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Abstract

Biodiversity conservation in commercial boreal forests requires both longer rotation periods and leaving retention trees to create structural elements of old and decaying wood, to support variety of species. We define analytically in an extended Hartman model the first-best instruments to induce the Faustmannian or Hartmanian private landowners to behave in a socially optimal manner. A fully synchronized combination of subsidy and tax instruments is needed both to lengthen the privately optimal rotation period and to provide an incentive to leave retention trees. With Finnish data for Scots pine, when combined with a harvest tax, the retention tree subsidy is 1000 and 7500 euros per ha in the Faustmann and in the Hartman model, respectively. When combined with a timber subsidy or a site value tax, the retention tree subsidy is 1900 euros per ha in both models. The harvest tax rate varies over the range 40-60 % in the Faustmann model and 20-40 % in the Hartman model, while timber subsidy is between 0.5 and 1.0 %..

JEL Classification: D62, H21, Q23.

Keywords: rotation, green tree retention, biodiversity management.

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1. Introduction

Modern approaches to forest biodiversity conservation rely on the management of forests as a connected network consisting of different types of forests and stands. Entirely preserved forest areas are core of the biodiversity conservation network. Around this core should be built a pattern of buffer zone forests, commercial forests with restricted management and regular commercial forests in which biodiversity conservation is actively taken into account. All parts of the network are linked to each other so as to ensure the interconnection and continuum of forest landscapes (for the literature, see e.g. Franklin 1993, Franklin and Forman 1987, Lindenmayer and Franklin 2002, Hunter 1999, and Swallow et al. 1997).

Biodiversity maintenance in commercial boreal forests implies lengthening rotation ages, promoting tree species diversity and creating new structural elements, such as the volumes of dead and decaying wood (Hunter 1999). The role of tree species diversity and the structural elements is to increase habitats and sustain species diversity. In Nordic countries and elsewhere, the key instrument in creating structural elements in the stand management is leaving retention trees permanently standing at the final harvest.[1]

The notion of green tree retention is of relatively young origin, dating back to the 1990's. It represents a forest management method in boreal forests that is more capable of sustaining biodiversity than conventional clear-cutting. Green tree retention refers to tall, old trees left permanently unharvested in commercial forests. It attempts to mimic natural disturbance regimes in commercial boreal forests. Leaving retention trees has three general objectives. It aims at "lifeboating" species and processes over the forest regeneration phase; it increases structural variation in the stand by creating

[1] In Finland and Sweden leaving retention trees (5-10 tall, old trees per hectare) are recommended by national forest laws. Moreover, forest certification systems (FSC and FFCs) in these countries require the same. Some provinces in Canada have similar requirements, and similar plans exists in the U.S (for a survey, see Vanha-Majamaa and Jalonen 2001).

uneven-aged structures and the amount of dead wood; also it enhances connectivity on a landscape level (Franklin et al. 1997).

Biodiversity maintenance by using green tree retention has recently been analyzed in an extended Hartman rotation model by Koskela et al. (2004). They show that private harvesting solutions, provided by the basic Faustmann or Hartman models, do not reflect the socially optimal solution for biodiversity maintenance. Private solutions entail too short rotation ages and no retention trees. In this paper we shift the focus on policies promoting green tree retention in boreal commercial private forestry. The research task is to find instruments or instrument combinations capable inducing the private landowners to manage biodiversity of their stands in a socially optimal manner. We focus on forest taxes/subsidies targeted to rotation age and on taxes/subsidies targeted to retention trees, and analyze the first-best policy design of alternative instrument combinations and assess their magnitudes in a numerical simulation–optimization model calibrated for the Finnish forestry.

We show analytically that a retention tree subsidy has to be used simultaneously and in synchrony with a corrective tax/subsidy targeted to the rotation age. The rate of the forest tax/subsidy depends on the level of the retention tree subsidy. We assess their magnitudes in a numerical simulation–optimization model calibrated for the Finnish forestry for a typical pine stand in Southern Finland. When combined with a timber subsidy or a site value tax, the size of the retention tree subsidy is about 1900 euros per ha both in the Faustmann and in the Hartman model. If combined with a harvest tax, the retention tree subsidy is 1000 and 750 euros in the Faustmann and Hartman model, respectively. The harvest tax rate varies over the range 40-60% in the Faustmann model and 20-40% in the Hartman model, while timber subsidy is between 0.5 – 1.0% and site value tax is about zero. While combinations where harvest tax is applied result in budget surplus, others lead to budget deficit.

The rest of the paper is structured as follows. In section 2, we include retention trees with their associated benefits to the analysis of socially optimal choice of rotation period and the volume of retention trees. Section 3 outlines the private harvesting solutions. Section 4 is devoted to the examination of the first-best instrument combinations to achieve the socially optimal outcome. In Section 5 we provide a numerical application for the case of Finnish forestry. Finally, a brief concluding section 6 ends the paper.

2. Biodiversity Management in Commercial Boreal Forests: the Social Optimum

In this section we incorporate biodiversity benefits from green tree retention into the Hartman model and define the socially optimal rotation age and volume of retention trees in commercial forests. Because we are analyzing optimal tax policy design, we concentrate on the steady-state analysis and to omit the case of the initial stand.

In the steady-state, the social planner starts with bare (harvested) land, which contains a given volume of retention trees G, and plants new trees. The becoming harvest volume as a function of rotation age is defined by the forest growth function $f(T)$. Let p denote timber price, r real interest rate and c regeneration costs, which we assume to be constant. We will denote by V the present value of the timber production, defined as $V = (pe^{-rT}\left[f(T) - G\right] - c)(1 - e^{-rT})^{-1}$.

We assume that biodiversity benefits accrue both from the green tree retention and the stand itself. Benefits from of the stand can be thought to follow a path of conventional age-dependent pattern. Although the need for a more detailed analysis of the connections between biodiversity and green tree retention is acknowledged, the list of biodiversity benefits from retention trees includes many important features. Retention trees provide a steady flow of deciduous trees and dead wood, which are important for many species (especially many red-list beetles), but have been steadily decreasing in the forests (see Ehnström 2001). Retention trees promote understorey vegetation (especially vascular plants), provided that their volume is high enough. There is also evidence that retention trees actually promote lifeboating of species and processes and is beneficial to species that are sensitive to forest management operations (Hazell and Gustafsson 1999).

Equation (1) expresses biodiversity benefits as a sum of the benefits accruing from the age of the whole stand becoming harvested, and benefits from the retention trees, which reach their biological maturity and decay during the next rotation period.

$$BB = a(T) + v(T,G) = \int_0^T F(x)e^{-rx}dx + \int_T^{2T} B(x,G)e^{-rx}dx \,. \tag{1}$$

The first term, $a(T) = \int_0^T F(x)e^{-rx}dx$, is conventional amenity with $F'(T) > 0$, but is here applied to biodiversity.[2] The second term $v(T,G) = \int_T^{2T} B(x,G)e^{-rx}dx$ describes the biodiversity benefits from retention trees, chosen during the current rotation period and accruing during the next rotation period. Reflecting the long rotation periods in Northern boreal forests, the time between T and $2T$ is assumed to be long enough for the retention trees to decay to a point where they provide biodiversity benefits but their land area can, nevertheless, be replanted. We make the following assumptions concerning biodiversity benefits

$$v_T = \hat{B}(T,G,r) \equiv e^{-rT}\left[B(2T,G)e^{-rT} - B(T,G)\right] > 0 \tag{2a}$$

$$v_{TT} = \hat{B}_T(T,G,r) < 0 \tag{2b}$$

$$v_G = \int_T^{2T} B_G(x,G)e^{-rx}dx > 0\,;\; v_{GG} = \int_T^{2T} B_{GG}(x,G)e^{-rx}dx < 0 \tag{2c}$$

$$v_{TG} = v_{GT} = e^{-rT}\left[B_G(2T,G)e^{-rT} - B_G(T,G)\right] > 0\,, \tag{2d}$$

where $\hat{B}_T = e^{-rT}\left[e^{-rT}2(B_T(2T,G) - rB(2T,G)) - B_T(T,G))\right]$

Interpretation goes as follows. Marginal biodiversity benefit in (2a) is defined as a positive difference in diversity value of green retention between the beginning and the end of the second rotation period. Assumptions in (2a) and (2b) imply that the age of retention trees has decreasing marginal biodiversity benefits. The same is assumed to hold true for marginal benefits from the volume of green tree retention, G by (2c). Finally, the cross-derivative in (2d) indicates that increasing the number (volume) of standing trees increases the marginal utility derived over time from these trees.

The social planner's economic problem is now to choose rotation age T and the volume of retention trees G so as to maximize

$$SW = \left[pe^{-rT}\left[f(T)-G\right]-c+\int_0^T F(x)e^{-rx}dx+\int_T^{2T} B(x,G)e^{-rx}dx \right](1-e^{-rT})^{-1}. \quad (3)$$

The first-order conditions for this problem read as

$$SW_G = -pe^{-rT} + \int_T^{2T} B_G(x,G)e^{-rx}dx = 0 \quad (4a)$$

$$SW_T = pf'(T) - rp\left[f(T)-G\right] + F(T) + B(2T,G)e^{-rT} - B(T,G) - rSW = 0 \quad (4b)$$

From equation (4a), the optimal volume of retention trees is chosen so as to equate the present value of the marginal loss of the harvest revenue with the present value of sum of the marginal utility of retention trees over their whole decaying process. According to (4b), the optimal rotation age is chosen so that marginal return of delaying the harvest by one unit of time equals the opportunity cost of delaying the harvesting. While the former is defined by the sum of the harvest revenue and biodiversity benefits during the first and the second rotation period, the latter includes the interest cost on standing timber and on land.

[2] In what follows, derivatives of a function with one argument are denoted with primes, while

The second-order conditions hold and are expressed as

$$SW_{GG} = \int_{T}^{2T} B_{GG}(x,G)e^{-rx}dx) < 0 \tag{5a}$$

$$SW_{TT} = e^{-rT}\left\lfloor pf''(T) - rpf'(T) + F'(T) + \hat{B}_T(T,G,r)\right\rfloor < 0 \tag{5b}$$

$$D = SW_{GG}SW_{TT} - SW_{TG}^2 > 0\,, \tag{5c}$$

We ask next: How does the privately optimal harvesting behavior relate to the social optimum?

3. Private Landowners and Biodiversity Externalities

How do private landowners value forest amenities? Traditionally, two hypotheses have been presented and used. The most common assumption is that the landowner maximizes the present value of harvest revenue from timber production over infinite series of rotation. In this case the landowner behaves as described in the Faustmann rotation model. An alternative approach - which lies in conformity with some indirect empirical evidence (see e.g. Binkley 1981 and Kuuluvainen et al. 1996) - is to assume that the landowner maximizes the present value of the sum of harvest revenue and amenity services over infinite time horizon, behaving thus like the landowner in the Hartman model.

For the purposes of this paper, we ask: is there evidence on a possibility that the landowners value biodiversity in their own forest? Unfortunately, there are no empirical studies concerning this issue. While the landowners may sometimes put value on some species or land areas, it is plausible to think that typically they do not take into account the whole spectrum of biodiversity. This is especially true when the

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partial derivatives of functions with more than one argument are denoted by subscripts.

stands are interdependent (see Amacher et al. 2004), but most likely it holds also for case of a single stand. Given these considerations we will focus on both basic types of landowner preferences in this section. Thus, the landowner is assumed to behave either in the Faustmannian or Hartmanian way.

When the landowner follows Faustmann model, he maximizes the following present value of harvest revenue from timber production over infinite cycles of rotation

$$V = (pe^{-rT} f(T) - c)(1 - e^{-rT})^{-1} \tag{13}$$

The solution to this problem is well-known (see, for instance, Johansson and Löfgren 1985). The following first-order condition characterizes the private rotation age: $V_T = pf'(T) - rpf(T) - rV = 0$. The Faustmann behavior produces a solution pair $\{T^F, G^F\}$, for which it holds that $G^F = 0$. Therefore, we have $T^F < T^*$ and $G^F < G^*$, where the variables with asterisk refer to the socially optimal choices by (4a) and (4b).

Under the Hartman behavior, the landowner maximizes the present value of the sum of harvest revenue and amenity services over infinite time horizon (Hartman 1976 and Strang 1983). To distinguish the private valuation of amenity services from biodiversity benefits, we denote the landowner's amenity valuation by $A(x)$. This valuation may relate to biodiversity or to some other types of amenities. Hence, the objective function is given by

$$W = (pf(T)e^{-rT} - c + \int_0^T A(x)e^{-rx} dx)(1 - e^{-rT})^{-1}. \tag{14}$$

The first-order condition, $W_T = pf'(T) - rpf(T) + A(T) - rW = 0$, implicitly defines the solution pair $\{T^H, G^H\}$, for which it holds that $G^H = 0$. Therefore, also in the Hartman framework we have that $G^H < G^*$ and, if the landowner values young stands, we also have that $T^H < T^*$. However, if the landowner values old stands the Hartman rotation age may be longer or shorter than the biodiversity benefits based rotation age depending on how biodiversity (age) valuation function $F(T)$ and the private amenity valuation function $A(T)$ relate to each other. For the purposes of the tax design we will denote by K the present value of private amenity benefits, i.e, $K = \int_0^T A(x)e^{-rx}dx(1-e^{-rT})^{-1}$.

Both solutions fail to achieve the socially optimal rotation age and the socially optimal volume of retention trees. Thus, an externality is created. What does the internalization of this externality require? Under perfect information and in the first-best case, having two targets (rotation age, retention trees) requires two instruments (see Tinbergen 1952). Generally, the government should punish the landowners for a too short private rotation age in the way that lengthens it, and it should bribe them to provide an incentive for the landowners to leave retention trees.[3] Thus, a subsidy is needed to retention trees. As for the rotation age, we have many alternatives among forest taxes affecting the rotation age, thoroughly studied in the previous literature (see e.g. Johansson and Löfgren 1985 and Koskela and Ollikainen 2001). We present their comparative statics effects on the rotation age in Table 1.

Table 1. Comparative statics of forest taxation

Forest tax	Faustmann Model	Hartman Model
Harvest tax (x=t,τ)	$T_x^F > 0$	$T_x^H > 0$, as $F'(T) > 0$
Site prod. tax, l	$T_l^F = 0$	$T_l^H = 0$
Site value tax, β	$T_\beta^F = 0$	$T_\beta^H > 0$, as $F'(T) > 0$
Timber tax, α	$T_\alpha^F < 0$	$T_\alpha^H < 0$
Profit tax θ	$T_a^F = 0$	$T_\theta^H > 0$, as $F'(T) > 0$

[3] For a general discussion of the incentive effects of punishing and subsidizing instruments in the case of biodiversity and habitat conservation, see e.g. Innes et al. (1998).

From Table 1, taxes affecting the rotation age include a yield tax (τ) (levied on the harvest revenue), a unit tax (*t*) (called sometimes a severance tax and levied on the volume of harvested timber) and timber tax (α) (levied on the value of growing stand). Property taxes (the site value tax, β, and the site productivity tax, *l*), and the profit tax (θ) are neutral. Therefore, they cannot be used to change the privately optimal rotation period.[4]

4. Optimal First-Best Instrument Combinations for Biodiversity

We now design formally the optimal combination of punishing and encouraging Pigouvian instruments and study how they affect the private landowners behavior by using an approach outlined in a different forestry context by Englin and Klan (1990).[5] We start with the case of harvest revenue maximizer a'la Faustmann, and levy subsidy and tax instruments on the landowner, equating the resulting private first-order conditions with the socially optimal choices and solving this for socially optimal instrument rates.

Thus, we can design three instrument combinations: retention tree subsidy can be used jointly with yield (or unit) tax, timber subsidy or with site value (profit) tax. The two former combinations apply to both Faustmann and Hartman landowners. The last combination, however, can be used only in the case of Hartman landowner, because it causes no rotation effects in the Faustmann framework.

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[4] Only the site productivity tax and the timber tax have qualitatively similar effects in both models. Note that the effects of site value tax and the profit tax, as well as those of harvest taxes, may have positive or negative effects depending on the nature of marginal amenity valuation. Here we report only those signs relevant to biodiversity maintenance.

[5] Note that we study this issue in the absence of government budget constraint. Allowing for a government revenue requirement in the presence of distortionary taxes or subsidies would modify results. For an application of the second best analysis in the Hartman framework with binding government budget constraint, see Koskela and Ollikainen (2003).

A. A combination of retention tree subsidy and yield tax

Under a combination of the yield tax and retention tree subsidy, the objective function of the private landowner in the Faustmann framework reads as $V = (p^* e^{-rT}[f(T) - G] + s(G)e^{-rT} - c)(1 - e^{-rT})^{-1}$, where $p^* = p(1-\tau)$ and $s(G)$ describes a non-linear retention tree subsidy. Choosing T and G optimally yields the following first-order conditions for the private landowner

$$V_G = -p^* + s'(G) = 0 \tag{15a}$$

$$V_T = p^* f'(T) - rp^*[f(T) - G] - rs(G) - rV = 0 \tag{15b}$$

According to (15a), it is optimal to increase the volume of retention trees up to the point, where the marginal subsidy from doing so $(s'(G))$ is equal to the harvest revenue lost, defined by the after-tax timber price (p^*). Condition (15b), defining optimal rotation age as a function of the yield tax, is well-known and evident.

In the case of the Hartman landowner, the objective function, W, reads as

$$W = \left[p^* e^{-rT}[f(T) - G] + s(G)e^{-rT} - c + \int_0^T A(x)e^{-rx}dx \right](1 - e^{-rT})^{-1}.$$

We assume that the landowner's preferences to amenities (the last term in brackets) are identical to those of the society. The first-order conditions for the privately optimal choice in the presence of this instrument combination are

$$W_G = -p^* + s'(G) = 0 \tag{16a}$$

$$W_T = p^* f'(T) - rp^*[f(T) - G] + A(T) - rs(G) - rW = 0\,. \tag{16b}$$

Setting next (15a) equal to (4a) and (15b) equal to (4b) and solving them for optimal $s'(G)$ and τ yields for in the Faustmann case

$$s'(G)_F^* = (1-\tau_F^*)e^{rT}\int_T^{2T} B_G(x,G)e^{-rx}dx \tag{17a}$$

$$\tau_F^* = -\frac{\left[\eta rs(G) + (F(T) - rE) + (\hat{B}(T,G,r) - rH)\right]}{p\left[f'(T) - r\eta(f(T) - G)\right]} \tag{17b}$$

where $\eta = (1-e^{-rT})^{-1}$, $\hat{B}(T,G,r)$ is defined in (2a), $E = (1-e^{-rT})^{-1}\int_0^T F(x)e^{-rx}dx$, and $H = (1-e^{-rT})^{-1}\int_T^{2T} B(x,G)e^{-rx}dx$. In (17b) the denominator is negative due to the first-order condition of for the social optimum (7b). It can be shown that according to (17b), the optimal yield tax rate is positive but less than one, given that older stands yield higher biodiversity benefits, and it depends on timber price, interest rate and marginal amenity benefits as well as on the subsidy rate.[6] From (17a) we can see that the shape of marginal subsidy to retention trees follows the decreasing social marginal biodiversity benefits from retention trees. Because the positive yield tax will lengthen the rotation age, the marginal subsidy is adjusted to the yield tax rate. Thus, we can also conclude that the levels of both instruments should be synchronized in the first-best situation. Finally, note that (17a) defines the optimal marginal rate of the subsidy, not its general level. Hence, there is some freedom of choosing the total subsidy.

In the similar way as above, we obtain by comparing the conditions governing the privately optimal solution with the socially optimal first-order conditions (16a to 4a and 16b to 4b):

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[6] Similar result holds for the unit tax as well. Proof is available upon request. This is due to the fact the timber price is given for the representative landowner. If timber markets were imperfectly competitive, the situation would be different. Then the effects of yield and unit taxes are not qualitatively similar. See e.g. Anderson and de Palma and Kreider (2001) and Delipallah and Keen (1992).

$$s'(G)^*_H = (1-\tau^*_H)e^{rT}\int_T^{2T} B_G(x,G)e^{-rx}dx \tag{18a}$$

$$\tau^*_H = -\frac{\left[\eta rs(G) + (\hat{B}(T,G,r) - rH) + \Omega\right]}{p\left[f'(T) - r\eta(f(T)-G)\right]}, \tag{18b}$$

where $\Omega = (F(T)-rE)-(A(T)-rK) \geq (<) 0$ is the difference between the social biodiversity benefit valuation and private amenity valuation. In most cases it is plausible to think that Ω is positive. However, in some cases it is possible that Ω is negative indicating that the private valuation of amenity benefits is higher than the age-related biodiversity valuation. However, this would not change the sign of numerator in (18a), because benefits from retention trees plausibly dominate Ω in this case. Naturally, higher difference between social biodiversity benefit valuation and private amenity valuation gives rise to higher optimal yield tax, and vice versa.

Economic interpretation of (18a) and (18b) is then as follows. Because the denominator in (18b) is negative due to the first-order condition of social optimum (4b) but numerator is positive, we see that the optimal yield tax rate is positive and depends on timber price, interest rate and marginal amenity benefits as well as on the subsidy rate. Relative to the case, where private landowners follow Faustmann behavior, the optimal yield tax in (18b) is smaller, because when older stands are preferred the Hartman rotation age is longer than the Faustmann rotation age. (This can be seen by noting that now the numerator is smaller than in Faustmann case). Moreover, according to equation (18a), the marginal subsidy to retention trees is higher than in the Faustmann case. This is because the after tax timber price and the opportunity cost of retention trees are higher. Like in the Faustmann case, we can find that the levels of both instruments depend on each other and should be designed in a synchrony.[7]

[7] Also in the Hartman case we can show that the result for the unit tax is qualitatively similar as the respective results for the yield tax.

B. A combination of retention tree subsidy and a timber tax

If society uses a timber tax instead of harvesting taxes the objective function of the private landowner is $V = \left[pe^{-rT}(f(T) - G) + s(G)e^{-rT} - \alpha \int_0^T pf(s)e^{-rs}ds - c \right](1 - e^{-rT})^{-1}$.

The respective first-order conditions for the private optimum are

$$V_G = -p + s'(G) = 0 \tag{19a}$$

$$V_T = pf'(T) - rp[f(T) - G] - rs(G) - \alpha[pf(T) - rU] - rV = 0\,, \tag{19b}$$

where $U = (1 - e^{-rT})^{-1} \int_0^T pf(s)e^{-rs}ds$ and $(pf(T) - rU) > 0$ (see Koskela and Ollikainen 2001a). Interpretation of (19a) is similar to previous case with the exception that now timber price is untaxed. Condition (19b) defines the optimal rotation period as a function of timber tax α.

In the Hartman case, the landowner's objective function reads as

$$W = \left[pe^{-rT}(f(T) - G) + s(G)e^{-rT} - c - \alpha \int_0^T pf(s)e^{-rs}ds + \int_0^T A(x)e^{-rx}dx \right](1 - e^{-rT})^{-1}$$

The optimal choice of rotation age and the volume of retention trees is characterized by

$$W_G = -p + s'(G) = 0 \tag{20a}$$

$$W_T = pf'(T) - rp[f(T) - G] + A(T) - rs(G) - \alpha(pf(T) - rU) - rW = 0 \tag{20b}$$

They define the retention trees and rotation age as a function of the instrument combination.

Equalizing, again, the private Faustmann and social solutions (4a to 19a, and 4b to 19b) gives the optimal $s'(G)$ and α

$$s'(G)_F^* = e^{rT}\int_T^{2T} B_G(x,G)e^{-rx}dx \tag{21a}$$

$$\alpha_F^* = -\frac{\lfloor \eta s(G) + (F(T) - rE) + (\hat{B}(T,G,r) - rH) \rfloor}{pf(T) - rU} \tag{21b}$$

From (21a), the marginal subsidy to retention trees decreases in G, which follows from the decreasing social marginal biodiversity benefits from reserved trees. This subsidy is independent of the timber tax**,** because it does not distort timber price, which determines the opportunity cost of leaving retention trees. In (21b) both numerator and denominator are positive, so that we have a timber subsidy instead of timber tax. This makes sense, because from Table 1 we know that timber tax shortens but timber subsidy lengthens the rotation age. The optimal timber subsidy depends on the present value of the retention tree subsidy. Its optimal size reflects the ratio of the net marginal biodiversity benefits (over their opportunity costs terms), and of the effect of the timber subsidy for timber production.

Finally, we obtain by equating (20a) to (4a) and (20b) to (4b) the following optimal first-best design in the Hartman case

$$s'(G)_H^* = e^{rT}\int_T^{2T} B_G(x,G)e^{-rx}dx \tag{22a}$$

$$\alpha_H^* = -\frac{\lfloor \eta s(G) + \hat{B}(T,G,r) - rH + \Omega \rfloor}{pf(T) - rU}. \tag{22b}$$

where $\Omega = (F(T) - rE) - (A(T) - rK) \geq (<) 0$ is the difference between the social biodiversity benefit valuation and private amenity valuation. From (22a) we can see that the marginal subsidy to retention trees is similar as in the Faustmann case and independent of the timber subsidy with a similar interpretation. In fact, the optimal marginal subsidy rate is the same as in the Faustmann case. The reason is obvious. In both cases there are no incentives to leave retention trees. As for the timber subsidy, α^*, the whole expression is plausibly negative. The denominator is now smaller than under Faustmann model reflecting the landowner's amenity valuation and thus the smaller size of externality caused by private harvesting. Finally, again, the timber subsidy rate is independent on the retention tree subsidy. Like in the earlier case, higher difference between social biodiversity benefit valuation and private amenity valuation gives rise to higher optimal timber subsidy, ceteris paribus.

C. A combination of retention tree subsidy and a site value tax

Finally, suppose that now the government uses a combination of tree retention subsidy and the site value tax, β, (or the profit tax, θ, which is equivalent to the site value tax, see Koskela and Ollikainen 2001a for the proof). The site value tax is levied on the value of land, and the profit tax on net harvest revenue, which coincide. Thus, the private landowner in the Hartman framework has the following objective function

$$W = \left[(1-\beta)\left[pe^{-rT}(f(T)-G) + s(G)e^{-rT} - c\right] + \int_0^T A(x)e^{-rx}dx \right](1-e^{-rT})^{-1},$$

where we assume that also the retention tree subsidy is subject to the tax as it increases the value of the forestland.

The first-order conditions for the privately optimal choice of retention trees and rotation age are

$$W_G = 0 \Leftrightarrow -p + s'(G) = 0 \tag{23a}$$

$$W_T = (1-\beta)\left[pf'(T) - rp(f(T)-G) - rs(G) - rV\right] + F(A) - rK = 0. \tag{23b}$$

From (23a), the site value tax does not matter for the choice of retention trees, so that the volume of green tree retention is determined by equality of timber price and the marginal rate of retention tree subsidy. The optimal condition for the rotation age is conventional and here the site value tax matters, because it changes relative benefits of harvesting revenue and amenity valuation.

By comparing these privately optimal conditions (23a) and (23b) with the socially optimal (4a) and (4b) yields

$$s'(G)^{*} = e^{rT}\int_{T}^{2T} B_G(x,G)e^{-rx}dx \tag{24a}$$

$$\beta^{*} = -\frac{\left[\eta s(G) + \hat{B}(T,G,r) - rH + \Omega\right]}{pf'(T) - rp(f(T)-G) - rV - \eta s(G)}\,. \tag{24b}$$

Thus, the marginal retention tree subsidy is similar as in (21a) and (22b) and independent of the level of site value tax. The optimal site value tax is positive, because, under our assumptions the numerator is negative due to the first-order conditions, but the denominator is positive. The optimal site value tax reflects the net marginal biodiversity benefits relative to net harvest revenue. Moreover, higher difference between social biodiversity benefit valuation and private amenity valuation, defined by Ω, gives rise to higher optimal site value tax, ceteris paribus. Finally, one can be shown that the same outcome holds for the combination of retention tree subsidy and profit tax (see Koskela and Ollikainen 2001a).

5. An Empirical Application to Finnish Forestry

We now illustrate our model by using a complex numerical simulation–optimization model developed for Finnish Forestry. First, we describe the model and drawing on Finnish empirical studies develop our estimates of biodiversity valuation. We then assess empirically the length of the rotation period and the volume of retention trees in the Faustmann, Hartman and our biodiversity model. Drawing on these we then define the optimal instrument combinations capable of adjusting the Faustmannian and the Hartmanian landowner to behave in the socially optimal way.

5.1 The numerical simulation – optimization system

A simulation – optimization system was developed for numerical optimization of the rotation length and amount of retention trees. The simulation system calculates the value of the objective function with the combination of our decision variables, while the optimization system gradually modifies the values of decision variables based on the feedback from the simulation system, and eventually finds the optimal rotation length and volume of retention trees. The algorithm developed by Hooke and Jeeves, and adopted from Osyczka (1984), for non-linear derivative-free optimization was used (see Pukkala and Miina 1997 for more details).

Simulation of stand development is based on individual trees. The simulation begins with bare land with no retention trees and no deadwood. The stand establishment is predicted with the models of Miina and Saksa (2004). The models predict the number of surviving planted trees per hectare, as well as the amount of naturally regenerated pine, spruce, birch, and hardwood coppice. Stand development is simulated in 5-year time steps. Various Finnish models are used to predict the juvenile height growths and diameters of seedlings from the seedling stage to the sapling stage (dbh 5 cm), after which the individual-tree growth models of Nyyssönen and Mielikäinen (1971) are used. A tending treatment is simulated at a stand age of 5 to 20 years (depending on site and planted tree species). It removes all coppices and regulates the frequencies of other trees. The stand establishment and tending costs, used in the simulator, are based on cost statistics.

The self-thinning models of Pukkala and Miina (1997) are used to calculate the maximum stand density for a given mean tree diameter. Mortality occurs when this limit is passed, creating one or several cohorts of standing deadwood (snags). During a time step, a part of a snag cohort forms a down-wood cohort, its relative frequency being equal to the probability of falling down. Both snag and down-wood cohorts decompose with time, the decomposition rate being clearly higher for down-wood than for snags.

Stand development is simulated until the rotation age is reached, after which a final cut is simulated. Retention trees may be left to continue growing, depending on the current input value of the retention tree parameter. The roadside value of the removed volume (gross income) is calculated using user-supplied unit prices of different timber assortments. The assortment volumes are calculated using the taper functions of Laasasenaho (1982). The harvesting cost is calculated with the models of Valsta (1992).

Simulation is continued for three additional rotations, keeping the deadwood cohorts and retention trees of the previous rotation(s). The simulation is otherwise similar as during the first rotation except that there are now initial retention tree cohorts and initial deadwood. The growth of retention trees is simulated using the growth models of Nyyssönen and Mielikäinen (1971). A part of a retention tree cohort is wind-thrown and another part may die of senescence during a time step, the relative frequencies of these new cohorts depending on the probabilities of these events. Dead retention tree cohorts decompose with the same rate as the other deadwood cohorts. A standing deadwood cohort originating from a retention tree cohort falls down with the same probability as other snags.

Retention trees are assumed to reduce the growing space that is available to the other trees: their effect to the other growing stand is simulated through an area multiplier. The share of growing space taken by retention trees is equal to the ratio of the basal area of retention trees to the maximum stand basal area that the site can sustain. If the basal area of retention trees decreases due to mortality, the growing space available to other trees increases creating accelerated growth. It is assumed that the other trees can fully utilize the growing space left by dead retention trees. This kind of simulation is reasonable when retention trees occur in dense and small groups, which is the current practice.

In addition to costs and incomes, the simulator calculates a biodiversity index for the stand at every time point. The biodiversity index is as a weighted sum of scaled values of various structural elements present in the stand. The structural elements are: volumes of different tree species, volumes 10-cm diameter classes, and volumes deadwood components (standing deadwood and down-wood of different tree species). Each element increases the index fast up to certain level ("satisfactory amount") after which its additional contribution becomes very small.

The monetary value (€$ha^{-1}a^{-1}$) of the maximum biodiversity index is a user-supplied parameter. We used Finnish estimates for valuation of biodiversity conservation as a part of normal practices in commercial forestry. A contingent valuation study by Rekola and Pouta (1999) suggests that the mean of WTP for an increase of retention trees from current 15 to 30 would be 40 euros. We calibrate our quadratic biodiversity valuation function to reflect this estimate as follows. The value (VAL_{BD}) of biodiversity index was calculated from equation $VAL_{BD} = WTP_{BD}\ (BD/BD_{max})$, where WTP_{BD} is the value of the maximum biodiversity index (BD_{max}) of the stand.

This estimate will be used in two alternative versions of biodiversity model. In BIODIV I the society values only biodiversity benefits and in BIODIV II it values also other amenities in addition to biodiversity. In this study we interpret that other amenities refer to recreation, because for it there are empirical estimates available. The simulator calculates a recreation index for the stand using the empirical models of Pukkala et al. (1988). Relying on Finnish studies we use the following estimates Rekola and Pouta (1999), focusing explicitly on retention trees, suggests that as the maximum value of the biodiversity index equals 40 euros/ha (WTP_{BD}), and for the amenity benefits we refer to Kniivilä et al. (2002) and set the value of maximal recreational index to 50 euros/ha (WTP_A). The monetary value of the amenities (recreation) of a stand is calculated from $VAL_A = WTP_A(RI/RI_{max})$ where RI is the recreation index of the stand and RI_{max} is the highest possible value of the recreation index.

The objective function value was calculated from the last (fourth) simulated rotation, which was assumed to be repeated to the infinity. The other rotations were used to initialize the steady-state amounts of deadwood and retention tree cohorts, present in the beginning of the last rotation. Next we report the simulation results.

5.2 Simulation Results

Our results are solved for pine under typical growth conditions in Southern Finland without thinning treatment**.** We first solved the privately and socially optimal solution, which provide the benchmarks for levying the instruments. Then instrument combinations were solved for. We present our results in the same order.

A. Benchmark Rotation Ages and Retention Tree Volumes

In Table 2 we report four models in terms of rotation ages, retention volumes and resulting harvests and economic benefits. The first two are the Faustmann and the Hartman for private landowners. The last two are our biodiversity models: in BIODIV I the society values only biodiversity benefits and in BIODIV II also other amenities in addition to biodiversity benefits. In all models we use the value of 0.03 as the real interest rate**.**

Table 2. *The privately and socially optimal rotation ages: Faustmann, Hartman, and Biodiversity models*

	Faustmann Private	**Hartman Private**	**BIODIV I Social**	**BIODIV II Social**
Rotation Age	60	66	64	67
Retention m^3/ha	0	0	7.7	7.9
Mean annual harvest	4.20	4.42	4.17	4.08
Mean annual net income	152	171	157	159
Timber benefit	1013	1026	952	873

Amenity benefit	0	518	0	524
Biodiversity benefit	0	0	250	320
Total benefit (SEV)	**1013**	**1544**	**1202**	**1717**

From Table 2, the rotation ages range from 60 to 67 increasing from private solutions to the socially optimal biodiversity solution. In our example, the private amenity valuation leads to a slightly longer rotation age than BIODV I, but shorter than BIODIV II. The reason to this outcome is that we employ the 50 €/ha valuation from studies mentioned above and it exceeds the willingness to pay for biodiversity, 40 € found in previously mentioned studies. All rotation ages are rather short relative to current Finnish forestry practice. The main reason for this is that, following our theoretical models, we omit commercial thinning, which naturally tends to postpone the optimal age for final felling (see e.g. Pukkala et al. 1998). In Appendix 1 we demonstrate that differences between rotation ages increase considerably for lower values of the real interest rate. Under our forest growth function, the mean annual harvest ranges between 4.08 – 4.42. Thus, biodiversity conservation does not imply any major decrease in timber supply.

Naturally, the volume of retention tree is zero in Faustmann and Hartman models. In the BIODIV I and II models, the amount of retention trees is positive, being about 8 m^3/ha. Because the stand volume at final felling is about 300 m^3/ha, this means that 2.7% of wood biomass is left in the stand as small groups of trees. Biodiversity benefits account for about 25% of timber benefits.

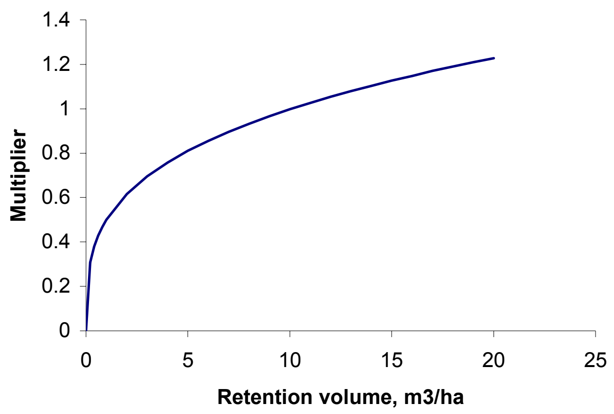
B. Optimal instrument combinations

When calculating the optimal instrument combinations we used the retention volume and rotation age of BIODIV II model as our targets.[8] The retention tree subsidy

[8] Note that adopting BIODIV I model would have slightly changed the results obtained here. As private rotation age is longer than the socially optimal one, the harvest tax rate would become a harvest subsidy and timber subsidy would be a tax.

function was approximated by $s = 0.5G^{0.3}$. Thus, it has a concave shape providing decreasing marginal subsidy, as the theoretical model requires. We had no a priori information for the shape parameters, and they were chosen for convenience, Figure 1 illustrates its shape.

Figure 1. *The shape of the retention tree subsidy function*



We collect the all five possible set of instrument combinations in Table 3 and illustrate part of the search processes in Figures 1 – 5 in Appendix 2. Notation in Table 3 is just like before, thus s denotes retention tree subsidy, τ harvest tax, α timber tax and β site value tax (we showed in the theoretical model that yield and unit taxes behave in a similar manner, thus we here focus solely on the yield tax).

Table 3. Optimal first-best subsidy and tax instrument combinations.

Combination	**Faustmann**		**Hartman**	
s & τ	s = 1000	τ = 40 - 65 %	s = 750	τ = 20 – 40 %

s & α	s = 1500-2500	α = - 1%	s = 1900	α = - 0.5%
s & β	--	--	s = 1700	β = 0 %

Theoretical analysis suggested that the retention tree subsidy and harvest tax rates will differ between the Faustmann and Hartman models in the instrument combination (s & τ). Table 3 clearly exhibits this feature. Due to discontinuities in the simulation model (flat response surface with several local optima), the harvest tax rates are not uniquely defined, however, but are defined by a range. From our theoretical framework we know that the harvest tax rate should be higher in the Faustman model than in the Harman model, and Table 3 verifies this empirically. The retention tree subsidy is higher for the Faustmann model (recall we had higher marginal subsidy for the Hartman model, which implies lower overall subsidy in this model under a concave subsidy function). Interestingly, for the Hartman model we obtain a harvest tax rate range into which the actually applied Finnish yield tax rate, 29%, fits. For the Faustmann model the optimal harvest tax rate clearly exceeds the current Finnish yield tax.

Our theoretical analysis revealed that the retention tree subsidies should be equal in Faustmann and Hartman models in the combination (s & α), because retention tree subsidy was independent of timber subsidy. We can ascertain this to happen in Table 3. The minus marks in the third and fifth columns of this combination (third row) demonstrate that, indeed, we have a timber subsidy. The second column in turn shows the range of retention tree subsidy in the Faustmann model. This range has a mean almost identical to retention tree subsidy in the Hartman model, just as the theoretical analysis required.

The final instrument combination, a retention tree subsidy with the site value tax, is reported for the Harman model in the last row of Table 3. The site value tax was modeled by charging it in the initial planting year. It turned out that site value tax was not required to have the Hartmannian private optimum nearly similar with the social optimum. However, the private optimum had a rotation length one year shorter than the social optimum, which means that a very small site value tax would in fact be the correct instrument level. Recall that theoretical model predicts the same retention tree subsidy as in the previous case. Due to discontinuities of the simulation model and inaccuracies in numerical optimization, the retention tree subsidy is, however, slightly lower than in the previous case.

C. Budget effects of the optimal design of instruments

It is interesting to compare how our instrument combinations affect the government forestry budget. Even though we assume here the first-best instrument combinations, the budget burden of alternative instrument combinations is always important when these policy packages are compared with each other. These effects are collected in Table 4.

Table 4. *Budget effects of optimal instrument combinations*

Model and instruments	Size of subsidy/ 10 m^3	Tax rate	Received subsidies €/ha	Tax payment €/ha	Budget burden
F: subsidy (s) & harvest tax (τ)	1000	60	916	8644	7728 (+)
F: subsidy (s) & timber tax (α)	2000	-1	1866	-496	2362 (-)
H: subsidy & harvest tax (τ)	750	30	689	4468	4298 (+)
H: subsidy (s) & timber tax (α)	1900	-0.5	1786	-248	1538 (-)
H: subsidy & site value tax (β)	1700	0	1490	0	1490 (-)

Drawing on the optimal rates of subsidies and taxes we report the received subsidies and paid taxes over one rotation period in fourth and fifth columns. Their difference indicates both the private net support and the government budget burden and is reported in the sixth column. When the forestry budget exhibits surplus it is indicated by (+) and budget deficit is denoted by (-). Clearly, with two exceptions, where harvest tax is applied, budget is in deficit. This deficit is largest for the combination (s & α) under Faustmann behavior and smallest for the combination (s & β) under Hartman behavior.

Table 4 implies important lessons**.** First, different instrument combinations have different budget impacts. They depend on i) the characteristics of available forest taxes and on ii) the assumption concerning whether the private landowners have amenity valuation. Naturally, if the landowners behave in the Hartmanian way the budget burden will be lower than in the case of Faustmann behavior.

5. Conclusions

We analyzed biodiversity conservation policies at the stand level for commercial boreal forests when retention trees are the key instrument in promoting habitat and species diversity. We solved first the socially optimal rotation age and the volume of retention trees, and compared them with the private solution when the landowner behaves according to either Faustmann or (the basic) Hartman model. In the first best solution, two instruments are needed – one to promote leaving retention trees and another to lengthen the privately optimal rotation age.

Our special focus was in designing the optimal instrument combinations. We demonstrated that a fully synchronized combination of retention tree subsidy and tax instruments is needed to induce the landowner to lengthen the privately optimal rotation period and to provide an incentive to leave retention trees. A retention tree subsidy reflects the marginal biodiversity benefits from retention trees. We show that a retention tree subsidy has to be used simultaneously and in synchrony with a corrective tax/subsidy targeted to the rotation age.

By using a simulation model for Finnish forestry, we assessed empirically the rotation ages and retention tree volumes in the Faustmann, Hartman and biodiversity models.

The rate of the forest tax/subsidy depends on the level of the retention tree subsidy. When combined with a timber subsidy or a site value tax, the size of the retention tree subsidy is about 1700 - 2000 euros per ha both in the Faustmann and in the Hartman model. If combined with a harvest tax, the retention tree subsidy is 1000 and 750 euros in the Faustmann and Hartman model, respectively. The harvest tax rate varies over the range 40-60% in the Faustmann model and 20-40% in the Hartman model, while timber subsidy is 0.5 – 1.0% and site value tax is close to zero. While combinations where harvest tax is applied result in budget surplus, others lead to budget deficit.

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Appendix 1. Sensitivity of optimal solutions to real interest rate

Table 1. Sensitivity of optimal solutions: r = 2%

	Faustmann Private	**Hartman Private**	**BIODIV I Social**	**BIODIV II Social**
Rotation Age	66	66	71	71
Retention m^3/ha	0	0	9.0	9.0
Mean annual harvest	4.42	4.41	4.27	4.27
Mean annual net income	172	167	169	169
Timber benefit	3355	3230	3066	3066
Amenity benefit	0	892	0	971
Biodiversity benefit	0	0	621	621
Total benefit (SEV)	**3355**	**4122**	**3687**	**4658**

Table 2. Sensitivity of optimal solutions: r = 1%

	Faustmann Private	**Hartman Private**	**BIODIV I Social**	**BIODIV II Social**
Rotation Age	71	76	75	101
Retention m^3/ha	0	0	9.8	7.9
Mean annual harvest	4.42	4.41	4.25	4.20
Mean annual net income	174	180	173	183
Timber benefit	11148	11234	10815	9766
Amenity benefit	0	2277	0	2928
Biodiversity benefit	0	0	1675	2619
Total benefit (SEV)	**11148**	**13511**	**12490**	**15313**

Appendix 2. Numerical illustrations of optimal instrument combinations.

Figure 1. Harvest tax and subsidy in the Faustmann model

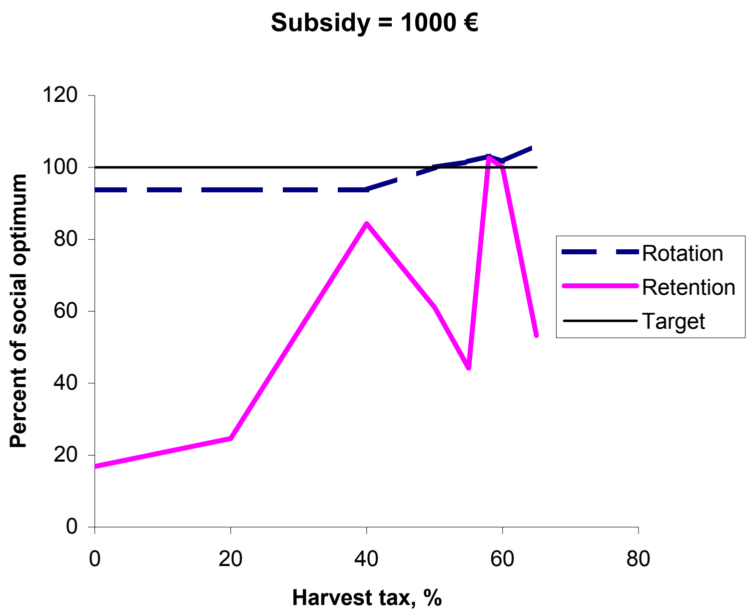

Figure 2. Timber tax and subsidy

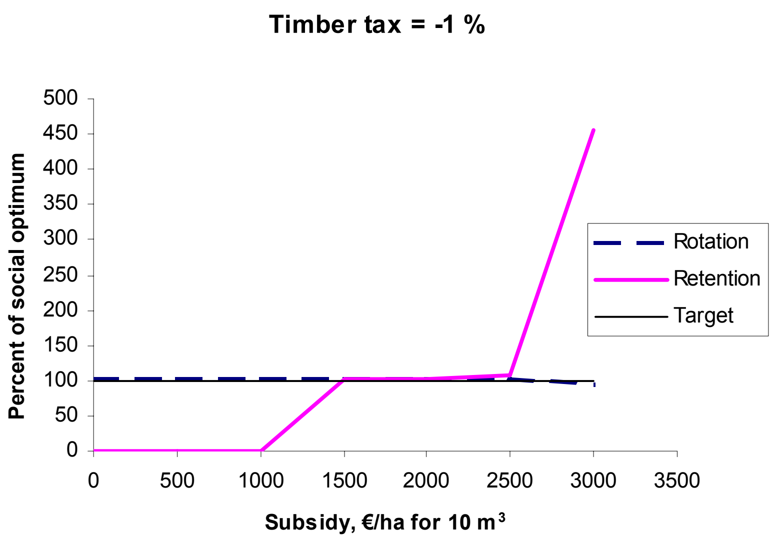

Figure 3. Harvest tax + subsidy in the Hartman model

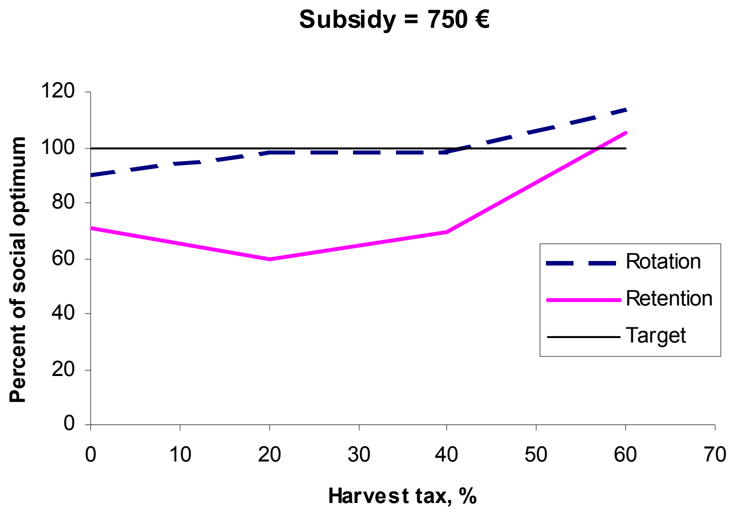

Figure 4. Timber tax and subsidy in the Hartman

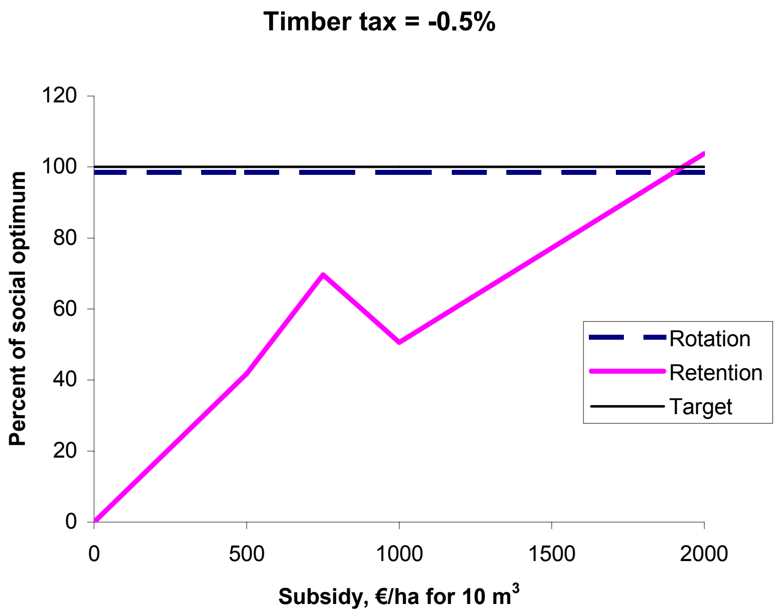

Figure 5. Site value tax and subsidy in the Hartman model