the stand when the value of marginal growth equals the interest cost of postponing the harvest. Stand growth is valued by the sum of the stumpage price and the value of carbon storage net of released carbon and the harvested wood by the difference between stumpage price and the value of carbon release.

Proposition 1: Given assumptions (A1) and $\hat{F}(p-\tau\beta) - w + \tau\int_0^\infty F'(s)e^{-\delta s}ds > 0$, *a finite optimal rotation period* t^* *exists, is unique and* $J''(t^*) < 0$.

Proof: When $w > 0$ and $t \to 0$ from above $J'(t) \to \infty$ by $F(0) = 0$. When $w = 0$, $J'(t) \to \eta$ by the $L'H\hat{o}spital's$ rule, where η is some nonnegative constant. When $\eta = 0$ it holds that $J'' > 0$ by the assumption $F'' > 0$ when $t < \hat{t}$. Thus, either $J'(t) > 0$ or $J'(t)$ approaches zero from above when $t \to 0$. When $t \to \infty$, $F' \to 0$ and $J' \to -r\left[-w + \hat{F}(p-\tau\beta) + \tau\int_0^\infty F'(s)e^{-rs}ds\right]$, which is negative by assumption. Thus, an optimal finite rotation exists. Differentiation of (2) yields

$$J''(t) = \left[p + (1-\beta)\tau\right]F'' - r(p-\tau\beta)F' - rJ'. \tag{3}$$

The sign of $J''(t)$ equals the sign of

$$y(t) \equiv \frac{F''(t)}{F'(t)} - \frac{r\left(p-\tau\beta\right)}{p+\left(1-\beta\right)\tau} - \frac{rJ'(t)}{F'(t)\left[p+\left(1-\beta\right)\tau\right]}. \tag{4}$$

Let t^* denote the lowest level of t where $J\left(t\right)$ changes its sign and $J'(t^*) = 0$. At t^* the last quotient of $y(t)$ is zero and for t^* to be a maximum it is necessary that $y(t^*) \leq 0.$ Because F''/F' is decreasing in t by (A1), it follows that in any potential $t > t^*$ with $J'(t) = 0$ it must hold that $y(t) < 0.$ As $J'(t)$ is continuous this rules out any optimality candidate with $t > t^*$. Assume that $y(t^*) = J''(t^*) = 0$. Since $J'(t) < 0$ as $t \to \infty$, there must then exist some $t^* < \tilde{t}$ where $y(\tilde{t}) = 0$ and $J'(\tilde{t}) > 0.$ This leads to a contradiction in (4), as $d\left(F''/F'\right)/dt < 0$ and $J'(\tilde{t}) > 0$, implying that $y(\tilde{t}) < 0.$ Thus, it must hold that $J'(t^*) < 0.$ Q.E.D.

In the classic Faustmann model it is not optimal to clearcut if regeneration is mandatory and $p\hat{F} - w < 0$. Our existence condition shows that given carbon pricing, it is not optimal to clearcut if the value of harvested wood net of the costs of carbon release and regeneration falls short of the present value of carbon storage from the subsequent rotation. Carbon storage may cause the nonoptimality of harvesting only if $\beta > 0$. If β is close enough to zero, carbon pricing may lead to forest resources utilization albeit harvesting would not take place without carbon pricing.

Proposition 2: Given the assumptions in Proposition 1, a positive carbon price lengthens the rotation period if $\beta = 1$ and $r > 0$ and shortens it if $\beta < 1$, $r = 0$ and $w > 0$.

Proof: Write the optimality condition (2) as

$$J'(t) = \tau\left\{(1-\beta)F'(t) - \frac{r\int_0^t F'(s)e^{-rs}ds - \beta F\left(t\right)}{1-e^{-rt}}\right\} + pF'(t) - \frac{r[pF(t)-w]}{1-e^{-rt}} = 0. \tag{5}$$

When $\beta = 1$ and $r > 0$, we obtain

$$\frac{\partial J'}{\partial \tau} = -r\frac{\left\{\int_0^t F'(s)e^{-rs}ds - F(t)\right\}}{1-e^{-rt}} > 0.$$

Because $J''(t^*) < 0$ the rotation period becomes longer. When $r \to 0$ it follows that

$$J'(t) \to \tau \left\{ (1-\beta)\left[F'(t) - \frac{F(t)}{t} \right] \right\} + p\left[F'(t) - \frac{F(t)}{t} \right] + \frac{w}{t} = 0 . \qquad (6)$$

In (6) $[\bullet] < 0$, if $w > 0$ implying that a positive carbon price decreases the rotation if $\beta < 1$. Q.E.D.

IPCC's (2006) guidelines recommend accounting the carbon impacts of harvests as if all carbon were released immediately, i.e. $\beta = 1$. As national regulators need to comply with international rules, this assumption of "immediate oxidation" is followed both in carbon accounting of the European Union and in the New Zealand Emission Trading Scheme (Manley and Maclaren 2012). Under these policy conventions carbon pricing thus lengthens optimal rotation. However, we observe that carbon pricing does not change the optimal rotation if interest rate is zero, and all carbon is released immediately at the clearcut. Under these special conditions the use of forest resources may be understood economically as "carbon neutral", as optimal carbon storage does not have any implications on optimal solutions.

We have analyzed the effects of carbon pricing assuming bare land as an initial state. If the initial state is a regenerated stand with initial age equal to $t_0 > 0$ the stand value is different. It is obtained from (1) by eliminating the initial regeneration cost and discounting over the initial age t_0 in addition to eliminating the value of carbon sequestration until t_0. Stand value $J(t_0)$ is thus given as

$$J_{t_0}(t) = w + J(t)e^{rt_0} - \tau\int_0^{t_0} F'(s)e^{-rs}ds. \qquad (7)$$

Because the original objective function is modified by constants, the optimal rotation is independent of the initial stand age. However, this procedure implies that if $\beta > 0$, the forest owner must pay for unsubsidized carbon. This creates perverse incentives and early clearcuts if the subsidy scheme cannot be implemented without notice. To eliminate this problem the regulator must pay for the carbon already stored in the initial stand, i.e. the sum $e^{rt_0}\tau\int_0^{t_0} F'(s)e^{-rs}ds.$

The subsidization scheme specified in model (1) may become rather expensive, as the regulator is subsidizing both for the additional carbon storage and the carbon storage that would occur when the forest owners solely maximize the conventional wood income. One simple possibility of subsidizing solely for additional storage is to levy a tax ℓ (p.a. and per forest hectare) that satisfies

$$\frac{\ell}{r} = \frac{\int_0^{t_f} \tau F'(s) e^{-rs} ds - e^{-rt_f} \tau\beta F(t_f)}{1 - e^{-rt_f}},$$

where t_f is the optimal rotation for problem (1) without carbon pricing. Since ℓ enters problem (1) as a constant, it does not change the forest owner incentives. A similar outcome is obtained by applying a profit tax rate u for bare land value that satisfies

$$u = \frac{\dfrac{\int_0^{t_f} \tau F'(s) e^{-rs} ds - e^{-rt_f} \tau\beta F(t_f)}{1 - e^{-rt_f}}}{J(t^*)}.$$

A study by Niinimäki et al. (2013) serves as a stand-level empirical example on the level of carbon subsidies and the effects of such schema on public funds. The results of their study are based on a detailed empirical growth model with harvesting cost modules, several wood quality categories and detailed wood and paper product decay. Thinning (or intermediate harvests) and initial stand density are optimized in addition to the rotation period. Despite of several differences with the analytical model studies here their results are well in line with ours. Table 1 shows the results from Niinimäki et al. (2013) for a typical Nordic Norway spruce stand when interest rate equals 3%. Increasing carbon price per CO_2 from 0 to €60 increases average carbon storage over the rotation from 104 to 167 tons of CO_2 per hectare, lengthens the optimal rotation from 85 to 114 years, and decreases the present value of income gained from wood production from €1268 to €877. However, the increase in total BLV is nearly quadruple and when the carbon price is €60, the subsidy for both the baseline carbon storage and the additional storage (€4093) is more than seven times higher than the subsidy with the same incentive effects, but based on the additional storage only (€558). These figures suggest that the regulator may have a clear interest to apply the additionality principle to decrease the level of public expenditures. The other observation we can make from Table 1 is that average carbon storage over the rotation increases 1.6-fold if the carbon price increases from zero to €60. This possibility of increasing carbon storage per unit of forestland is completely excluded in suggestions for subsidizing wood burning for bioenergy (Favero and Mendelsohn 2014) and the subsidization of afforestation (Mason and Plantinga 2013).

Table 1.

τ_{CO_2} €	t^* years	BLV €	Wood income €	Gross subsidies/ subsidies for additional storage €	Average carbon storage over rotation $t\,CO_2$
0	85	1268	1268	0/0	104
20	101	2329	1062	1267/13	142
40	109	3608	894	2714/244	165
60	114	4970	877	4093/558	167

Note: all figures per hectare, τ_{CO_2} social price of CO_2
Source: Niinimäki et al (2013).

Albeit the application of the site productivity or profit tax may look neural measures to decrease the burden for public funds they are neutral only in the sense that the rotation decision may remain unaffected. We note that it is optimal to keep land in forestry use or afforest a piece of land only if

$$J\left(t^*\right)-\frac{\ell}{r}\geq L \Leftrightarrow (1-u)\,J\left(t^*\right)\geq L,$$

where L is the value of land in some competing use. To study these effects of subsidization schemes, we switch to market-level analysis with endogenous land allocation.

3 Carbon storage at the market level

We analyze the market-level optimization of timber harvests, carbon storage, and the allocation of land applying the market-level age class model studied in Mitra and Wan (1985, 1986), extended to include land allocation between agriculture and forestry in Salo and Tahvonen (2002, 2004) and

Piazza and Roy (2015). The model is used by Akao (2013) for carbon storage without land allocation, and by Cunha-e-Sá et al. (2013) with land allocation. We first analyze the social planning problem, and next the problem is decentralized as a model of competitive markets with government subsidization and site productivity taxation.

Forests are divided into n age classes. The area of stands in class s at the beginning of period t is x_{st}, $s = 1,...,n$, $t = 0,1,...$. All stands aged n or older are allocated to class n. Agricultural area is y_t, and defined as the complement of total forest area that equals one. The volume of harvestable timber per hectare in age class s is f_s. We assume $f_1 \geq 0$, $f_s < f_{s+1}$, $s = 1,...,n-2$ and $f_{n-1} = f_n$. The total per period harvest is c_t and given as

$$c_t = \sum_{s=1}^{n-2} f_s \left(x_{st} - x_{s+1,t+1} \right) + f_n \left(x_{nt} + x_{n-1,t} - x_{n,t+1} \right). \tag{8}$$

The carbon content depends linearly on wood volume, and let τ denote the social price of CO_2 per cubic meter of wood. This price is an exogenous constant, as the inclusion of a varying or endogenous price is not essential for our results here. The beginning period total wood volume of living trees equals $\sum_{s=1}^{n} f_s x_{st}$. The share $\beta, 0 \leq \beta \leq 1$ of CO_2 in harvested wood is accounted as a source of immediate carbon release as in the stand-level model. Thus the value of per period net carbon inflow in living trees and wood products equals

$$\tau Q_t = \tau \left[\sum_{s=1}^{n} f_s \left(x_{s,t+1} - x_{st} \right) + (1-\beta)\, c_t \right], \tag{9}$$

where the term $(1-\beta)c_t$ equals the inflow of carbon in wood products. Let $D_c(c_t)$ and $D_y(y_t)$ denote the inverse demand functions for wood and agricultural land, implying that the utility functions can be given as $U(c_t) = \int_0^{c_t} D_c(c)dc$ and $W(y_t) = \int_0^{y_t} D_y(y)dy$, respectively. Assuming that regeneration costs are zero and that there are no other forestry costs, $U(c_t)$ can be interpreted as social welfare from timber consumption. Similarly, $W(y_t)$ is the social welfare from agricultural land. Assume that U and W are $\mathbb{C}^2$ and $U'>0$, $U''<0$, $W'>0$ and $W''<0$. Given the discount factor is $0<b<1$, the social maximization problem takes the form:

$$\max_{\{x_{st},s=1,\dots,n,t=0,1,\dots\}} V=\sum_{t=0}^{\infty} b^t\left[U(c_t)+W(y_t)+\tau Q_t\right], \tag{10}$$

subject to

$$x_{s+1,t+1}\le x_{st},\ s=1,\dots,n-2 \ \ and \ \ x_{n,t+1}\le x_{nt}+x_{n-1,t}, \tag{11}$$

$$\sum_{s=1}^{n} x_{st}\le 1, \tag{12}$$

$$x_{st}\ge 0,\ \ s=1,\dots,n, \tag{13}$$

$$x_{s0}\ge 0\ \ s=1,\dots,n\ \ given, \tag{14}$$

$$y_t=1-\sum_{s=1}^{n} x_{st}\,. \tag{15}$$

The objective is to maximize utility from harvests, agricultural land use, and CO_2 storage. The problem during each period is to choose the shares of forest land harvested in each age class and how much bare land is kept in forestry or allocated to agriculture. If $\tau=0$, the model equals that in Salo and Tahvonen (2004), with the exception that age class n stands may remain unharvested.

The Lagrangian for problem (8)–(15) is

$$L=\sum_{t=0}^{\infty} b^t\left\{U(c_t)+W(y_t)+\tau Q_t+\lambda_t\left(1-\sum_{s=1}^{n} x_{s,t+1}\right)+\sum_{s=1}^{n-2}\mu_{st}(x_{st}-x_{s+1,t+1})+\mu_{n-1,t}(x_{nt}+x_{n-1,t}-x_{n,t+1})\right\},$$

where λ_t and μ_{st} are Lagrangian multipliers. The Kuhn-Tucker conditions for $t = 0,1,...$ are

$$b^{-t}\frac{\partial L}{\partial x_{1,t+1}} = bf_1 U'\left(c_{t+1}\right) - bW'\left(y_{t+1}\right) - \lambda_t + b\mu_{1,t+1} + \sigma_1 \le 0, \tag{16}$$

$$b^{-t}\frac{\partial L}{\partial x_{s+1,t+1}} = -f_s U'\left(c_t\right) + bf_{s+1} U'\left(c_{t+1}\right) - bW'\left(y_{t+1}\right) - \lambda_t - \mu_{st} + b\mu_{s+1,t+1} + \sigma_{s+1} \le 0,\ for\ s = 1,...,n-2, \tag{17}$$

$$b^{-t}\frac{\partial L}{\partial x_{n,t+1}} = -f_n U'\left(c_t\right) + bf_n U'\left(c_{t+1}\right) - bW'\left(y_{t+1}\right) - \lambda_t - \mu_{n-1,t} + b\mu_{n-1,t+1} + \sigma_n \le 0, \tag{18}$$

$$x_{s,t+1} \ge 0,\ x_{s,t+1}\frac{\partial L}{\partial x_{s,t+1}} = 0,\ s = 1,...,n, \tag{19}$$

$$\mu_{st} \ge 0, \mu_{st}\left(x_{st} - x_{s+1,t+1}\right) = 0, s = 1,...,n-2; \mu_{n-1,t} \ge 0, \mu_{n-1,t}(x_{nt} + x_{n-1,t} - x_{n,t+1}) = 0, \tag{20}$$

$$\lambda_t \ge 0, \lambda_t\left(1 - \sum_{s=1}^{n} x_{s,t+1}\right) = 0, \tag{21}$$

where, $\sigma_s = \tau[f_s(1-b\beta) - f_{s-1}(1-\beta)],\ s = 1,...,n-1,\ f_0 \equiv 0$ and $\sigma_n = \tau f_n\beta(1-b)$.

The case where all forestland is converted to agricultural land is considered (without carbon storage) in detail by Piazza and Roy (2015). We study equilibria where land area is allocated to both forestry and agriculture. Based on Salo and Tahvonen (2004) and Cunha-e-Sá et al. (2013), we restrict the analysis to steady states that do not contain cycles found in Salo and Tahvonen (2002, 2004) in the case where all land is allocated to forestry.

Let the variables without a time index denote their steady-state values. Let m denote the rotation age and assume $1 < m < n$. This implies that steady states with smooth harvesting must be associated with an age class structure, where the harvested forestland is constant over time and

$x_s = x_{s+1},\ s = 1,...,m-1$ and $x_s = 0,\ s = m+1,...,n-1, x_n \geq 0.$. As a result, agricultural area and all the Lagrangian multipliers are also constant and the steady state satisfies:

$$bf_1U' - bW' + b\mu_1 + \sigma_1 = 0, \tag{22}$$

$$\left(bf_{s+1} - f_s\right)U' - bW' - \mu_s + b\mu_{s+1} + \sigma_{s+1} = 0,\ \ s = 1,...,m-1, \tag{23}$$

$$\left(bf_{s+1} - f_s\right)U' - bW' - \mu_s + b\mu_{s+1} + \sigma_{s+1} \leq 0,\ s = m,...,n-2, \tag{24}$$

$$\left(bf_n - f_n\right)U' - bW' - \mu_{n-1}\left(1-b\right) + \sigma_n \leq 0, \tag{25}$$

where $\mu_s \geq 0,\ s = 1,...,m-1,\ \mu_m = 0,\ \mu_s \geq 0,\ s = m+1,...,n-1$ and $y = 1 - \sum_{s=1}^{n} x_s > 0.$

The system (22) and (23) is linear in $\mu_s,\ s = 1,...,m$ and given

$$\mu_s = W'\sum_{i=0}^{s-1} b^{-i} - U'f_s - \sum_{i=0}^{s-1} \sigma_{i+1} b^{-(s-i)},\ s = 1,...,n-1, \tag{26}$$

(22)–(24) are solved by equalities and the LHS of (25) is nonpositive if

$$f_nU' + \frac{bW'}{1-b} \geq \frac{\sigma_n}{1-b} - \mu_{n-1}. \tag{27}$$

In the absence of carbon storage and $\sigma_s = 0,\ s = 1,...,n$ system (26) is simplified and after multiplying by $b^s / (1-b^s)$ it can be written as

$$\frac{bW'}{1-b} - \frac{f_s b^s}{1-b^s}U' = \frac{b^s}{1-b^s}\mu_s \geq 0,\ s = 1,...,n-1. \tag{28}$$

The steady state must additionally satisfy $\mu_s \geq 0,\ s = 1,...,m-1, m+1,...,n-1.$ These requirements are satisfied if the rotation period m maximizes the bare land value under the given stumpage price, and if the land allocation between agriculture and forestry satisfies (28) with $\mu_m = 0.$ Thus the steady state can be expressed as

$$\frac{bW'(y)}{1-b} = \max_{\{1 \le s \le n\}} \left\{ \frac{b^s f_s U'(x_m f_m)}{1-b^s} \right\}, \; y = 1 - \sum_{s=1}^{m} x_s, \; x_s = x_{s+1}, \; s = 1, \ldots, m-1. \qquad (29)$$

where $W'(y)$ and $U'(x_m f_m)$ are endogenous land rent and stumpage price respectively. In the absence of carbon storage, equation (27) (or 25) is always satisfied as an inequality by the nonnegativity of μ_{n-1} implying that $x_n = 0.$ This last finding is natural as no stand growth occurs between age class $n-1$ and $n.$

The determination of the steady state becomes somewhat more complicated in the presence of carbon storage. Cancelling terms in the latter sum in (26) and multiplying by $b^s/(1-b^s)$ yields

$$\frac{W'b}{1-b} - \frac{f_s b^s}{1-b^s}(U' - \tau\beta) - \tau \frac{\left[f_1 + \sum_{i=1}^{s-1} b^i \left(f_{i+1} - f_i \right) \right]}{1-b^s} = \frac{\mu_s b^s}{1-b^s} \ge 0, \; s = 1, \ldots, n-1 \qquad (30)$$

and by $\mu_s \ge 0, \; s = 1,..,m-1, \; m+1, \ldots, n-1$ and $\mu_m = 0$ we obtain for the cases $m < n$:

$$\frac{W'(y)b}{1-b} = \max_{\{1 < s \le n-1\}} \left\{ \frac{f_s b^s}{1-b^s} \left[U'(x_m f_m) - \tau\beta \right] + \tau \frac{\left[f_1 + \sum_{i=1}^{s-1} b^i \left(f_{i+1} - f_i \right) \right]}{1-b^s} \right\}, \qquad (31)$$

where $y = 1 - \sum_{s=1}^{m} x_s, \; x_s = x_{s+1}, \; s = 1, \ldots, m-1$. In (31) the maximum holds under taking U' constant implying that $\mu_s > 0, s \ne m$ in (30) are satisfied.

The value of agricultural land, on the LHS in (31), is the discounted stream of future marginal utilities. Forest bare land value on the RHS consists of discounted value of harvest valued by marginal utility from wood and value of carbon storage from all future rotations. The marginal utility from harvests $U' - \tau\beta$ is given net of the value of carbon release.

In addition to (31), the solutions must satisfy (27) (or 25). Recalling that $\sigma_n = \tau\beta f_n(1-b)$ and $f_{n-1} = f_n$ enables to write (27) in the form

$$(U' - \tau\beta) f_{n-1} + \frac{bW'}{1-b} \geq -\mu_{n-1}. \tag{32}$$

This condition is always satisfied as an inequality, i.e. $x_n = 0$ when the marginal utility (net of the negative effect on carbon storage) from clearcutting the last land unit from age class $n-1$ plus the value of bare land is positive. Assume that $m = n-1$, implying that $\mu_{n-1} = 0$. If the LHS of (32) is negative, the solution $x_n = 0$ fails to satisfy the necessary optimality conditions and it is optimal to leave part of the land unharvested as age class n forest. In this case the optimal steady state and the two unknowns x_{n-1} and x_n satisfy (31) and

$$\frac{bW'(y)}{1-b} + U'(c) f_{n-1} = \tau\beta f_{n-1}, \tag{33}$$

where $y = 1 - x_n - x_{n-1}(n-1)$ and $c = x_{n-1} f_{n-1} / (n-1)$. In this equilibrium stands are thus harvested as $n-1$ periods of age and a part of the land is conserved purely for carbon storage.

If $U'(0)$ is bounded, a high enough value of τ implies that (33) is satisfied only with $x_{n-1} = 0$. In these cases the utility net of the carbon release value from harvesting the marginal unit of forest land from the oldest age class falls short of the marginal value of agricultural land (i.e. bare land value). This condition looks seemingly different from the existence condition for optimal finite rotation in our Proposition 1. However, close investigation reveals a clear connection: according to the stand-level existence condition it is optimal to clearcut as long as the clearcut revenues net of the value of released carbon (possibly negative) exceed the regeneration cost, and the value of maximum carbon storage from the next rotation. In this case the last two terms denote the bare land value as the rotation period approaches infinity.

Decentralization and the additionality principle

To study the effects of the additionality principle at the market level, we present the model for market interactions between a landowner producing wood and renting out agricultural land, and a buyer of wood and an agricultural producer who pays for land tenure. All actors are price-takers. For simplicity, we allocate the emissions responsibility to the landowner.

The landowner's objective is to maximize the sum of discounted profits, π, by the choice of forest harvesting decisions and land allocation between forestry and agriculture. Timber price, land rent, and the tax per forest land area are denoted p_{ct}, p_{yt} and ℓ, respectively. The land owner has perfect foresight of the future price development. In this respect the landowner's maximization problem resembles e.g. the households' consumption-savings optimization problem in the Ramsey-Cass-Koopmans model (Ramsey 1928, Cass 1965, Koopmans 1965), which is reviewed in standard macroeconomic textbooks, e.g. Romer (2001, p. 47). The regulator applies the carbon subsidy and the additionality principle motivated tax. The landowner's problem is to

$$\max_{\{\mathbf{x}_t\}} \pi = \sum_{t=0}^{\infty} b^t \left[p_{ct}c_t + p_{yt}y_t + \tau Q_t - \ell \sum\nolimits_{s=1}^{n} x_{st} \right], \tag{34}$$

subject to (8)-(9)-(11)-(15). The Lagrangian is

$$\tilde{L} = \sum_{t=0}^{\infty} b^t \left\{ p_{ct}c_t + p_{yt}y_t + \tau Q_t - \ell \sum\nolimits_{s=1}^{n} x_{st} + \lambda_t \left(1 - \sum_{s=1}^{n} x_{s,t+1} \right) + \sum_{s=1}^{n-2} \mu_{st}(x_{st} - x_{s+1,t+1}) + \mu_{n-1,t}(x_{nt} + x_{n-1,t} - x_{n,t+1}) \right\}$$

and the first three Karush-Kuhn-Tucker conditions for all $t = 1, \ldots, \infty$ are

$$b^{-t} \frac{\partial L_P}{\partial x_{1,t+1}} = bf_1 p_{ct} - bp_{yt} - b\ell - \lambda_t + b\mu_{1,t+1} + \sigma_1 \leq 0, \tag{35}$$

$$b^{-t} \frac{\partial L_P}{\partial x_{s+1,t+1}} = -f_s p_{ct} + bf_{s+1} p_{c,t+1} - bp_{y,t+1} - b\ell - \lambda_t - \mu_{st} + b\mu_{s+1,t+1} + \sigma_{s+1} \leq 0,\ s = 1, \ldots, n-2, \tag{36}$$

$$b^{-t}\frac{\partial L_P}{\partial x_{n,t+1}} = -f_n p_{ct} + bf_n p_{c,t+1} - bp_{y,t+1} - b\ell - \lambda_t - \mu_{n-1,t} + b\mu_{n-1,t+1} + \sigma_n \le 0. \tag{37}$$

The other conditions are equivalent to (19)–(21). Let S_c and S_y denote the discounted sum of periodic surpluses incurred by the wood buyer and agricultural producer respectively. They choose c_t and y_t over time to

$$\max_{\{\mathbf{c}_t\}} S_c = \sum_{t=0}^{\infty}\left(\int_0^{c_t} D_c(c)dc - p_{ct}c_t\right)b^t, \tag{38}$$

$$\max_{\{\mathbf{y}_t\}} S_y = \sum_{t=0}^{\infty}\left(\int_0^{y_t} D_y(y)dy - p_{yt}y_t\right)b^t. \tag{39}$$

Substituting $\int_0^{c_t} D_c(c)dc = U(c_t)$ and $\int_0^{y_t} D_y(y)dy = W(y_t)$ into (38) and (39) and differentiating with respect to c_t and y_t, we obtain the first-order necessary conditions

$$b^{-t}\frac{\partial S_c}{\partial c_t} = U'(c_t) - p_{ct} = 0, \tag{40}$$

$$b^{-t}\frac{\partial S_y}{\partial y_t} = W'(y_t) - p_{yt} = 0, \tag{41}$$

for all $t = 1,...,\infty$. In the market equilibrium, the seller's and buyer's optimality conditions must both hold. From (39) and (40) we obtain $p_{ct} = U'(c_t)$ and $p_{yt} = W'(y_t)$. Substituting these prices into (35)–(37) shows that the regulated market equilibrium conditions coincide the conditions for social optimality when the tax for forestland is zero, i.e. $\ell = 0$. When the tax is positive, repeating similar steps as in studying the social optimum leads for $m < n$

$$\frac{W'(y)b}{1-b} = \max_{\{1<s\le n-1\}}\left\{\frac{f_s b^s}{1-b^s}\left[U'(x_m f_m) - \tau\beta\right] + \tau\frac{\left[f_1 + \sum_{i=1}^{s-1} b^i\left(f_{i+1} - f_i\right)\right]}{1-b^s} - \frac{b\ell}{1-b}\right\}, \tag{42}$$

where $y = 1 - \sum_{s=1}^{m} x_s$, $x_s = x_{s+1}$, $s = 1,...,m-1$, where m satisfies (42) and

$$(U' - \tau\beta) f_{n-1} + \frac{b(\ell + W')}{1-b} \geq -\mu_{n-1}. \tag{43}$$

In (42) the price of agricultural land is the discounted flow of future land rents. Forest bare land value on the RHS consists of discounted timber income and carbon subsidies from all future rotations. The term $U' - \tau\beta$ is the market price of wood net of the sum landowners or sellers of wood must pay for CO_2 release per unit of wood. An alternative approach is to hold the buyers of wood responsible for the release of CO_2. In this case the market price of wood would be lower as buyers must pay $\tau\beta$ for emissions. However, the bare land value remains unchanged, as the decrease in the landowner's wood revenues is countered by not paying the CO_2 taxation. For the buyers' the market price is lower but their net cost of consuming wood stays the same, as they must pay the tax on CO_2 release.

The tax on forestland in the RHS of (42), in addition to distorting the land allocation between agriculture and forestry may change the rotation due to effects on wood and land prices. Equation (43) shows that the tax works against conserving part of forestland purely for carbon storage.

In Figure 1 the market-level solutions are characterized by the aim of a numerical example[2]. The model is solved as a nonlinear programing problem with 200 periods horizon length applying Knitro optimization software (version 10.1). This horizon is long enough to obtain a solution with transition toward a steady state. As shown, optimal carbon storage increases forestland area and wood production. The steady-state rotation age increases from 75 years to 90 years. The value of carbon storage without carbon pricing is 4 monetary units, while the regulator cost burden in

[2]The parameter values are: $U(c) = c^{\frac{1}{2}}$, $W(y) = 3y^{\frac{1}{2}}$, $b = 0.95$, $\tau = 0.2, \beta = 1$, $f_s = 0,\ 0,\ 10,\ 15,$ $22,\ 30,\ 40,\ 51,\ 65,\ 82,\ 101,123,\ 148,\ 173,\ 197,\ 215,\ 229,\ 241,\ 251,\ 260,\ 269,\ 277,\ 284,$ $288,\ 291,\ 292,\ 292$, $x_{s0} = 0.02, 0, ..., 0$. Period length 5 years.

applying the optimal policy is 7.4 units. Thus, more than half of the burden is related to the baseline carbon storage. In Figure 1 we apply the additionality principle and set the site productivity tax at a level that would eliminate baseline subsidies if forest owners did not react to the associated land allocation incentives. The site productivity tax decreases forestland area, but simultaneously the carbon subsidy effect is the reverse. The net effect is an increase in forest land area implying that the regulatory cost burden is lower than expected, i.e. 1.3 monetary units. As shown in Figure 1c, the steady-state carbon storage is lower than optimal.

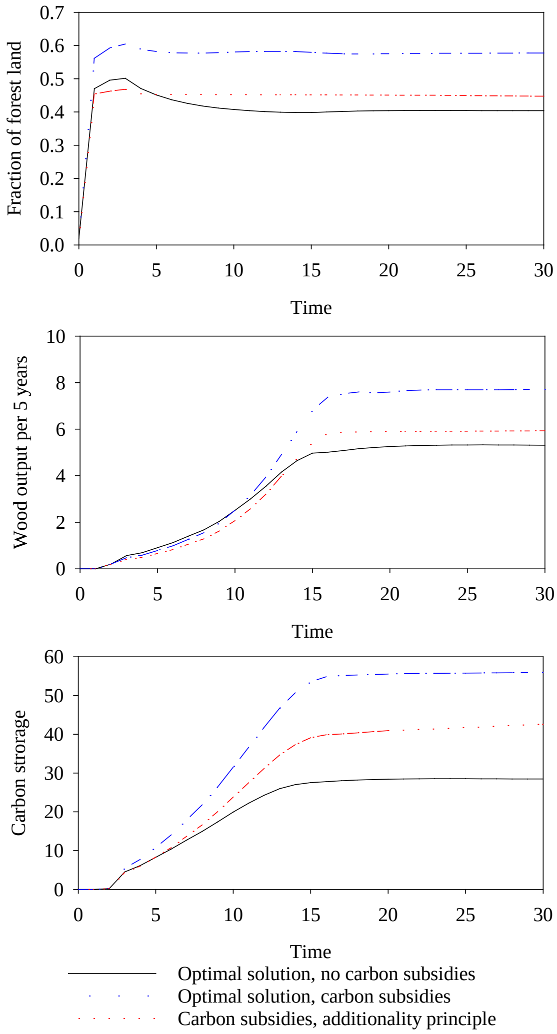

Figure 1. Time development of land allocation, wood production and carbon storage
Parameter values: see the text

Table 1 describes the setup from a somewhat different angle. The additionality principle is applied to reach the same steady-state carbon storage as in the first-best optimal solution. This requires applying a higher carbon subsidy (0.215 vs. 0.200 monetary units). The regulatory cost burden is lower than in the first-best optimum, but land allocation, rotation period and market equilibrium are distorted. The last two columns show the outcomes if carbon storage incentives will be based on afforestation subsidies as suggested by Mason and Plantinga (2013), or wood production subsidies as suggested by Favero and Mendelsohn (2014)[3]. Both methods lead to overly high forest land area and timber production while the rotation period remains at the baseline level. In addition, without applying additionality principles these methods (in the given example) yield a much higher regulatory cost burden than the first-best policy.

The first-best policy and the additionality principle could be implemented by applying a lump sum tax to both forest and agricultural land. In our model this may not cause strong opposition from the representative landowner as she owns both land types and the carbon subsidization policy will in any case increase the landowner welfare. However, the situation may be different if some land owners own agricultural land, only albeit carbon storage leads to increases in their land rent.

Table 1. Outcomes of various policy alternatives

Variable/ policy option	Optimal solution, no carbon subsidies	Optimal solution, carbon subsidies	Carbon subsidies, additionality principle	Subsidy on afforestation/ tax on deforestation	Subsidy on wood production
Forest land area[1]	0.40	0.58	0.51	0.8	0.8
Wood output[1]	5.30	7.7	6.6	10.5	10.4
Carbon storage[1]	28.46	56	56	56	56
Rotation period[1]	75	90	105	75	75
Value of carbon stored[2]	4.0	7.4	8.9	8.2	7.8
Regulatory cost[2]	0	7.4	4.1	26.7	28.35
Welfare[2]	78.3	83.7	83.4	80.8	80.2

[1]Steady-state values
[2]Present value over 750 years

[3] In their argumentation Favero and Mendelson (2014) refer to the “carbon neutrality” of forestry. This view is questionable since it neglects the time lag between emission increases and future sequestration.

4 Conclusions

Increasing the carbon storage of forests is an option that cannot be neglected by economically efficient policy that aims to decrease global net CO_2 emissions. In many countries forests are mainly privately owned, raising the question how to create incentives for carbon storage. As carbon storage represents negative emissions, subsidizing storage is a natural starting point. However, such subsidy leads to a high regulatory cost burden, and trying to avoid this problem easily destroys economic efficiency. First-best optimality under the additionality principle could be aimed for by increasing general land taxation and a second best solution applying site productivity taxation in forestry. The problems related to the second best policy depends on the possibilities to switch land use between agriculture and forestry and may not be overwhelming in Nordic countries where major part of forest land does not have alternative use. The situation may be very different in tropics, for example. Suggestions for subsidizing wood production or afforestation neglect the possibilities of developing management measures, such as planting, thinning, rotation and perhaps tree species diversification which can be used to increase carbon storage per land unit. Stand-level studies suggest that these methods may lead to large and low cost increases in sequestrated carbon. Additionally, they may have positive side effects on biodiversity, and their use helps to prevent the price increase of agricultural land and agricultural products caused by afforestation.

References

Akao, K-I. 2011. Optimum forest program when the carbon sequestration service of a forest has value. Environmental Economics and Policy Studies 13:323–343.

Asante, P. and Armstrong, G., 2016. Carbon sequestration and the optimal forest harvest decision under alternative baseline policies. Canadian Journal of Forest Reseach 46: 656-665.

Carbon Dioxide Information Analysis Center, 2013. Recent Greenhouse Gas Concentrations. DOI 10.3334/CDIAC/atg.032 Cited April 2013

Cass, D., 1965. Optimum growth in an aggregative model of capital accumulation. Review of Economic Studies 32: 233-240.

Cunha-e-Sá M.A., Rosa R., Costa-Duarte C., 2013. Natural carbon capture and storage (NCCS): Forests, land use and carbon accounting. Resource and Energy Economics 35:148–170

Faustmann M., 1849. Berechnung des Wertes welchen Waldboden sowie noch nicht haubare Holzbestände für die Waldwirthschaft besitzen. Allgemeine Forst- und Jagd-Zeitung 15:441–455

Favero, A, Mendelsohn, R. 2014. Using Markets for Woody Biomass Energy to Sequester Carbon in Forests. Journal of the Association of Environmental and Resource Economists 1: 75-95.

Hoen H.F., Solberg B., 1994. Potential and Economic Efficiency of Carbon Sequestration in Forest Biomass Through Silvicultural Management. Forest Science 40(3):429–451

IPCC, 2006. IPCC Guidelines for National Greenhouse Gas Inventories. Volume 4: Agriculture, Forestry and Other Land Use. Institute for Global Environmental Strategies, Hayama

Koopmans, T.C. 1965. On the concept of optimal economic growth. Pontificiae Academiae Scientiarum Scripta Varia 28: 225–287

Lubowski R.N., Plantinga A.J., Stavins R.N., 2006. Land-use change and carbon sinks: Econometric estimation of the carbon sequestration supply function. Journal of Environmental Economics and Management 51:135–152

Manley B., Maclaren P., 2012. Potential impact of carbon trading on forest management in New Zealand. Forest Policy and Economics 24:35–40

Mason C.F., Plantinga A.J., 2013. The additionality problem with offsets: Optimal contracts for carbon sequestration in forests. Journal of Environmental Economics and Management 66:1–14

Mitra, T., Wan, H.Y., 1985. Some theoretical results on the economics of forestry. Review of Economic Studies LII, 263–282.

Mitra, T., Wan, H.Y., 1986. On the Faustmann solution to the forest management problem. Journal of Economic Theory 40, 229–249.

Niinimäki S., Tahvonen O., Mäkelä A., Linkosalo T., 2013. On the economics of Norway Spruce stands and carbon storage. Canadian Journal of Forest Research 43:637–648

Pan, Y., Birdsey, R., Fang, Y., Houghton, R., Kauppi, P., Kurz, W., Phillips, O., Shvidenko, A., Lewis, S., Canadell, J., Ciais, P., Jackson, R., Pacala, S., McGuire, McGuire, A.D., Piao, S., Rautiainen, A., Sitch, S., Hayes, D. 2011. A Large and Persistent Carbon Sink in the World’s Forests. Science 333: 988–993.

Piazza A., Roy S., 2015. Deforestation and optimal management. Journal of Economic Dynamics & Control 53: 15-27.

Pihlainen S., Tahvonen O., Niinimäki S., 2014. The economics of timber and bioenergy production and carbon storage in Scots pine stands. Canadian Journal of Forest Research 44: 1091–1102

Pohjola J., Valsta L., 2007. Carbon credits and management of Scots pine and Norway spruce stands in Finland. Forest Policy and Economics 9:789–798

Ramsey, F.P., 1928. A mathematical theory of saving. Economic Journal 38: 543–559.

Romer, D., 2001. Advanced Macroeconomics. McGraw-Hill, New York, 651 p.

Salo, S., and Tahvonen, O., 2002. On equilibrium cycles and normal forests in optimal harvesting of tree vintages. Journal of Environmental Econonomics and Management 44: 1–22.

Salo S., and Tahvonen O., 2004. Renewable resources with endogenous age classes and allocation of land. American Journal of Agricultural Economics 86(2):513–530

Samuelson P.A., 1976. Economics of forestry in an evolving society. Economic Inquiry 14:466–492.

Tahvonen O., 1995. Net national emissions, CO_2 taxation and the role of forestry. Resource and Energy Economics 17:207–315

United Nations, 1998. The Kyoto Protocol to the United Nations Framework Convention on Climate Change. United Nations, New York.

United Nations, 2006. Report of the Conference of the Parties serving as the meeting of the Parties to the Kyoto Protocol on its first session, held at Montreal from 28 November to 10 December 2005. Addendum Part Two: Action taken by the Conference of the Parties serving as the meeting of the Parties to the Kyoto Protocol at its first session. United Nations, New York.

United Nations, 2012. Report of the Conference of the Parties serving as the meeting of the Parties to the Kyoto Protocol on its seventh session, held in Durban from 28 November to 11 December 2011. Addendum Part Two: Action taken by the Conference of the Parties serving as the meeting of the Parties to the Kyoto Protocol at its seventh session. United Nations, New York.

van Kooten, G.C., Binkley C.S., Delcourt G., 1995. Effect of carbon taxes and subsidies on optimal forest rotation age and supply of carbon services. American Journal of Agricultural Economics 77:365–374.