Cost-Effective Measures for Diffuse Load Abatement in Forestry

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This paper theoretically and empirically analyzes the design of cost-effective diffuse load abatement in forestry. Harvesting with related forest regeneration and drainage maintenance increases nutrient leaching, while riparian buffer strips and adjustments in drainage maintenance technology can be used to prevent this leaching. By utilizing a two-period model it is shown that cost-efficiency requires the establishment of a buffer strip system and a reduction in both current harvesting, and in drainage maintenance – if practized – relative to the private optimum to reflect their effects on water pollution. A simulation analysis was conducted to assess the magnitudes of the decision variables of the theoretical model, as well as to evaluate alternative technologies for the implementation and use of buffer strips and for the adjustment of drainage maintenance. The results for a representative forest holding in the southern half of Finland show that it is possible to considerably reduce total phosphorus leaching with minor cost.

Keywords buffer strips, cost effectiveness, drainage maintenance, nutrient leaching

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1 Introduction

Timber management practices in forestry contribute to the diffuse load of watercourses. In forestry, diffuse load is caused, e.g., by drainage and drainage maintenance (also called ditch network maintenance or improvement ditching) on peatlands and clear cuttings with related mechanical site preparation measures on mineral soils. Fertilization of forest lands may also be a significant source of nutrient leaching. In some areas, road construction and landings on shorelands may also cause significant disturbance to water ecosystems. Potential effects of timber management practices on watercourses can be associated, for example, with changes in hydrology, erosion and sedimentation, logging debris, nutrient input, food production, cover and temperature. Some of these changes can also improve the characteristics of watercourses. For example, runoff water pH increases and concentrations of dissolved organic carbon (DOC) decrease after drainage maintenance (Joensuu et al. 2001).

As pollution control for point sources and agriculture becomes tighter, cost-efficiency also requires the control of diffuse load from forestry.

The means of reducing the diffuse load from forestry are various. In addition to imposing limits upon polluting activities, there are many preventive measures for diffuse load abatement in forestry. For instance, it is possible to modify timber management operations within riparian buffer strips. In drainage and drainage maintenance, we can use sedimentation pools and overland flow areas to reduce diffuse load.

In this context, the question of how one conducts the cuttings with related forest regeneration and improvement works so that the water protection targets will be met arises. Previously, several studies have dealt with some aspects of this question. For example, Bren (1995, 1998) examined the geometry of buffer strips and various methods for buffer strip design in forestry. Weller et al. (1998) developed heuristic models for material discharge from landscapes with riparian buffer strips. Yoshimoto and Brodie (1994) analyzed short- and long-term impacts of riparian zone spatial restrictions on harvest scheduling (see also Matero 1996). Kline et al. (2000) examined the willingness of nonindustrial private forest owners to forego harvesting within riparian areas to improve riparian habitat. In the study by Carlén et al. (1999), riparian buffer strips had no significant effect on the net revenue of final logging and were considered as a very cost efficient environmental consideration measure. Kangas et al. (1996) assessed the impacts of drainage maintenance on water ecosystems on the basis of expert knowledge and presented a method to integrate the assessments into decision analysis. Sallantaus et al. (1998) examined the prevention of detrimental impacts of forestry operations on water bodies using buffer zones created from drained peatlands.

Unfortunately, previous literature does not provide a comprehensive theoretical analysis of the features of cost-efficient control of diffuse load from forestry. In addition, an integrated analysis, where the impacts of abatement measures on the overall profitability of forestry and on diffuse load are examined simultaneously, is missing. In this study, I extend previous literature by first characterizing theoretically the relationship between the private optimal and cost-efficient solution in forest management when a social planner takes into account the effects on watercourses. For this purpose I applied a two-period model, which, apart from harvesting, includes endogenous allocation of forest into buffer strips and choice of the intensity of drainage maintenance, and I analyzed its comparative static properties. Furthermore, I combined the empirical information about the impacts of abatement measures on forestry and on the diffuse load of total phosphorus to examine how to choose different abatement measures in a cost-efficient way. I also examined the effect of

List of Symbols

Q	Initial forest stock, m^3 (ha^{-1})
E	Drainage maintenance intensity, m (ha^{-1})
x	Harvest in the current period, m^3 (ha^{-1})
z	Harvest in the future period, m^3 (ha^{-1})
p_1	Timber price in the current period, € m^{-3}
p_2	Timber price in the future period, € m^{-3}
c	Costs of drainage maintenance, € m^{-1}
Π	Present value of the net harvest revenue, € (ha^{-1})
r	Discount rate, dimensionless parameter
α	Extent of uncut riparian buffer strips, m^3 (ha^{-1})
a	Nutrient leaching from cuttings, mass unit m^{-3}
N	Present value of the nutrient leaching, mass unit (ha^{-1})
k	Total number of forest plots
$\bar{N}$	Target for the present value of nutrient leaching from total forest area, mass unit (ha^{-1})
$\bar{n}$	Target for the present value of nutrient leaching from the representative forest plot, mass unit (ha^{-1})
$b(\alpha)$	Present value of the buffer strip retention, mass unit (ha^{-1})
$h(\mathrm{E})$	Present value of the nutrient leaching from drainage maintenance, mass unit (ha^{-1})
λ	Lagrangian multiplier, € mass unit^{-1}

a phosphorus leaching target level on the profitability of forestry.

The remainder of this paper is organized as follows. In Section 2 I first theoretically analyze the choice of a private forest owner between harvesting now and in the future as well as in stand investment by drainage maintenance. I then assume that the government sets a given reduction target for nutrient leaching and study the cost-effective measures of diffuse load control in forestry. In Section 3, following the theoretical model, I present empirical simulations for the private optimal and for the cost-efficient solutions, respectively. Section 4 concludes with a brief discussion.

2 A Theoretical Model for Diffuse Load Abatement in Forestry

In this section, I consider a representative forest plot located near a watercourse. In part of the forest plot, the soil suffers from excess water. Therefore, drainage, which dries the soil, can be used to boost forest growth and, thus, future harvest revenue. I first analyze how a private forest owner chooses between harvesting now and in the future as well as in stand investment by drainage maintenance. I then assume that the government sets a given diffuse load reduction target and study the cost-effective choice of harvesting, drainage maintenance and other measures which affect diffuse load in forestry.

2.1 Private Optimum

Assume that part of the forest plot has been previously drained and that the forest owner can increase forest growth by drainage maintenance investment E in the current period. The forest owner has the initial forest stock Q. In a two-period model, a proportion of the stock, x, is harvested in the current period and another part, z, in the future period. Between the periods the forest stock grows according to a concave growth function $f\,[(Q-x)E]$ with $f' > 0$, $f'' < 0$. This function assumes that growth depends multiplicatively on drainage maintenance intensity, E (see Amacher et al. 1991, 1999). The amount of future harvesting, z, is uniquely determined by the current harvesting and the forest growth rate according to Eq. 2 (for a general presentation of the two-period model and its comparison with rotation model, see e.g. Ovaskainen 1992, Ollikainen 1996).

Assume first that the forest owner ignores the nutrient leaching caused by harvest (with related forest regeneration) and drainage maintenance and that he/she chooses harvest x and drainage maintenance E so that the present value of the net harvest revenue will be maximized. Let p_1 and p_2 denote the timber prices in the current and future periods and c the costs of drainage maintenance. The maximization problem of the forest owner is then given by

$$\underset{\{x,E\}}{Max}\; \Pi = p_1 x + R^{-1} p_2 z - cE \tag{1}$$

$$s.t. \quad z = (Q-x) + f\left[(Q-x)E\right] \tag{2}$$

where R^{-1} is the discount factor and $R = (1 + r)$ with a discount rate r. The first-order conditions for private optimum are as follows:

$$\Pi_x = p_1 - R^{-1} p_2 (1 + f'E) = 0 \tag{3}$$

$$\Pi_E = R^{-1} p_2 f'(Q-x) - c = 0 \tag{4}$$

According to Eq. 3 the forest owner chooses to increase current harvesting until the marginal revenue is equal to the opportunity cost of harvesting, which is given by the present value of the last unit cut if it were left to grow. Condition (Eq. 4) states that the marginal benefits are equal to marginal costs in optimal drainage maintenance.

2.2 Cost-Efficient Solution for Nutrient Leaching Abatement

Nutrient leaching is a harmful by-product of harvesting (with related site preparation) and drainage maintenance. Assume that the social planner wishes to reduce nutrient leaching to a predetermined level with minimum costs. Consequently, the social planner is interested in the trade-off between harvest revenue and nutrient leaching.

In order to reduce nutrient leaching, the forest owner may leave uncut riparian buffer strips, α or/and use some adjustments in drainage maintenance technology. Hence, the nutrient leaching from the forest plot *i* (in present value terms) is determined by

$$N_i = a_i x - b_i(\alpha) + R^{-1} a_i (Q - x - \alpha) + h_i(E) \;; \quad b' > 0, b'' < 0, h' > 0, h'' > 0 \tag{5}$$

where *a* is the polluting effect of cuttings with related site preparation, *b*(α) describes the (combined) capacity of buffer strips to neutralize leaching (in both periods), and *h*(*E*) the technology dependent effect of drainage maintenance on nutrient leaching. Note that the polluting effect of cuttings is specified essentially as nutrient leaching per cutting area (and not per volume), since the growth between the periods, $f[(Q - x - \alpha)E]$, does not contribute to the leaching of cuttings in the future period. Due to varying site-specific factors, e.g. slope or mire type, there can be variation in each coefficient, denoted by subscript i between forest plots.

To account the time pattern of benefits arising from changes in nutrient leaching and in order to make different leaching flows comparable, the physical leaching values are discounted (Eq. 5). Thus, it is assumed that marginal reduction in leaching is just like any other commodity which is contributing to the total welfare of society and must, therefore, be evaluated correspondingly (see Hoen and Solberg 1994). According to Adams et al (1999), discounting yields an exact index if benefits are a fixed function of incremental reductions in leaching and if this link between benefits and reductions in leaching is constant over time. Hoen and Solberg (1994) argued that alternatives for discounting do not provide a consistent intertemporal evaluation.

Hence, the problem of the social planner is to maximize the present value of net harvest revenue for all forest owners, *i* = 1…*k*, subject to the given predetermined leaching requirement. To achieve this leaching requirement the planner can use three variables *x*, α and *E* (Eq. 7).

$$\underset{\{x,\alpha,E\}}{Max} \sum_{i=1}^{k} \Pi_i = \sum_{i=1}^{k} p_1 x_i + R^{-1} p_2 z_i - cE_i \tag{6}$$

$$s.t. \sum_{i=1}^{k} N_i = \sum_{i=1}^{k} a_i x_i - b_i(\alpha) + R^{-1} a_i (Q - x - \alpha) + h_i(E) \le \bar{N} \tag{7}$$

$$z = (Q - x - \alpha) + f\left[(Q - x - \alpha)E\right] \tag{8}$$

where $\bar{N}$ is the target level for the nutrient leaching from totally k forest plots. By defining the target in terms of nutrient leaching instead of nutrient concentration in watercourses, we implicitly assume that the watercourses are reversible without internal load (see eg. Marttunen 1998, Carpenter et al. 1999). To find the necessary conditions of the optimum solution, the Lagrangian for the representative forest owner can be written as

$$L_i = p_1 x + R^{-1} p_2 z - cE + \lambda\left[\bar{n} - ax + b(\alpha) - R^{-1} a (Q - x - \alpha) - h(E)\right] \tag{9}$$

where $\bar{n}$ is the target level for the nutrient leaching from the representative forest plot. After eliminating z from Eq. 9 and assuming an interior solution, the optimum is then defined by the following first-order conditions:

$$L_x = p_1 - R^{-1} p_2 \left[1 + f'(y)E\right] - \lambda\delta = 0 \tag{10}$$

$$L_\alpha = -R^{-1} p_2 \left[1 + f'(y)E\right] + \lambda\phi = 0 \tag{11}$$

$$L_E = R^{-1} p_2 f'(y) v - c - \lambda h' = 0 \tag{12}$$

$$L_\lambda = \bar{n} - ax + b(\alpha) - R^{-1} a (Q - x - \alpha) - h(E) = 0 \tag{13}$$

where $y = [(Q - x - \alpha)E]$, $\delta = (1 - R^{-1})$, $\phi = (b' + R^{-1}a)$ and $\nu = (Q - x - \alpha)$.

The conditions can be interpreted as follows: according to Eq. 10, current harvesting is increased to the point where the marginal revenue equals the marginal opportunity cost of cutting, which consists of foregone harvest revenue in the future period and the cost of nutrient leaching in the current period instead of the future period. Eq. 11 tells us that buffer strips are left to the extent where the marginal cost of buffer strips in terms of foregone harvest revenue in the future period (the first term) is equal to marginal benefit in terms of reduced nutrient leaching (the second term). Note that the leaching reduction consists of two parts: a combined buffer retention in both periods (b') and source elimination in the future period ($R^{-1}a$). According to Eq. 12, drainage maintenance is increased up to the point where the marginal revenue in terms of increased future harvest revenue is equal to the sum of marginal input costs of drainage maintenance and the marginal (shadow) cost of nutrient leaching caused by drainage maintenance.

Conditions (Eqs. 10 to 12) can be rearranged and combined so that the ratio of marginal costs is equal to the ratio of marginal benefits between all the decision variables (condition for the cost efficiency). In other words, the first-order conditions implicitly determine the cost efficient level for the current harvest, buffer strips and drainage maintenance (with possible adjustments) simultaneously. Condition in Eq. 13 holds if we assume that the leaching constraint is binding (i.e. if the nutrient leaching in the private optimum exceeds the target level).

The second-order conditions are as follows:

$$L_{xx} = R^{-1} p_2 f''(y) E^2 < 0 \tag{14}$$

$$L_{\alpha\alpha} = R^{-1} p_2 f''(y) E^2 + \lambda b'' < 0 \tag{15}$$

$$L_{EE} = R^{-1} p_2 f''(y) v^2 - \lambda h'' < 0 \tag{16}$$

$$\Delta_1 < 0; \Delta_2 > 0; \Delta_3 < 0; \Delta_4 < 0 \tag{17}$$

The conditions (Eqs. 14–16) are satisfied when $f'' < 0$ (Eq. 14), $b'' < 0$ (Eq. 15) and $h'' > 0$ (Eq. 16). The conditions in Eq. 17 state that the bordered Hessian matrix H has to be negative definite (see Appendix 1).

2.3 Comparative Statics

Given that the second-order conditions hold, the comparative statics can be solved from the first-order conditions by differentiating them with respect to endogenous and exogenous variables. The results of the comparative statics analysis can be summarized as follows (see Appendix 2 for details):

$$x = x(\underset{+}{p_1}, \underset{-}{p_2}, \underset{+}{c}, \underset{+}{\bar{n}}) \tag{18}$$

$$\alpha = \alpha(\underset{?}{p_1}, \underset{?}{p_2}, \underset{?}{c}, \underset{-}{\bar{n}}) \tag{19}$$

$$E = E(\underset{-}{p_1}, \underset{+}{p_2}, \underset{-}{c}, \underset{?}{\bar{n}}) \tag{20}$$

Higher current timber prices increase the marginal return of harvesting, thus boosting current supply. Consequently, the profitability of future harvesting decreases, so that drainage maintenance is less profitable and therefore reduced. The effect on the buffer strip remains ambiguous: higher price tends to decrease it, but increased current harvesting increases nutrient leaching, which requires larger buffer strips. It is an empirical question regarding which of the opposing effects dominates.

Interpretation of the effect of future timber price is analogous, with the exception that now the profitability of future harvesting, and, therefore, drainage maintenance, is increased. Again, the effect on buffer strips remain ambiguous. Higher drainage maintenance costs decrease the profitability of drainage maintenance, decreasing also the marginal opportunity cost of harvesting. Therefore, current supply increases but drainage maintenance decreases. The effect on buffer strips remains an empirical question, again. Relaxing the leaching constraint decreases the marginal cost of harvesting, thus increasing current harvesting. Simultaneously, the marginal return of buffer strips decreases, resulting in smaller buffer strips. Hence, whether drainage maintenance decreases or increases depends on the relative effects of decreased future harvesting (as current harvesting has increased) and of decreased buffer strips on the diffuse load from forestry. To conclude, this analysis shows that it is not possible to unambiguously characterize all effects of exogenous parameters on the cost-effective measures.

3 Empirical Analysis

Following the theoretical model, I present in this section simulations for the private optimal and for the cost-efficient solutions, respectively. Because of the lack of empirical studies the variation between forest holdings due to differences in soil type, slope and shoreline length will be ignored. The empirical results are calculated for the representative forest holding in the southern half of Finland. I assume that there is 0.298 ha of previously drained peatland per forest land hectare (see Aarne 1992). In addition, the mean shoreline length (or drainage density) of 11 m per forest land hectare is assumed (see Matero 1996, Bren 1998). This implies that the share of buffer strips is about 1.1–3.3% of the total forest land, if the width of the buffer strip is 10–30 m.

In the analysis, all the abatement costs are allocated to the reduction of total phosphorus leaching only. However, nitrogen leaching is reduced simultaneously. If the reductions in nitrogen leaching are taken into account they have to be converted to (site-specific) phosphorus equivalents. Seppälä (1997), for example assessed that the *average* eutrophication effect of 1 kg N from Finnish forestry is equivalent to the eutrophication effect of 0.034 kg P from Finnish forestry. The equivalent factors are not used in this study, however, because neither of them have been applied in the calculations of abatement costs for other sectors (Pipping 1992, Vehkasalo 1999).

3.1 Private Optimum

I solve the private optimal harvesting and drainage maintenance by using the following assumptions. The forest owner maximizes the present value of net harvest revenue from homogenous forest land (3% PV with 1992 stumpage prices) with a sustainable timber production constraint, the effect of which is only –1% (see Matero 1996). As for the drainage activity, it is assumed, in accordance with the properties of the representative forest plot, that the land has been previously drained, but requires constant drainage maintenance. Note that this assumption does not differ much from the treatment of E in the theoretical model, because it concerns only the magnitude. More specifically, the drainage maintenance (D-M) is carried out annually on 4% of the peatlands previously drained for a period of 25 years. In addition, all the previously drained peatlands are assumed to be similar at their respective times of drainage maintenance, providing a net harvest revenue of 156 € ha^{-1} drained (3% PV with 1996 stumpage prices without the state grant) (see Hytönen and Aarnio 1998). The results of the private optimum are given in Table 1.

Table 1. Net harvest revenue and phosphorus leaching in private optimum.

	Net harvest revenue € ha^{-1} forest land (3% PV)	Phosphorus leaching kg P ha^{-1} forest land (3% PV)
Cuttings	3535 (99.1%)	0.67 (67%)
Drainage maintenance	33 (0.9%)	0.33 (33%)
Total	3568 (100%)	1.00 (100%)

The share of drainage maintenance from the total net harvest revenue (3% PV) (3 568 € per forest land hectare) is 0.9% in the private optimum. The private optimum yields, by assumption, the flow of (total) phosphorus leaching with a present value (3%) of 1 kg per forest land hectare. This corresponds to an even flow of 0.03 kg P ha^{-1} a^{-1} (see Saukkonen and Kortelainen 1995, Kenttämies and Saukkonen 1996, Kortelainen and Saukkonen 1998, Kortelainen et al. 1999). The share of drainage maintenance is assumed to be 33% (drainage maintenance is assumed to cause leaching of 1.55 kg P per ha drained (3% PV), see Kenttämies and Vilhunen 1999; cf. Kenttämies et al. 1995, Ahti et al. 1998).

3.2 Cost-efficient Solution

3.2.1 Basic Assumptions

In this section I study how alternative leaching reducing instrument combinations can be used to achieve cost-efficient reduction in diffuse load from forestry. Throughout the analysis I assume that harvesting is kept at a steady-state level. Hence, I will focus on buffer strips as well as on drainage maintenance, D-M (delaying D-M is ignored, although it also reduces PV$_P$). For the drainage maintenance I introduce, as a "fixed technology" choice, the option of three alternatives: i) D-M without any adjustments; ii) D-M with excavation of sedimentation pools and pits and iii) D-M with an untouched sedimentation field near a watercourse (see e.g. Kangas et al.

Table 2. Assumed effects of various adjustment technologies in buffer strips by the width of the buffer strip, reduction in the phosphorus leaching, kg P ha^{-1} forest land (3% PV) (%) and reduction in the net harvest revenue, € ha^{-1} forest land (3% PV) (%).

Adjustment technology in buffer strips	Width of buffer strip, m	Reduction in the leaching kg P	(%)	Reduction in the net harvest revenue €	(%)
No clear-cuttings	10	0.27	(27)	5	(0.2)
	20	0.31	(31)	11	(0.3)
	30	0.33	(33)	16	(0.5)
No regeneration cuttings	10	0.40	(40)	17	(0.5)
	20	0.48	(48)	34	(1.0)
	30	0.52	(52)	51	(1.5)
No treatment	10	0.43	(43)	39	(1.1)
	20	0.50	(50)	78	(2.2)
	30	0.53	(53)	117	(3.3)

1996, Hyyrönmäki 1997). Likewise, I also enlarge the possibilities for the treatment of the buffer strips (Matero 1996).

The various adjustments in buffer strips are tentatively assumed to reduce the leaching of (total) phosphorus from cuttings by 40 to 80% (i.e. 0.27–0.53 kg P per forest land hectare (3% PV)) depending on the width of the buffer strip (see also Ahtiainen and Huttunen 1999) (Table 2). Note that due to the nature of the assumption, a variable-width buffer retains less material than a uniform-width buffer of equivalent average width and that consequently, to achieve a given leaching target, a variable-width buffer must have a greater average width than a uniform-width buffer (see Weller at al. 1998). Alternative adjustments in buffer strips are assumed to reduce the net profit from cuttings as follows: 14% (no clear cuttings) and 44% (no regeneration cuttings) (Matero 1996). Consequently, the adjustments in buffer strips reduce the total net harvest revenue by 5 to 117 € per forest land hectare (3% PV) depending on the width of buffer strip (Table 2).

The total cost of abatement actions in D-M consists of two parts: 1) the possible increase in D-M costs and 2) the possible reduction in the value of the growing stock due to reduction in stand growth. Hytönen and Aarnio (1998) assessed that D-M provided, on average, 146 € ha^{-1} (PV 3%) without the state grant on some oligotrophic pine mires in the planning period of 20 years. I assumed that the share of abatement actions in the costs determined by Hytönen and Aarnio (1998) were about 10 € ha^{-1} (see Matero and Saastamoinen 1998). Consequently, the total adjustment cost of the No treatment -alternative was estimated to be 156 € ha^{-1} (PV 3%) when compared to D-M without diffuse load abatement.

In the case study by Hyyrönmäki (1997), the excavation of sedimentation pools and pits increased the D-M costs by 24 € ha^{-1} drained. This cost included the excavation of small sedimentation pits (one per 200 m ditch) (6 € ha^{-1} drained), the planning and excavation of sedimentation pools (7 € ha^{-1} drained) and the removal of accumulated material from sedimentation pools 2, 7 and 15 years after D-M (11 € ha^{-1} drained). On the other hand, leaving untouched sedimentation fields near watercourses decreased the costs by 1.3 € ha^{-1} drained (Hyyrönmäki 1997).

Kangas et al. (1996, Table 1) estimated that excavation of sedimentation pools reduced stand growth by 9%. The reduction in stand growth was 13% if a sedimentation field was left near a stream and 21% in the case of no (D-M) treatment at all (Kangas et al. 1996). In other words, Kangas et al. (1996) estimated that about 40–60% of the additional stand growth due to D-M was lost when sedimentation pools or sedimentation fields were used. In the case study by Hyyrönmäki (1997), the No treatment -alternative (i.e. no D-M) reduced stumpage value even more, by about 30% when the reduction in stand growth was assumed to be 17%, because of less valuable

Table 3. Assumed effects of alternative adjustments in drainage maintenance, D-M, compared to the base alternative (as present values, 3% PV at the time of D-M).

Technology	Change in D-M costs	Change in stumpage value	Net harvest revenue € ha^{-1} drained	Phosphorus leaching kg P ha^{-1} drained
No adjustments (base)	0	0	156 (±0%)	1.55 (±0%)
With sedimentation pools	+24	–17	–41 (–26%)	–0.23 (–15%)
With sedimentation field	–1.3	–34	–32 (–21%)	–0.31 (–20%)

timber assortment. Hyyrönmäki (1997), however, assumed that the two other abatement alternatives (sedimentation pools and sedimentation field) did not reduce the stand growth and stumpage value. Neither did Hytönen and Aarnio (1998) mention any growth effects due to diffuse load abatement, although some abatement costs were included in profitability calculations. On the other hand, stand growth of the untreated control plots was estimated to be 17% smaller than the average growth over the period of 20 years after drainage maintenance (Hytönen and Aarnio 1998). In this study, I assumed that the reduction in stumpage value (PV 3%) was, on average, 34 € ha^{-1} drained (sedimentation field) or 17 € ha^{-1} drained (sedimentation pools) (Table 3). This reduction presumably varies according to the topography of the drainage area.

The results by Hyyrönmäki (1997) suggested that different abatement actions would reduce the diffuse load of D-M only by about 15% at maximum. Respectively, in the case study by Kangas et al. (1996) the expert assessment implied that the abatement actions reduced the impacts of D-M on water ecosystems by about 20–25% (in utility terms). I assumed that these results give at least the magnitude of the impacts of abatement actions on water-based values. Thus, sedimentation pools were assumed to reduce the leaching of phosphorus by 15% and a sedimentation field by 20% (Table 3). For comparison, Joensuu et al. (1999) found that the sedimentation ponds (pools) reduced the concentration of suspended solids by about 17% as a 3-year average (the average of the annual means weighted by concentration). This change was most probably connected with a corresponding decrease in the concentration of particulate phosphorus (Joensuu et al. 2001).

To conclude, I assume that leaving an untouched sedimentation field near a watercourse decreases the net harvest revenue of drainage maintenance (3% PV) by 21% and the total phosphorus leaching (3% PV) by 20% (Table 3). Respectively, the reduction in the net harvest revenue due to excavation of sedimentation pools is assumed to be 26% and in the total phosphorus leaching 15% (Table 3). These assumptions imply that drainage maintenance with the excavation of sedimentation pools or with a sedimentation field near a watercourse are not cost-efficient technologies in reducing phosphorus leaching: the average marginal costs are 178 € kg^{-1} P (i.e. 41 € divided by 0.23 kg P) and 103 € kg^{-1} P respectively. Instead, it is more cost-efficient to decrease the amount of drainage maintenance without any adjustments (average marginal cost 101 € kg^{-1} P).

3.2.2 Results

The cost-efficient solution consists of a set of actions that are ordered from the cheapest to most expensive ones. Therefore, I start by first examining how phosphorus leaching can be reduced by buffer strips and their management only. Then I add drainage maintenance into the analysis to produce a cost-efficient strategy for reducing phosphorus leaching.

When considering only the adjustments in buffer strips, by giving up clear cuttings it is possible, by assumption, to reduce total phosphorus leaching by 33% with a 0.5% reduction in net

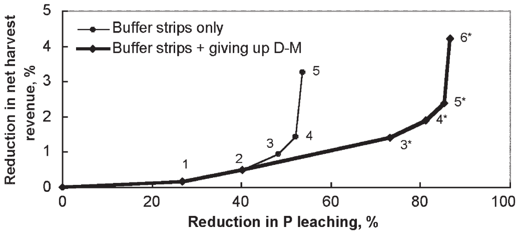

Fig. 1. Least-cost solutions (reduction in net harvest revenue vs. reduction in phosphorus leaching) when buffer strips are the only abatement option and when giving up drainage maintenance (D-M) is included as an additional abatement option (figures in the least-cost curves refer to the text).

harvest revenue when the buffer width is 30m (see Table 2). By giving up regeneration (all) cuttings, the maximum reduction in phosphorus leaching is 52% (53%) with a 1.5% (3.3%) reduction in net harvest revenue, respectively. Therefore, the least-cost abatement ”path” consists of: 1) No clear-cuttings with a buffer strip width of 10 m (resulting in a 27% reduction in total phosphorus leaching with an average marginal cost of 19 € kg^{-1} P, i.e. 5 € ha^{-1} divided by 0.27 kg P ha^{-1}); 2) No regeneration cuttings, 10 m (40%, 92 € kg^{-1} P, i.e. (17 – 5) / (0.40 – 0.27)); 3) No regeneration cuttings, 20 m (48%, 214 € kg^{-1} P); 4) No regeneration cuttings, 30 m (52%, 429 € kg^{-1} P); and 5) No cuttings, 30 m (53%, 6521 € kg^{-1} P) (Fig. 1). Note that in order to proceed from Stage 1 to Stage 2 with an average marginal cost of 92 € kg^{-1} P, we have to divide the buffer strip for two parts with different adjustment technologies. By increasing the share of ”No regeneration cuttings (Nrc)” from 0% to 100% (and decreasing the share of ”No clear-cuttings (Ncc)” from 100% to 0%, respectively), we can proceed from 1) to 2). For example, if the goal is a 31% reduction in the phosphorus leaching, then a combination of (70% Ncc + 30% Nrc) with a 10 m-buffer strip is cheaper (the reduction in net harvest revenue is 9 € ha^{-1} forest land) than ”No clear-cuttings” with a 20 m-buffer strip (11 € ha^{-1} forest land) (see Table 2).

When the option to decrease the amount of drainage maintenance, D-M is included, it is possible to independently achieve a 33% reduction in phosphorus leaching with an additional 0.9% reduction in net harvest revenue, i.e. with an average marginal cost of 101 € kg^{-1} P (see Table 1). Hence, the least-cost “path” becomes: 1) No clear-cuttings with a buffer strip width of 10 m (resulting in a 27% reduction in total phosphorus leaching with an average marginal cost of 19 € kg^{-1} P); 2) No regeneration cuttings, 10 m (40%, 92 € kg^{-1} P); 3*) No regeneration cuttings, 10 m and giving up drainage maintenance, D-M (73% (40% + 33%), 101 € kg^{-1} P (17 + 33 – 17) / (0.40 + 0.33 – 0.40) = 33/0.33); 4*) No regeneration cuttings, 20 m and giving up D-M (81%, 214 € kg^{-1} P); 5*) No regeneration cuttings, 30 m and giving up D-M (85%, 429 € kg^{-1} P); and 6*) No cuttings, 30 m and giving up D-M (86%, 6521 € kg^{-1} P) (Fig. 1). To sum up, proceeding through stages one to three it is possible to reduce total phosphorus leaching from forestry by 73% with the average cost of 69 € kg^{-1} P. When further proceeding to Stage 4, a reduction of 81% is achieved at an average cost of 84 € kg^{-1} P.

The results suggest that it is possible to considerably reduce phosphorus leaching from private optimal forest management in a representative forest holding in the southern half of Finland with minor cost. Therefore, it is interesting to compare the costs of diffuse load abatement in forestry with those of other relevant sectors. Based on the results by Vehkasalo (1999) and Koikkalainen et al. (1999) the average costs for reducing the load of phosphorus in agriculture by 10–20% (i.e. 330–660 t annually) are about 101–336 € kg^{-1} P. Vehkasalo (1999) estimated the average costs for the nutrient load reduction in municipal wastewater treatment to be of the same magnitude, i.e. 84–252 € kg^{-1} P. For the Finnish pulp and paper industry Pipping (1992) proposed a charge rate of 336 € kg^{-1} P for effluents exceeding certain target discharge levels. The lowest marginal costs at the effluent levels attained in 1991 were about 101–168 € kg^{-1} P. To conclude, (by applying the so-called averting expenditures valuation method) it seems that at least those abatement measures with marginal costs lower than 101 € kg^{-1} P are justifiable for socially optimal forestry. However, if we take into account possible site- and sector-specific variation in transfer and effect factors, as well as a demand for water quality, this conclusion may change quite radically.

3.2.3 Sensitivity Analysis

Fig. 2 reports on the sensitivity of the results for the effectiveness of buffer strips. If the effectiveness of buffer strips in reducing phosphorus leaching is allowed to vary in ±10%-units, the marginal costs of adjustments in buffer strips change, but not the ranking of the adjustments in the least-cost solution (Fig. 2).

The variation in the leaching from drainage maintenance keeps the leaching from cuttings constant (by assumption). When the variation in the phosphorus leaching from D-M is between –52% … +12% from the base (1.55 kg P ha^{-1} drained as 3% PV at the time of D-M), the ranking of different adjustments in the least-cost solution remains unchanged. If the leaching from D-M increases by 13%, it is possible to achieve a reduction of 0.37 kg P ha^{-1} forest land (3% PV) with an average marginal cost of 89 € kg^{-1} P by giving up D-M. Consequently, it is cost-efficient to already give up D-M in Stage 2 (before applying "No regeneration cuttings" in a 10 m-buffer stip in cuttings in Stage 3). On the other hand, if the leaching from D-M decreases by 53%, it is possible to achieve only a reduction of 0.16 kg P ha^{-1} forest land (3% PV) with an average marginal cost of 215 € kg^{-1} P by giving up D-M. Then, it is not cost-efficient to give up D-M until in Stage 4 (after applying "No regeneration cuttings" in a 20 m-buffer strip in cuttings in Stage 3).

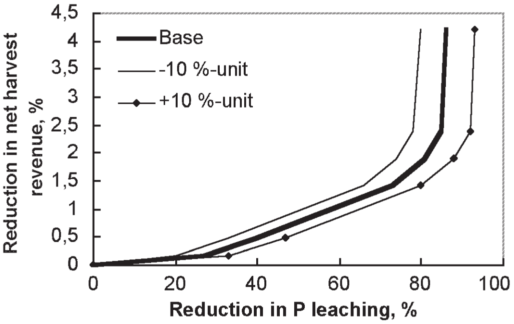

Fig. 2. Least-cost solutions (reduction in net harvest revenue vs. reduction in phosphorus leaching) when the effectiveness of buffer strip is increased or decreased by a 10%-unit from the base.

4 Discussion

I first theoretically analyzed how a private forest owner chooses between harvesting now and in the future as well as in stand investment by drainage maintenance. I then assumed that the government sets a given diffuse load reduction target and studied the cost-effective choice of harvesting, drainage maintenance and other measures affecting diffuse load in forestry. Following the theoretical model, a simulation analysis was conducted to assess the magnitudes of decision variables of the theoretical model. Moreover, empirical analysis was also used to evaluate alternative technologies for the implementation and use of buffer strips and for the adjustment of drainage maintenance in cost-efficient diffuse load reduction. Simulations were conducted by assuming that harvests are kept at a steady state level.

By utilizing the two-period model, it was shown that cost-efficiency requires the establishment of a buffer strip system and a reduction in current harvesting. In addition, drainage maintenance – if practized – will be reduced relative to the private optimum to reflect its effects on diffuse load. It was not possible to unambiguously characterize all effects of exogenous parameters on the cost-effective measures. The results of the empirical analysis suggested that it is possible to considerably reduce phosphorus leaching from private optimal forest management in a representative forest holding in the southern half of Finland with minor cost. The results should be regarded with caution, however, because of many unavoidable assumptions and site-specific conditions.

Previous literature was extended by the theoretical analysis of cost-efficiency in diffuse load abatement in forestry. The information about the impacts of abatement measures on forestry and on phosphorus leaching was also combined to empirically examine how to choose different abatement measures in a cost-efficient way to achieve a socially optimal leaching target.

There remain several issues for future research. First, it would be of interest to study the effect of forest owners' *in situ* preferences, particularly in riparian zones, on private optimum. Second, it would be useful to include for analysis possible positive externalities on biodiversity protection and on other forest uses provided by buffer strips. Thirdly, distributional impacts should be analyzed by allowing variation between forest holdings in relevant model parameters. Finally, it would be important to extend the analysis by a (dynamic and site-specific) model of eutrophication, for example, to study the design of a socially optimal leaching target, as well as to analyze alternative policy instruments and implementation methods for moving forest management towards cost-efficiency and social optimality.

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Appendix 1. Determinant Δ of the bordered Hessian matrix *H*.

$$\Delta_1 = L_{xx} < 0 \tag{A1.1}$$

$$\Delta_2 = L_{xx}L_{\alpha\alpha} - L_{x\alpha}{}^2 > 0 \tag{A1.2}$$

$$\Delta_3 = \lambda b''(L_{xx}L_{EE} - L_{xE}{}^2) < 0 \tag{A1.3}$$

$$\begin{aligned}\Delta_4 = \Delta = &-(h')^2(L_{xx}L_{\alpha\alpha} - L_{x\alpha}{}^2) - \phi^2(L_{xx}L_{EE} - L_{xE}{}^2) - \delta^2(L_{\alpha\alpha}L_{EE} - L_{\alpha E}{}^2)\\ &-2\delta\phi(L_{xx}L_{EE} - L_{xE}{}^2) + 2\delta h'\lambda b''L_{xE} < 0\end{aligned} \tag{A1.4}$$

Sufficient condition: $-\phi(L_{xx}L_{EE} - L_{xE}{}^2) + h'\lambda b''L_{xE} < 0$

Appendix 2. Comparative statics.

The comparative statics effects of p_1, p_2, c and $\overline{n}$ can be solved by applying Cramer's Rule from

$$\begin{bmatrix} L_{xx} & L_{x\alpha} & L_{xE} & -\delta \\ L_{\alpha x} & L_{\alpha\alpha} & L_{\alpha E} & \varphi \\ L_{Ex} & L_{E\alpha} & L_{EE} & -h \\ -\delta & \varphi & -h & 0 \end{bmatrix} \begin{bmatrix} dx \\ d\alpha \\ dE \\ d\lambda \end{bmatrix} = -\begin{bmatrix} 1 & -A & 0 & 0 \\ 0 & -A & 0 & 0 \\ 0 & B & -1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} dp_1 \\ dp_2 \\ dc \\ d\overline{n} \end{bmatrix} \tag{A2.1}$$

where $A = R^{-1}[1 + f'(y)E] > 0$ and $B = R^{-1}f'(y)v > 0$

The effects are

$$\frac{dx}{dp_1} = \Delta^{-1}\left\{L_{\alpha\alpha}(h')^2 + 2L_{\alpha E}h'\phi + L_{EE}\phi^2\right\} > 0 \tag{A2.2}$$

$$\frac{d\alpha}{dp_1} = \Delta^{-1}\left\{\phi(L_{EE}\delta - L_{xE}h') + h'(L_{xE}\delta - L_{xx}h')\right\} = ? \tag{A2.3}$$

$$\frac{dE}{dp_1} = -\Delta^{-1}\left\{L_{\alpha\alpha}\delta h' + L_{x\alpha}\phi h' + L_{xE}\phi(\delta + \phi)\right\} < 0 \tag{A2.4}$$

$$\frac{dx}{dp_2} = -\Delta^{-1}\left\{\lambda b''h'(Ah' + B\delta) + (\delta + \phi)\left[L_{xE}(Ah' + B\phi) + L_{EE}A\phi + L_{xx}Bh'\right]\right\} < 0 \tag{A2.5}$$

$$\frac{d\alpha}{dp_2} = -\Delta^{-1}\left\{(\delta + \phi)\left[A(L_{EE}\delta - L_{xE}h') + B(L_{xE}\delta - L_{xx}h')\right]\right\} = ? \tag{A2.6}$$

$$\frac{dE}{dp_2} = \Delta^{-1}\left\{\lambda b''\delta(Ah' + B\delta) + (\delta + \phi)^2(L_{xx}B + L_{xE}A)\right\} > 0 \tag{A2.7}$$

$$\frac{dx}{dc} = \Delta^{-1}\left\{L_{xx}\phi h' + L_{\alpha\alpha}\delta h' + L_{xE}\phi(1 + \phi)\right\} > 0 \tag{A2.8}$$

$$\frac{d\alpha}{dc} = \Delta^{-1}\left\{(\delta + \phi)(L_{xE}\delta - L_{xx}h')\right\} = ? \tag{A2.9}$$

$$\frac{dE}{dc} = -\Delta^{-1}\left\{L_{xx}\phi^2 + 2L_{x\alpha}\delta\phi + L_{\alpha\alpha}\delta^2\right\} < 0 \tag{A2.10}$$

$$\frac{dx}{d\overline{n}} = -\Delta^{-1}\left\{\delta(L_{\alpha\alpha}L_{EE} - L_{\alpha E}{}^2) + \varphi(L_{xx}L_{EE} - L_{xE}{}^2) - \lambda b''L_{xE}h'\right\} > 0 \tag{A2.11}$$

$$\frac{d\alpha}{d\overline{n}} = \Delta^{-1}\left\{(L_{xx}L_{EE} - L_{xE}{}^2)(\delta + \varphi)\right\} < 0 \tag{A2.12}$$

$$\frac{dE}{d\overline{n}} = \Delta^{-1}\left\{\lambda b''(L_{xE}\delta - L_{xx}h')\right\} = ? \tag{A2.13}$$