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Economics of strip harvesting in drained boreal peatland forests

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Abstract

This study examines the economics of strip harvesting on drained boreal peatlands as an alternative method to traditional even-aged forest management that causes high negative externalities due to nutrient loads to receiving water courses. Strip harvesting avoids large clear-cuts, eliminates the need for ditch network maintenance and facilitates maintaining the water table at an environmentally beneficial level, thus reducing negative eutrophication externalities. In the rotation framework, a forest manager maximizes the present value of net harvest revenue subject to a constraint on the water table level. Starting with an initial even-aged stand, the harvesting regime consists of a transition period and steady-state period. In the transition period, the initial stand area is allocated between parallel strips to be harvested in a row with simultaneous determination of rotation ages in the strips. In the steady state, only the rotation ages are chosen. In the considered drained Scots pine-dominated peatland site located in southern Finland, even-aged management provides higher private net revenue than strip harvesting. From society's viewpoint, strip harvesting significantly reduces nutrient load damage compared to even-aged management. The water table level constraint plays an important role in the design of harvesting and the resulting social net benefits.

Keywords: continuous cover forestry, even-aged forest management, nutrient loads, peatland forestry, profitability

JEL classification: Q23, Q24, Q25

1. Introduction

Approximately 15 M ha of peatlands have been drained for forestry in boreal and temperate regions, and particularly in Northern Europe, peatland forestry has significant economic importance (Päivänen and Hånell 2012). In Finland, the area of drained peatlands is 4.7 Mha or one-fifth of the total forest area, and it is a highly important source of wood for industry (Korhonen et al. 2021). Most of the initial drainage was carried out during the 1960s and 1970s (Päivänen and Hånell 2012) and significant share of these forests are now mature or almost mature.

In peat soils, a high water table level (WTL) close to the ground level is a limiting factor for tree growth, and drainage is often needed to lower the WTL, ensuring favorable conditions for forest growth in peatland forests. Even-aged forest management on drained boreal peatlands entails clear-cuts and ditch network maintenance (DNM) operations, which cause high nutrient and sediment loads to watercourses (Joensuu 2002; Nieminen 2003; 2004; Nieminen et al. 2010; Kaila et al. 2014, 2015). Recent studies suggest that forestry on peatlands results in significantly more profound and longer-lasting nutrient exports than previously thought (Finér et al. 2021; Nieminen et al. 2022). Furthermore, the WTL in soil affects discharged water quality on drained peatlands. Low WTLs in mature stands with high evapotranspiration capacity increase aerobic peat mineralization, thus resulting in enhanced mobilization and export of nutrients (Nieminen et al. 2022). In contrast, the increase in WTL after clear-cutting due to a drastic reduction in the evapotranspiration capacity of tree stands and surface vegetation is also detrimental to water quality, as it increases nutrient exports by chemical redox reactions (Kaila et al. 2014, 2016). Thus, even-aged management regime causes significant negative externalities on water quality. Increased nutrient loads to watercourses enhance eutrophication, which has significant adverse impacts on aquatic ecosystems and the recreational use of both inland and coastal waters (e.g., Bonsdorff et al. 1997; Vesterinen et al. 2010).

Given the high negative water quality externalities, peatland forestry should avoid clear-cutting and drainage and maintain the WTL at an environmentally favorable stable level (Nieminen et al. 2018a). More precisely, drawing on recent studies, the WTL in late summer (July–August) should be maintained within the range of 30 to 40 cm from the soil surface. In that range, tree stand growth remains still satisfactory without further lowering of the water table by DNM (Sarkkola et al. 2012), and redox reactions and peat mineralization presumably result in significantly lower nutrient exports than with higher or lower WTLs. Maintaining a stable WTL requires the avoidance of clear-cuts, which raise the WTL due to the cessation of tree stand evapotranspiration. It also requires harvesting in such a way that the entire peatland tree stand does not grow so stocked that its evapotranspiration capacity results in very low WTLs. Improving the sustainability of forest management on drained peatlands thus requires finding efficient solutions to managing their hydrology and soil WTLs.

Continuous cover forestry (CCF) offers a promising alternative for peatland forest management. It avoids clear-cutting, eliminates or significantly decreases the need for DNM operations and results in significantly smaller WTL variations than even-aged management. CCF on drained peatlands is compatible with different harvesting options (Nieminen et al. 2018a). CCF is traditionally associated with selection cuttings, where the harvested trees are selected based on their size classes. For comparisons between the economic performance of CCF and even-aged forestry, see Hanewinkel (2002); Tahvonen (2016); Juutinen et al. (2018); Parkatti et al. (2019), and for the inclusion of GHG emissions in their economic performance, see Pukkala et al. (2011), Assmuth and Tahvonen (2018); Ahtikoski et al. (2022a). An alternative harvest regime for CCF is strip harvesting (Stenberg et al. 2022). It refers to management in which parallel strips of a stand are clear-cut in a row over time so that strips of older as well as younger trees are growing in the stand at the same time (Pothier 2000; Anderson et al. 2020). Due to this property, strip harvesting helps to manage a stable WTL at the desired 30-40 cm level provided that the size of the strips and age of harvested trees (i.e., their evapotranspiration capacity) are determined according to the required WTL (Nieminen et al. 2018a). Compared to selection cuttings, strip harvesting has also other advantage than water quality maintenance. First, strip harvesting is easier and safer to implement than selective cuttings, in which harvesting may damage the remaining trees. Second, the harvesting costs are presumably lower in strip harvesting, in which parallel strips of a stand are clear-cut instead of harvesting individual trees in different size classes. Third, strip harvesting is better suited for shade-intolerant tree species, such as Scots pine, than selective harvesting.

In this study, we examine the economic and environmental performance of strip harvesting on drained peatland stands. The forest manager maximizes the net present value of harvest revenue under an environmentally motivated WTL constraint that is set to minimize the adverse water quality impacts. Under this constraint, the forest manager accounts for the evapotranspiration capacity of the stand and chooses the size of harvested strips and the age of harvested trees so that the constraint is not violated. Our research question is: what is the optimal share of harvested strips in the stand area and the age of harvested trees that keep the WTL at the desired level to avoid environmental impacts? We first outline a theoretical rotation framework for strip harvesting and examine its properties. We then apply our model to Finnish tree growth data on strip harvesting and determine the share of the harvested strips in the stand area, harvesting cycles, timber yields and harvest revenue and compare the findings to even-aged management. Finally, we examine *ex post* how the chosen WTL constraint reduces nutrient load damage from the stand under strip harvesting relative to even-aged management. Our analysis of water quality impacts focuses on nutrient loads, causing eutrophication in receiving water courses. Organic carbon loading responsible for the wide-spread brownification of waters is not included because of the lack of data to model organic carbon loads resulting from different harvesting methods.

The suggested economic model of strip harvesting is new in the forest economics literature. Studies on strip harvesting in drained boreal peatlands are largely lacking (Ahtikoski et al. 2022b). Most previous studies applied to peatlands have focused on even-aged management (Ahtikoski et al. 2012; Kojola et al. 2012; Hökkä et al. 2017; Miettinen et al. 2014; 2020a; 2020b). Juutinen et al. (2021) examined CCF in drained peatlands based on selective cuttings rather than strip harvesting. Closest to the strip harvesting framework are the studies by Jacobsen et al. (2018) and Halbritter (2015). Jacobsen et al. (2018) developed a CCF model with a special focus on the use of forestland area in the presence and absence of area restriction. Halbritter (2015) presents an analytical economic model of double-cohort forest resources and compares even-aged and uneven-aged forest management. The only study on strip harvesting concerning boreal drained peatlands is that by Ahtikoski et al. (2022b). They compare strip harvesting and even-aged management on drained peatlands in three different locations in Finland. They do not optimize but rather adopt exogenous management programs. Additionally, Rondon et al. (2010) examined the profitability of strip harvesting in tropical rainforests, where strip harvesting was originally introduced.

The remainder of the article is organized as follows. Section 2 presents the theoretical framework applied in this study. Section 3 provides ecological and economic data used in the numerical application of the developed theoretical model. The results of the numerical application are presented in Section 4. Finally, Section 5 is devoted to the discussion and conclusions.

2. Strip harvesting in drained boreal peatlands under constraint on WTL

We introduce strip harvesting to a previously drained peatland forest area with an initial stand of trees. Suppose that the forest manager is required or wishes to maintain a stable WTL at a given range to avoid the negative water quality impacts of forest management. This constraint rules out traditional even-aged management with clear-cut and DNM operations. Suppose further that the forest manager chooses strip harvesting as the practical solution to maintain WTL within the given depth limits. Strip harvesting has the benefit of easier implementation compared to selective cuttings, where harvesting of the selected trees may damage the remaining trees. It is also assumed to be better suited for shade-intolerant tree species than selection cutting. The manager chooses the share of harvested (and unharvested) strips and the age of harvested trees in the strips so that the WTL constraint is not violated.

2.1 Analytical framework

Consider a land area with an initial stand volume on a previously drained peatland forest. The stand volume as a function of harvest age (t) is denoted by the volume growth function per hectare $g(t)$. The initial stand age is a. Hence, $g(a)$ describes the initial stand volume. Under a binding WTL constraint, the whole stand cannot be harvested by clear-cutting, even though it would be economically profitable to do so. Therefore, the forest manager can harvest only a share of the stand. To keep WTL at approximately the same level throughout the land area, this share is allocated evenly over the land area by clear-cutting narrow strips of the stand. In addition, the manager has to simultaneously choose the time of harvest, as the stand volume (i.e., its transpiration demand) contributes to the WTL. To gain insight into the implications of the WTL constraint on decision-making, we first generally describe the relationship between the WTL and stand volume.

2.1.1 WTL and its determinants

Ecological studies indicate that the WTL in forest soil during growing seasons depends negatively on the stand volume and ditch depth and positively on monthly precipitation and latitude (Hökkä et al. 2008; and Sarkkola et al. 2010). For a given peatland stand, precipitation, latitude and ditch depth are exogenous and given. Thus, we can express WTL as a function of the stand volume, which changes over time via stand growth and harvesting and is thus endogenous (Hökkä et al. 2008; Sarkkola et al. 2010).

Let the WTL below the soil surface be a function w. We define the WTL as a function of the evapotranspiration (EVT) capacity ($\varepsilon > 0$) of the stand, $w\big(\varepsilon g(t)\big)$. For stand volume growth, evaluated by an increase in the rotation age, we have $dw/dt = w'\varepsilon g'(t) < 0$, as $w' < 0$. Figure 1 illustrates the WTL as a function of stand volume, in which the y-axis represents the WTL and the x-axis denotes the stand volume. The WTL decreases with increasing stand volume due to increasing EVT capacity. When the whole stand is harvested at the same time, the WTL reaches its maximum value. The constraint on the water table is set at a level that is expected to minimize the negative water quality impacts. The horizontal lines illustrate the desired range of the WTL. The points where the downward sloping water table level $w\big(\varepsilon g(t)\big)$ crosses the target levels of WTL values, are denoted by $\overline{w}$ and $\underline{w}$. This determines the relevant range for forest management. Hence, it is required for the harvesting and consequent forest growth that $\underline{w} < w\big(\varepsilon g(t)\big) < \overline{w}$. Provided that the tree growth is slow enough, the lower targeted WTL rarely becomes binding, as forest stands become economically mature before reaching the respective stand volume, while the upper targeted WTL is always binding and prevents harvesting treatment (clear-cutting) of the entire stand at the same time.

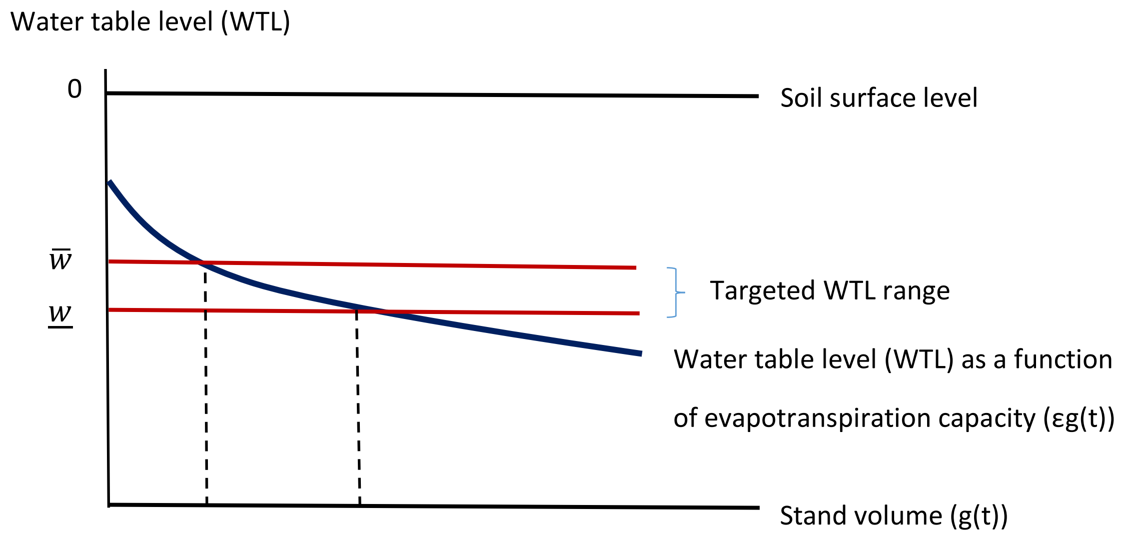

Figure 1. Water table level (WTL) as a function of stand volume per hectare.

2.1.2 Transitional harvests under a binding constraint on WTL

The forest manager must adopt the WTL constraint by simultaneously choosing a part of the stand for harvesting in strips and the timing of harvest so that the constraint remains binding. Land allocation to the strips is made only once, concurrently with the time of the first harvest decision. The first harvest decision therefore reforms the land area permanently into two sets of strips, whose stands are then managed with clear-cuts as those of even-aged stands. Thus, we must distinguish between a transitional harvest transforming the initial stand into a new spatial configuration and the steady-state harvest.

Let $0 < m_1 < 1$ denote the share of the stand that is harvested in the first transitional harvest and in subsequent steady-state harvests. Thus, the share of the initial stand left for harvesting in the second transitional harvest is $m_2 = 1 - m_1$. Accordingly, the whole forestland area is regenerated by two transitional harvests in two sets of strips. The choice of strips is made only once, but it depends on the whole planning period, including the infinite series of rotations.

We denote the first harvest age of the initial stand by t_1, so that the harvested timber volume is determined by $m_1 g_1(t_1)$. After the first transitional harvest, the stand grows in the strips and is harvested over subsequent rotations but under the WTL constraint. The stand volume left unharvested and to be cut during the second transitional harvest is $(1 - m_1)g_2(t_2)$, where the subscript 2 denotes both the volume growth of the remaining stand and its harvest age.. Let the stumpage price (p) and real interest rate (r) be constant. Thus, the present value of harvest revenue from the first harvest is $pm_1 g_1(t_1)e^{-r(t_1-a)}$ and from the second harvest is $p(1 - m_1)g_2(t_2)e^{-r(t_2-a)}$. As any delay in harvesting would reduce the net present value of harvest revenue, forest landowner harvests the forest using the minimum number of harvest cycles, which is two cycles. This incentive is reinforced by the fact that transporting harvesting machinery to forests is costly.

In the first transitional harvest of the share m_1, the forest manager must take care that the stand volume left unharvested, g_2, is grown to the minimum stand volume that keeps the water table at the required level, $\overline{w}$. Stand volume growth is evaluated at harvest age t_1 and WTL must be kept at a level below or equal to the upper constraint ($\overline{w}$), that is $w\big((1 - m_1)\varepsilon g_2(t_1)\big) \leq \overline{w}$. When the remaining unharvested share of the initial stand, $(1 - m_1)g_2(t_2)$, is harvested, the first harvested strips have a new naturally regenerated stand with a volume growth function per hectare, denoted by $f_1(T_1)$, where T_1 refers to its rotation age. This stand must reach the minimum stand volume, which fulfills the WTL constraint. The age when this minimum is achieved defines the rotation age in the second transitional harvest t_2 when the constraint is binding. Rotation age of the second transitional harvest, t_2 must be chosen so that WTL remains below or equal to the requirement for upper water table level, $w\big(m_1\varepsilon f_1(t_2 - t_1)\big) \leq \overline{\mathrm{w}}$. After the second transitional harvest, the total peatland area has been harvested once.

2.1.3 Harvest cycle and constraint on WTL during steady state

After the two transitional harvests of the initial stand, the stand volume growth is assumed to reach the steady state.[1] In the steady state, harvests will be conducted in the strip areas already harvested once. As we assume natural regeneration and fixed land use by the transitional harvest, the present values of harvest revenue in the two sets of strips can be simply expressed as $pf_1(T_1)(1-e^{-rT_1})^{-1}$ and $pf_2(T_2)(1-e^{-rT_2})^{-1}$. The steady-state revenue must naturally be discounted to the starting period, as Equation (1) shows. The WTL constraint for the choice of the rotation age for strip area 1 continues to depend on the calendar time, requiring accounting for past harvests. The forest management must be chosen to that WTL remains within the constraint $\overline{w}$, that is, $w\big(\varepsilon f_2(T_1-(t_2-t_1))\big) \leq \overline{w}$ for strip area 1, and, $w\big(\varepsilon f_1(T_2-(T_1-(t_2-t_1)))\big) \leq \overline{w}$ for strip area 2.

2.2 Determination of strip harvesting under a binding WTL constraint

The objective of the forest manager is to maximize harvest revenue both from the initial stand and steady state, subject to the constraint on the WTL set to minimize the negative water quality impacts. The structure of the problem and its solution is illustrated in Figure 2. We postulate natural regeneration and discount harvest revenues to the starting period. To solve the constrained maximization problem, we form a Lagrangian function L where Lagrange multipliers $(\lambda_1, \lambda_2, \mu_1, \mu_2)$ link the objective function of each harvest cycle and the respective constraint. The Lagrangian multipliers describe the shadow prices of restricting harvest decisions due to water quality reasons.

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[1] In previously drained peatlands it may require more than two transitional harvests to reach the steady-state growth. Our numerical analysis suggests for the used tree growth data that the steady-state tree growth is reached after the third harvest.

We define the Lagrangian function as follows:

$$\begin{aligned} L = {} & \{m_1 p g_1(t_1) + \lambda_1[\bar{w} - w((1-m_1)\varepsilon g_2(t_1))]\}\, e^{-r(t_1-a)} \\ & +\{(1-m_1) p g_2(t_2) + \lambda_2[\bar{w} - w(m_1 \varepsilon f_1(t_2-t_1))]\}\, e^{-r(t_2-a)} \qquad (1) \\ & +J_1 e^{-r(t_1-a)} + J_2 e^{-r(t_2-a)}, \end{aligned}$$

where

$$J_1 = \{m_1 p f_1(T_1) + \mu_1[\bar{w} - w((1-m_1)\varepsilon f_2(T_1-(t_2-t_1)))]\}\, e^{-rT_1}(1-e^{-rT_1})^{-1}$$

$$J_2 = \{(1-m_1) p f_2(T_2) + \mu_2[\bar{w} - w(m_1 \varepsilon f_1(T_2-(T_1-(t_2-t_1))))]\} e^{-rT_2}(1-e^{-rT_2})^{-1},$$

The choice variables of the constrained maximization problem are the optimal share of the strip area harvested first (m_1), the optimal rotation ages (t_1 and t_2) of the stand in the strip shares m_1 and m_2 and the optimal steady-state rotation ages (T_1 and T_2). We solve the model in two stages and first determine the steady-state rotation ages subject to the choice of the two sets of strips and then examine the properties of the initial harvesting cycle.

When the WTL constraint is binding, the choice of the steady-state rotation ages is characterized by

$$\begin{aligned} T_1^*\colon & [p f_1'(T_1) - r p f_1(T_1)(1-e^{-rT_1})^{-1}] = \mu_1 w' \frac{(1-m_1)}{m_1} \varepsilon f_2'(T_1-(t_2-t_1)) - \mu_2 w' \varepsilon f_1'(T_2-(T_1- \\ & (t_2-t_1))) X e^{-r(t_2-t_1)} \qquad \text{(2a)} \end{aligned}$$

$$T_2^*\colon (1-m_1)[p f_2'(T_2) - r p f_2(T_2)(1-e^{-rT_2})^{-1}] = \mu_2 w' m_1 \varepsilon f_1'(T_2-(T_1-(t_2-t_1))), \qquad \text{(2b)}$$

where $X = \frac{e^{rT_1}(1-e^{-rT_1})}{e^{rT_2}(1-e^{-rT_2})}$, that is, the ratio of discount factors and rotation period terms.

Starting interpretation with Equation (2a), the LHS terms denote the optimality condition of the Faustmann model with zero regeneration costs (for the share m_1 strips of the total forest land). In the absence of WTL constraint, the LHS term should be zero at the optimal rotation age. The RHS is a sum of marginal impacts of rotation age on the WTL constraint via future forest growth for the first and the second set of strips. Recall, the derivative $w' < 0$, therefore, the first RHS term is negative, while the second present value term is positive. The negative current value term may dominate the positive present value term but it must be ascertained numerically. Thus, the rotation age in the presence of a binding WTL constraint under strip harvesting may be longer than in the case where water table constraint is absent. It may pay to lengthen the rotation age, as higher timber volume helps to match the WTL constraint.

The interpretation of equation (2b) is straight-forward. The LHS terms denote again condition of the optimal rotation age (on the remaining share of forest land), and it should be zero. The RHS term is the marginal impact of rotation age on the WTL constraint, and it is negative. Thus, we witness a longer rotation age due to the WTL constraint.

Turning to the initial harvesting cycle, the choice of strips and first and second transitional harvests is characterized by the following first-order conditions, where we have again employed the fact that the WTL constraint is binding:

$$m_1 \colon pg_1(t_1) + \lambda_1 w'\varepsilon g_2(t_1) + \frac{\partial J_1}{\partial m_1} = \left[pg_2(t_2) + \lambda_2 w'\varepsilon f_1(t_2 - t_1) - \frac{\partial J_2}{\partial m_1}\right] e^{-r(t_2 - t_1)} \qquad \text{(3a)}$$

$$t_1 \colon\ m_1[pg_1'(t_1) - rpg_1(t_1)] = \lambda_1 w'(1 - m_1)\varepsilon g_2'(t_1) - \lambda_2 w' m_1 \varepsilon f_1'(t_2 - t_1) e^{-r(t_2 - t_1)} + rJ_1 - \left(\frac{\partial J_1}{\partial t_1} + \frac{\partial J_2}{\partial t_1} e^{-r(t_2 - t_1)}\right) \qquad \text{(3b)}$$

$$t_2 \colon (1 - m_1)[pg_2'(t_2) - rpg_2(t_2)] = \lambda_2 w' m_1 \varepsilon f_1'(t_2 - t_1) + rJ_2 - \left(\frac{\partial J_2}{\partial t_2} + \frac{\partial J_1}{\partial t_2} e^{-r(t_1 - t_2)}\right), \qquad \text{(3c)}$$

In equations (3b) and (3c) we have $\frac{\partial J_1}{\partial t_1} > 0$, $\frac{\partial J_2}{\partial t_1} < 0$, $\frac{\partial J_2}{\partial t_2} > 0$ and $\frac{\partial J_1}{\partial t_2} < 0$.

We start the interpretation with the allocation of land between first and second set of strips. Assume first, that the steady-state effects cancel each other out. Then, equation (3a) reduces to:

$$pg_1(t_1) + \lambda_1 w'\varepsilon g_2(t_1) = [pg_2(t_2) + \lambda_2 w'\varepsilon f_1(t_2 - t_1)]e^{-r(t_2 - t_1)}$$

The first LHS term is the harvest revenue from increasing the land area to the first set of strips. The second LHS term denotes the negative marginal impact of the land area choice on the WTL, evaluated at harvest age t_1 . Thus, the LHS is the net return to a marginal increase in land area allocated to the first set of strips. The RHS denotes the opportunity cost of increasing land to the first set of strips. It is a sum of revenue from future harvesting and the negative marginal WTL effect. Thus, the optimal choice is determined by equating the revenue from increasing the share of land to the first set of strips to the present value of future harvesting from the second set of strips. As RHS is a present value term, the optimality condition suggests that m_1 is larger than m_2.

Adding the steady-state effects complicates the choice, as shown by equation (3a). The logic remains the same, however, and the steady-state revenue from increasing the share of the first set of strips reinforces positive LHS term and the opportunity cost in the RHS side is increased by the lost steady-state revenue from the second set of strips. Note, finally that once m_1 is determined, m_2 becomes determined as well, as it is defined by $m_2 = 1 - m_1$.

Turning to the transitional rotation age of the first share of strip areas and assuming temporarily that steady-state impacts, again, cancel each other, we arrange the condition (3b) as follows:

$$t_1\colon\ [pg_1'(t_1) - rpg_1(t_1)] = \lambda_1 w' \frac{(1-m_1)}{m_1} \varepsilon g_2'(t_1) - \lambda_2 w'\varepsilon f_1'(t_2 - t_1)e^{-r(t_2 - t_1)}$$

The LHS is traditional forest resource condition requiring the marginal revenue from lengthening the rotation age to equal to its opportunity cost. The RHS entails the difference between the marginal effects of rotation age on the WTL constraint via forest growth in the first and the second set of strips. The first RHS term is negative and tends to lengthen the rotation age and the RHS second term is positive tending to shorten the rotation age. The last marginal impact term is a present value term, as the first set of strips is harvested as soon as the binding WTL constraint allows and as $t_2 > t_1$, suggesting that the first RHS term should dominate. However, the ratio of $\frac{(1-m_1)}{m_1}$ is plausibly small, as m_1 is greater than $(1-m_1)$. Also, forest growth derivatives may differ in size. Thus, the outcome is a priori ambiguous and needs to be numerically examined.

Adding the steady-state affects follows the same logic. In any case, numerical analysis is required to determine the final outcome.

Turning, finally, to the future transitional harvesting and assuming, again, that steady-state effects are absent, and dividing by $(1-m_1)$, we have,

$$t_2\colon [pg_2'(t_2) - rpg_2(t_2)] = \lambda_2 w' \frac{m_1}{(1-m_1)} \varepsilon f_1'(t_2 - t_1)$$

Resorting previous interpretation, we find that that the negative marginal impact of RHS term tends to lengthen the rotation age relative to the case, where the WTL constraint is absent. Accounting for the steady-state effects brings terms that are positive and negative, thus the outcome is a priori ambiguous.

All in all, we find that when strip harvesting is introduced to an initial stand on peatlands, the forest manager harvests initially as much as the WTL target allows. Therefore, the first set of strips harvested is greater than the second set. Furthermore, under this land-use configuration, the steady state rotation ages tend to be longer than those under conventional even-aged management because of WTL constraint.

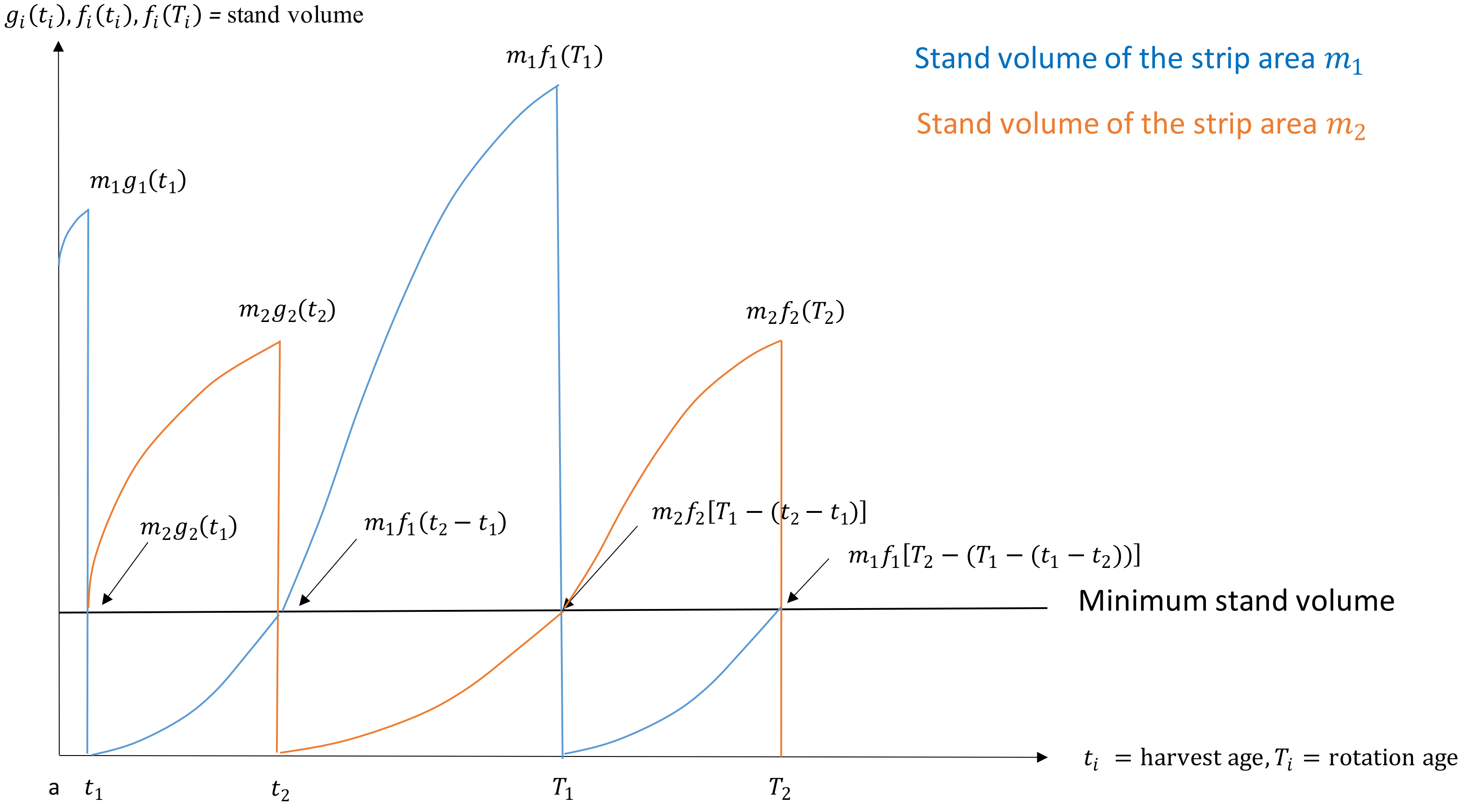

Figure 2. Graphical illustration of the strip harvesting model with two sets of harvested strips.

3. Numerical application of strip harvesting in drained boreal peatlands: ecological and economic data

We apply our model of strip harvesting to a previously drained peatland forest site located in southern Finland. The stand growth is simulated for two alternative forest management methods: CCF with strip harvesting and even-aged forestry with clear-cutting.

3.1 Stand characteristics, ditching and WTL

The representative Scots pine (*Pinus sylvestris* L.) stand used in the tree growth simulations is located in the Akaa municipality, southern Finland. The stand grows on a drained *Vaccinium vitis-idaea* II (Ptkg II)-type site, which is a typical and the most widespread medium-fertile site for Scots pine on drained peatlands (Vasander and Laine 2008). At the beginning of the tree growth simulations (see Section 3.2), the stand age was 65 years, the mean diameter at breast height was 20 cm, the stand dominant height was 18 m, and the total stand stem volume was 216 m^3 ha^{-1}. The soil type was assumed to be characterized by *Carex* peat.

We set the WTL constraint by utilizing the statistical equation of the dependence of the late summer WTL on the tree stand volume and hydrometeorological factors (mean monthly summertime precipitation, average ditch depth in the drainage network and latitude) presented by Sarkkola et al. (2010). We set the mean precipitation as 750 mm a^{-1}, which is the long-term average in southern Finland. Latitude is given as 61°N according to the assumed location of the stand. According to Hökkä et al. (2020), the depth of excavator-made ditches older than 40 years of age stabilizes at a depth of 50-55 cm. Thus, we used 50 cm as an average ditch depth. Once these parameter values are fixed, the depth of WTL in soil only depends on the tree stand volume.

Previous studies have shown that WTL should be maintained within a range of 30 to 40 cm to optimize forest management from an environmental perspective. We approximate this range using two alternative values for the WTL constraint. The first constraint is set 35 cm below the soil surface, which was defined as the target WTL in drained peatland forests in Hökkä et al. (2021). The other constraint is set to 37 cm to ensure that the respective tree stand volume or its transpiration demand is high enough to not let the WTL rise too high. Even though the difference in WTLs examined here is relatively small, it results in an approximately 12 m^3 ha^{-1} difference in the minimum tree stand volumes. We further assume an average WTL for the whole stand area. This is a simplification, as the WTL differs between areas m_1 and m_2 (because of different stand volumes and evapotranspiration capacities) and is most likely higher in recently harvested strips than in strips with standing forests (Stenberg et al. 2022).

3.2 Tree growth data and stand growth functions

Stand growth functions for the optimization models (Section 4) were estimated based on tree growth simulation data. Tree growth data for both even-aged management and strip harvesting are generated using the methods described in detail by Ahtikoski et al. (2022b)[2]. The development of stand growth was estimated by the MOTTI stand simulator (Hynynen et al. 2002; Salminen et al. 2005), taking into account the effect of stand edge by Siipilehto (2006). We employed 25 m as the strip width in the tree growth simulations and assumed that half of the stand area was cut in each harvest cycle. Thinnings are omitted in strip harvesting due to the fact that transporting harvest machinery to harvest site is

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[2] We did not model seedling establishment. Instead, we assume a moderate establishment of 4000 pine seedlings per ha, which is slightly lower than the average of a study on the effect of edge stand effect on seedling stand development (Siipilehto 2006), and in line with tentative results obtained from strip harvesting experiments (Sarkkola and Saarinen 2023).

costly, particularly when cutting removals tend to be low. At the beginning of the simulations, the first strip was harvested. The stand growth simulations are based on two different threshold stand volumes reflecting the two alternative WTL constraints: 64.5 m^3 ha^{-1} for 37 cm and 52.5 m^3 ha^{-1} for 35 cm. The second strip harvesting was performed when the first harvested strip reached these minimum threshold stand volumes. Then, a similar constraint was used in each of the following harvest cycles. Stand growth reached a steady state after the third strip harvest.

In the simulations of the even-aged management, the same initial stand was first thinned (50% of the stand volume) and then DNM was immediately implemented. After clear-cutting, DNM and regeneration (soil preparation and manual planting) were conducted at the beginning of the steady state[3].

Next, the simulation data on tree growth were converted to stand growth functions. Stand growth functions for our optimization models were estimated using the MATLAB Curve Fitting Tool (MATLAB R2021b, www.mathworks.com). The stand growth was estimated as a function of stand age. The growth functions for sawlog, pulpwood, and waste wood were estimated as the total stand volume per hectare.

We finally used Mathematica 13.0 (https://www.wolfram.com/mathematica/) to analyze the optimal harvesting and profitability of strip harvesting (Section 4.1) and MATLAB R2021b (www.mathworks.com) to solve the model of even-aged forestry (Section 4.2).

3.3 *Ex post* estimation of nutrient exports

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[3] Only DNM after clear-cutting of the stand is assumed to be implemented in the steady state. Thinnings and any additional DNM operations are not included in the steady state.

Estimation of the effects of the three alternative management scenarios (strip harvesting; WTL 35 cm, strip harvesting; WTL 37 cm, even-aged management) on nitrogen (N) and phosphorus (P) exports to water courses is based on the assumption by Nieminen et al. (2023) that forestry-induced nutrient exports from drained peatlands consist of the long-term legacy effect of past drainage operations (Nieminen et al. 2018b, 2020, 2022), the shorter-term effects of DNM and forest harvesting. The effect of DNM is based on the export coefficients presented by Finér et al. (2010). According to those coefficients, DNM does not result in increased exports of nitrogen (see also Joensuu et al. 2002, Nieminen et al. 2010) but increases phosphorus exports by 0.42 kg ha^{-1} during the first year after DNM treatment, after which the excess exports decrease to 0.007 kg ha^{-1} during the tenth year. The total DNM-induced excess phosphorus export is 0.93 kg ha^{-1}. Implementation of water protection is assumed in the export coefficients.

The effects of harvestings on total nitrogen and total phosphorus exports from the three alternative management scenarios were estimated using the relationships between harvested stem volume (per catchment area) and nutrient exports (Nieminen et al. 2023). It is thus assumed here that the effect of harvesting on nutrient exports is not so much related to the harvest method (clear-cut versus strip harvesting) as to the volume of the tree stand removed from the catchment area upon harvesting. This is a realistic assumption, as the removed stem volume is strongly related to the amount of harvest residues left on site as well as to the decrease in tree stand evapotranspiration capacity and resulting increase in WTL after harvesting. It thus has a strong influence on how much nutrients are released from harvest residues as well as on how much harvesting affects the release of redox-sensitive nutrients (Nieminen et al. 2017). Excess harvest-induced nutrient exports were assumed to last for 4 years.

The legacy effect of previous drainage operations accounts for most of the nutrient exports from drained peatland forests (Nieminen et al. 2020). The legacy effect for the alternative management scenarios was estimated using the SUSI ecohydrological process model (Laurén et al. 2021). The

SUSI has been widely used in recent studies to simulate forest growth and biogeochemical processes in drained peatland forests. SUSI describes hydrology, biogeochemical processes and stand growth along a 2D cross-section between two parallel ditches in a drained peatland forest. The structure of SUSI is modular. Hydrology modules simulate aboveground and belowground water fluxes and storages and compute daily WTL. The peat temperature module simulates temperatures at different depths in the peat. WTL and peat temperature affect the organic matter decomposition rate and the release and supply of nutrients from organic matter. The stand dimensions are determined by allometric functions and have feedback to the hydrology, decomposition, ground vegetation and net primary production modules. SUSI outputs include site water balance components, daily WTL, stand growth rates, aboveground biomass, and nutrient and carbon balance components.

Nutrient exports in SUSI arise from aerobic peat mineralization and because the nutrients released upon mineralization from the peat below the rooting zone (here 0.4 m) of trees and other vegetation are not adsorbed by soil or accumulated in vegetation but rather are exported to ditches. According to SUSI simulations, nutrient exports are particularly high from sites occupied by mature stands and from intensively drained areas, as their low WTLs enhance peat aerobic mineralization in deeper peat layers (below 0.4 m).

For this study, the source code of SUSI was slightly modified to allow different tree stand inputs for the strips. Strip harvesting was simulated utilizing two 25-m wide strips. The ditch spacing was set to 50 m in both the strip harvesting treatment and even-aged forest management simulations. The initial ditch depth in the strip harvesting scenario was set to 0.5 m. Because of the DNM treatment at the beginning of the simulations, the initial ditch depth was set to 0.9 m in the even-aged forest management scenario. Ditch depth diminished over time due to the temporal deterioration of the drainage network, as presented by Hökkä et al. (2020). Stand growth was fixed to follow the growth described in Section 3.2, and the optimized rotation periods for steady state were used for stand rotation (see Section 4.1). For forcing data, we used similar data for every year to ensure that the impacts of different rotation periods were not affected by variations in weather conditions. In the SUSI simulations, we used spatially averaged 10 km x 10 km daily meteorological data for Akaa for 2010 provided by the Finnish Meteorological Institute (Venäläinen et al. 2005).

3.4. Economic data

Table 1 presents all employed economic parameters, which were converted to the 2020 price level (Official Statistics Finland 2021). Stumpage prices for even-aged management and strip harvesting reflect average annual roundwood prices calculated based on statistics from 2016-2020 (Natural Resources Institute Finland 2021). The real interest rate used was 2.5%. DNM costs per hectare are based on statistics from 2014[4] (Natural Resources Institute Finland 2021). Regeneration costs include average unit costs of soil preparation and manual planting based on statistics from 2016-2020 (Natural Resources Institute Finland 2021).

Table 1. Economic parameter values used in the numerical analysis.

Description	Unit	Value	Source
Timber prices			
Scots pine, standing sales			
Sawlog	€ m^{-3}	56.8	LUKE (2021)$^{a)}$
Pulpwood	€ m^{-3}	17.1	LUKE (2021)$^{a)}$
Scots pine, thinning			
Sawlog	€ m^{-3}	50.0	LUKE (2021)$^{a)}$
Pulpwood	€ m^{-3}	16.2	LUKE (2021)$^{a)}$
Interest rate	%	2.5	
DNM^{b} cost	€ ha^{-1}	222	LUKE (2021)$^{a)}$
Regeneration costs	€ ha^{-1}	982	LUKE (2021)$^{a)}$

a) Natural Resources Institute Finland
b) DNM = ditch network maintenance

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[4] DNM cost statistics are only available per kilometer after year 2014. DNM costs includes both planning and water protection costs (Natural Resources Institute Finland 2021).

4. Numerical analysis: optimal forest management regime in drained peatland forestry

4.1 Optimal harvesting decisions, timber yields and profitability of strip harvesting

Table 2 reports the optimal harvest decisions, timber yields and net present values of harvest revenues.[5] Consider first the case where the WTL constraint is set at 37 cm below the soil surface. Now, the optimal share of the first harvested stand is 72.5% of the total stand area. The optimal time until the first harvest is 4 years, resulting in the stand being harvested for the first time at the age of 69 years. The area left unharvested in the first harvesting, 27.5% of the total peatland stand area, is harvested for the first time at the age of 122 years. According to the stand growth data, tree growth reached a steady state in the two sets of strips after the third and fourth harvests. Thus, the optimal rotation age at the time of the third harvest is 113 years, and that at the time of the fourth harvest is 102 years. After this transition period, tree growth reaches steady-state growth. The optimal rotation ages in the steady state are the same 103 years for both shares of land, m_1 and m_2. The net present value is €6513 ha^{-1}. The total timber yield in the steady state from both areas m_1 and m_2 is 328 m^3 ha^{-1} .

The upper WTL constraint (35 cm below the soil surface) increases the share of harvested stand area in the first harvest to 77.6% of the total stand area. This is as expected, as the upper WTL constraint allows for a lower threshold stand volume. Furthermore, the optimal harvest cycle is shorter both in the transition phase and steady state compared to the lower WTL. The net present value of harvest

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[5] Related shadow prices are presented in Appendix B in Tables B1 and B3 and the detailed timber yields in Tables B2 and B4.

revenues increases with the upper WTL constraint by €370 ha^{-1} to €6883 ha^{-1} because the 35 cm constraint allows for more intensive initial harvesting.

Table 2 and Appendix D report the sensitivity analysis of the key variables. From Table 2, varying the interest rates affects both the optimal share of the first harvested stand and the optimal harvest cycle. As can be expected, a lower interest rate lengthens the optimal harvest cycle. Even though the constraint on targeted WTL, defining minimum stand volume, is kept at the same level, the longer harvest cycle allows cutting a higher share of the total area in the first strip harvest. The impact of a lower interest rate on net present value is as expected; it increases the net present value. The lower interest rate decreases shadow prices both in the transition and steady-state harvests. As the lower interest rate results in a longer harvest cycle, it has a minor positive impact on total timber yield (Appendix B Table B2). If the real interest rate is higher, the effects are just the opposite. Thus, the impacts of the interest rate are similar to those in the Faustmann model.

Varying timber prices do not change the optimal shares of the two strips or their optimal harvest cycles (Appendix D) because the binding WTL constraint prevents changing the shares of the strips. Therefore, timber yields remain unchanged even though timber prices vary. Varying timber prices only affect the net revenue of strip harvesting. When the WTL target is 37 cm and 35 cm below the soil surface, decreasing timber prices by 20% gives net present values of €5209 ha^{-1} and €5505 ha^{-1}, respectively. Increasing the prices by 20% gives a net present value of €7815 ha^{-1} for 37 cm and €8259 ha^{-1} for 35 cm.

Table 2 shows that the constraint on the WTL has the most significant effect on the optimal share of harvested stand area. Even though the difference in the targeted WTL is only 2 cm, it has a considerable impact on the optimal solution. Under the upper WTL (35 cm below the soil surface), the optimal share of stand area harvested in the first harvest cycle is 7% larger than that with the lower WTL target. Furthermore, the profitability of strip harvesting is 5.7% higher with the upper 35 cm target. Lastly, the upper WTL target level results in smaller total timber yields in the steady state. This is due to shorter harvesting cycles. Figures C1 and C2 in Appendix C illustrate the optimal harvesting decisions, harvest cycles and timber yields of strip harvesting.

Table 2. Optimal harvesting decisions, timber yields and profitability of strip harvesting in southern Finland. Partial sensitivity analysis: real interest rate.

	m_1 (% of the total area)	m_2 (% of the total area)	Transitional harvests				Steady-state harvests		NPV (€ ha^{-1})	Timber yield steady state (m^3 ha^{-1})
			t_1 (years)	t_2 (years)	t_3 (years)	t_4 (years)	T_1 (years)	T_2 (years)		
WTL = 37 cm										
Basic run	72.5	27.5	69	122	113	102	103	103	6513	328
Sensitivity analysis										
Real interest rate (%)										
2	72.7	27.3	70	123	113	102	104	104	7376	329
3	72.3	27.7	69	121	112	102	103	103	5958	328
WTL = 35 cm										
Basic run	77.6	22.4	69	115	102	92	94	94	6883	312
Sensitivity analysis										
Real interest rate (%)										
2	77.8	22.2	70	117	103	93	94	94	7715	312
3	77.4	22.6	69	114	102	92	93	93	6341	311

WTL, water table level; m_1, share of area harvested in the first harvest cycle; m_2, share of area harvested in the second harvest cycle; t_1, stand age at first transitional harvest; t_2, stand age at second transitional harvest; t_3, rotation age at third transitional harvest; t_4, rotation age at fourth transitional harvest; T_1, steady-state rotation age of the first area harvested; T_2, steady-state rotation age of the second area harvested; NPV, net present value

4.2 Optimal harvesting decisions, timber yields and profitability of even-aged forest management

Suppose next that our forest site is subject to even-aged forest management. The target function for the economic choice with both the initial stand and steady-state rotation is described in Appendix A (for a more detailed description of the model, see Miettinen et al. 2020a). First, the initial stand is thinned (50% of the stand volume) followed by DNM. After clear-cutting of the initial stand, DNM and regeneration (soil preparation and manual planting) are implemented at the beginning of the steady-state rotation.

The optimal harvesting decisions, net present values and timber yields are reported in Table 3. In the basic run, the optimal clear-cutting of the initial stand is executed 10 years after thinning and DNM at the stand age of 75 years. The optimal steady-state rotation age is 60 years, and the net present value is €8252 ha^{-1}, of which €3205 is due to thinning of the initial stand. The timber yield from the initial stand is 252 m^3 ha^{-1} and in the steady state 303 m^3 ha^{-1}. In the sensitivity analysis, we changed values by 20% below or above the basic run estimate, except the real interest rate (see Table 3). The effects of timber prices, interest rates and regeneration costs on optimal harvesting decisions are conventional. As DNM costs are low, they do not have an effect on the optimal harvesting decisions and only have an effect on the net present values.

Table 3. Optimal harvesting decisions, timber yields and profitability of even-aged forest management in the studied stand in southern Finland (initial stand volume, 216 m^3 ha^{-1}; initial age, 65 years). Partial sensitivity analysis: timber prices, real interest rate, ditch network maintenance (DNM) and regeneration costs.

	t_1 (years)	T_1 (years)	NPV (€ ha^{-1})	Timber yield, initial stand [a] (m^3 ha^{-1})	Timber yield, steady state (m^3 ha^{-1})
Basic run	75	60	8252	252	303
Sensitivity analysis					
Timber prices					
-20%	77	61	6961	258	307
+20%	74	60	9550	248	303
Interest rate					
2%	77	63	9491	258	313
3%	73	58	7477	245	296
DNM cost (€ ha^{-1})					
178 (-20%)	75	60	8340	252	303
266 (+20%)	75	60	8164	252	303
Regeneration costs (€ ha^{-1})					
786 (-20%)	74	60	8451	248	303
1178 (+20%)	76	61	8059	255	307

t_1, stand age at clear-cut of the initial stand; T_1, steady-state rotation age; NPV, net present value

[a] Timber yield of the initial stand includes both thinning (50% of the stand volume) and final felling.

A comparison between Tables 3 and 2 indicates that the total timber yield in the steady state is lower in even-aged management than in the respective steady state of strip harvesting. In the basic run, the net present values in the even-aged management regime are from €1369 to 1739 ha^{-1} higher than the net present values in strip harvesting. In even-aged management, thinning revenues constitute a significant share of NPV (€3205 ha^{-1} in the basic run), making even-aged management more profitable than strip harvesting. The difference in net present values is 17% with the 35 cm WTL constraint and 21% with the 37 cm constraint. Varying interest rates, timber prices, DNM costs and regeneration costs still indicate higher profitability for even-aged management than strip harvesting. Note, however, that if we consider strip harvesting as a solution to reduce negative externalities, we still need to add the damage values of environmental impacts to the private net present values of harvesting.

4.3 Comparison of social net benefits when ex post nutrient load damage is taken into account

First, we compare the two harvesting regimes by taking into account their ex post nutrient loads in the steady state solutions[6]. Strip harvesting is not subjected to DNM and is less intensive in terms of harvested wood volume than clear-cutting (Figure 3), thus promoting water protection. For even-aged management, we assume that DNM and regeneration are conducted at the beginning of the period starting from bare land. Second, we estimate nutrient load damages and subtract damages from the net present values from steady state harvesting to produce estimates of social net benefits of both harvest regimes.

4.3.1 Estimation of nutrient exports

Both nitrogen and phosphorus exports are clearly higher from the steady-state even-aged management scenario than from the strip harvesting scenarios (Figure 3). Harvesting results in high peaks, particularly following clear-cutting, because of the large volume of harvested wood (Figure 3). The difference between even-aged management and strip harvesting is higher for phosphorus than nitrogen exports because DNM is assumed to only increase phosphorus exports. The legacy effect of drainage shows up as increasing nutrient exports between harvest occasions. It is somewhat higher for the even-aged than strip harvesting scenario because deeper ditches (due to DNM) and larger stand volume in mature even-aged stands result in low WTLs (Sarkkola et al. 2010), thus increasing

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[6] Time needed to reach the steady state differs significantly between even-aged management and strip harvesting. Therefore, we compare water quality damages only at the steady state. To be precise, the optimized timings of the harvests are used in the estimation of nutrient loads. The share of area harvested in each steady-state harvest is set as half of the total area when nutrient loads are estimated.

nutrient mineralization and exports according to SUSI model simulations. For the even-aged management scenario, the mean annual nutrient exports for nitrogen are 2 times and for phosphorus 3 times that of the strip harvest scenario. The differences in the exports between strip harvesting scenarios are small, and the legacy effect mostly explained the slightly smaller exports with a WTL constraint of 35 cm (Figure 3). This is a result of the shorter rotation period and smaller stand volumes.

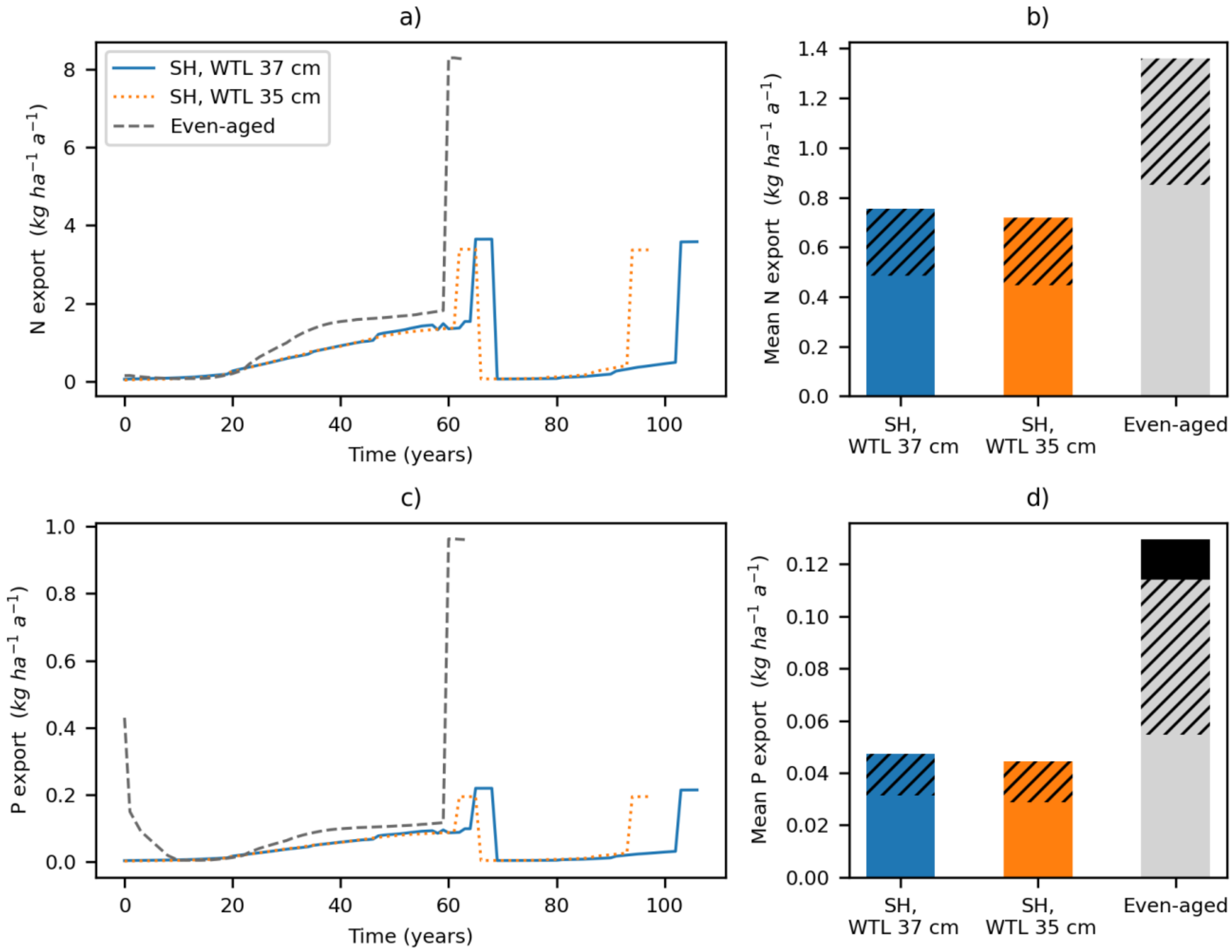

Figure 3. Annual (a) and mean annual (b) nitrogen (N) and annual (c) and mean annual (d) phosphorus (P) export over the steady-state rotation periods. SH refers to strip harvesting with water table level (WTL) constraints. In the even-aged management scenario, ditch network maintenance takes place at

year 0 (present time point). The hatched bar shows the share of harvest-related exports, and the black bar shows the share of ditch network maintenance-related exports.

4.3.2 Estimation of nutrient load damages and social net benefits

We need to determine an estimate of nutrient load damage for both harvest regimes. The introduction of nutrient load damage into our analysis is challenging due to the WTL constraints associated with strip harvesting. Therefore, we cannot use general damage estimates from valuation studies (for their use, see Miettinen et al. 2020). Instead, we apply here the revealed preference approach and assume that the WTL constraint reflects society's valuation of clean water, so that the shadow price reflects marginal damage valuation[7]. We combine the above nutrient exports and the shadow prices associated with steady-state strip harvesting (see Appendix B Tables B1 and B3) to determine nutrient load damage for both management regimes.

The estimates for nutrient load damage are calculated as follows. Steady-state shadow prices for both steady-state harvests (T1 and T2 reported in Appendix B Tables B1 and B3) are multiplied by the share of area harvested in each harvest cycle. Then, the average of these shadow prices is divided by the estimated decrease in nutrient export load compared to the even-aged management8 and discounted to present values using their respective steady-state rotation ages. When the WTL constraint is set at 37 cm and 35 cm below the soil surface, the nutrient load damage estimates are

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[7] [R]Recall, our model considers the WTL range as an exogenously adopted policy towards peatland forests. Therefore, and consistently with the theory of revealed preference we employ in our calculation the shadow value for this policy. (For the role and use of shadow values on environmental policy, see , for instance, by Baumol and Oates 1988).

[8] The shadow prices are expressed as euros per cm marginal change in WTL requirement. The marginal damage values are produced as follows. We first estimated the decreases in nutrient exports (kg Ne per hectare) when strip harvesting is applied instead of even-aged management. Second, we assumed that after clear-cut, the stand volume is zero and according to the model by Sarkkola et al. (2010) the WTL is at 21 cm below the soil surface. We calculated the difference in WTLs between strip harvesting and even-aged management. We then calculated the estimated decrease in nutrient export per cm change in WTL when strip harvesting is applied instead of even-aged management. Finally, the shadow prices were divided with these estimated decreases in nutrient exports compared to even-aged management.

€7.9/kg Ne9 and €4.3/kg Ne, respectively. These marginal damage values describe a shadow price of nutrient load decrease in both alternative cases of WTL constraints set for strip harvesting. The lower of these values, €4.3/kg Ne, is clearly lower than nutrient load damage estimates based on valuation studies (e.g., based on Gren (2001)[10], the nutrient load damage estimate converted to the 2020 price level is €8.0/kg Ne). However, the higher value, €7.9/kg Ne, is close to results from the valuation studies.

The average shadow price for strip harvesting (€6.1/kg Ne) is used to estimate the nutrient load damage of even-aged forest management. Then, the annual steady-state nutrient loads (kg Ne/ha/year) of each harvest regime are multiplied by their nutrient load damage values and discounted to present values. Finally, these periodic nutrient load damages are summed over the rotation period of each harvest regime.

Table 4 reports the key results on the ex post social net benefits from strip harvesting and even-aged management. We report nutrient loads and nutrient damage. We also report the net present value from steady-state harvesting (NPV) and subtract damages from the NPVs to produce the social net benefits. Finally, we illustrate the role of damage using the ratio of nutrient load damage to NPV.

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[9] The phosphorus loads reported in Section 4.3.1 are converted to nitrogen equivalents (Ne) using the Redfield ratio, which is the constant ratio of nitrogen and phosphorus mass among marine plankton (Wetzel 2001). The phosphorus loads are multiplied by 7.2 to calculate phosphorus loads as nitrogen equivalents.

[10] Based on Gren (2001), the marginal benefit of Ne reduction was 62 SEK kg^{-1} (in 1994 prices). We used Statistiska centralbyrån (2025) and Bank of Finland (2025) to convert the value first to the 2020 price level and then to euros.

Table 4. Steady-state nutrient loads, nutrient load damages, net present values of harvest revenues, social net benefits and ratio of nutrient load damages to net present value of harvest revenues for both harvest regimes – strip harvesting and even-aged forest management.

	Nutrient loads (kgNe/ha)	Nutrient load damages (€/ha)	NPV of steady-state harvests (€/ha)	Social net benefits ex post (€/ha)	Ratio of nutrient load damages to NPV
Strip harvesting (WTL = 37 cm)	117	246	870	624	0.28
Strip harvesting (WTL = 35 cm)	102	126	921	795	0.14
Even-aged forest management	147	374	1099	725	0.34

Note: Ne, nitrogen equivalent

Nutrient loads differ between the management regimes and in strip harvesting across WTL constraints. Strip harvesting decreases nutrient exports compared to even-aged management by 20-31%. Within the strip harvesting regime, the lower WTL constraint (37 cm below the soil surface) leads to higher nutrient exports, as can be expected, because higher harvesting volumes increase harvest-related nutrient exports and low WTLs enhance aerobic peat mineralization and nutrient mobilization and export according to the SUSI model (see Section 4.3.1). Accounting for the nutrient load damage leads to even larger differences between the harvesting regimes. Thus, strip harvesting significantly decreases nutrient load damage compared to even-aged management.

The net present values of steady-state harvesting in the absence of water quality impacts favor even-aged management. In strip harvesting under the lower WTL constraint (37 cm below the soil surface), a higher threshold stand volume is required than with the upper level constraint (35 cm below the soil surface). This means that both optimal harvesting cycles are longer and the share of the area harvested in the first harvest cycle is lower under the lower WTL constraint. Thus, strip harvesting under the lower WTL constraint (37 cm below the soil surface) is privately less profitable than under the upper WTL constraint.

The social net benefits of the management regimes depend on both the magnitude of the nutrient load damages and NPV of the steady-state harvests. Strip harvesting with the upper 35 cm WTL constraint gives €70 per hectare higher benefits than even-aged management. However, the social net benefits are sensitive to WTL constraint, and strip harvesting under the lower WTL constraint (37 cm below the soil surface) provides €101 per hectare lower social net benefits than even-aged forest management despite its lower nutrient load damage compared to even-aged management[11]. The ratio of the nutrient load damage to the net present values of harvest revenues provides the same message. Under strip harvesting, the share of damages to NPV is 14% for the upper WTL constraint and 28% for the lower WTL constraint. In the case of even-aged management, the share is 34%. In all cases, nutrient load damages are significant compared to private net present values of harvest revenues, implying that it is important to consider water quality impacts when making decisions on harvest regimes. Finally, under the lower water quality constraint, strip harvesting outperformed even-aged management in terms of both nutrient load damages and social net benefits under the used nutrient damage estimates.

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[11] In addition to nutrient loads, forest management in drained peatlands is a source of organic carbon runoff, which causes browning of surface waters (Kritzberg 2017; Finer et al. 2021). We do not, however, account for this source of water quality damage. There are no data available to model organic carbon loads for the harvesting methods analyzed in this study. Obviously, accounting for organic carbon runoff and the associated water quality damage, would have increased the water quality benefits of strip harvesting.

5. Conclusions

Current even-aged peatland forestry with clear-cuts and DNM causes adverse water quality impacts. CCF management practices can decrease these impacts, as they avoid clear-cuts and DNM and keep the water table at a stable and more favorable level from the viewpoint of nutrient exports than even-aged management. We developed an economic model of strip harvesting in which the forest manager maximizes the present value of harvest revenue subject to a constraint of keeping the water table at a level that minimizes adverse water quality impacts. Our model introduces the first analytical treatment of the economics of strip harvesting by concurrently assessing its effects on nutrient exports to water courses. Because we applied a constraint to keep WTL at a favorable level, our strip harvesting model entailed two decisions: allocation of the area of the stand between harvested and unharvested strips and determination of the timing of harvesting. The numerical application of the model shows that economically optimal strip harvesting produces a consistent relationship between the shares of the harvested strips and the rotation ages. Given the large area of drained peatland forests in boreal regions (Paavilainen and Päivänen 1995) and their important role in forestry in many countries, our model provides a good starting point for designing more sustainable solutions for forest management.

Our main findings are as follows: first, strip harvesting is an environmentally effective alternative to even-aged management, bringing significant water quality benefits but at the same time lower private harvest revenues. In the studied southern Finland drained peatland forest site, even-aged management turns out to be a more profitable option than strip harvesting for the private forest owner. This result is in line with the study by Ahtikoski et al. (2022b). From society´s viewpoint, strip harvesting reduces nutrient exports and associated negative externalities on water quality, performing better than traditional even-aged management with ditch network maintenance. However, our study indicated that the social net benefits are highly sensitive to the applied WTL constraint. In the case where the constraint was set to 35 cm below the soil surface, strip harvesting provided higher social net benefits than even-aged management. If the WTL constraint was set at a 2 cm lower level, strip harvesting was a poorer choice than even-aged management. Thus, a very small change in the WTL constraint significantly delays harvestings and lengthens harvest cycles due to the relatively large difference in the minimum stand volumes that determine the timing of harvests in our model. The binding WTL constraint also makes economic choices quite rigid; that is, timber prices do not affect the optimal choices, and the real interest rate has a relatively small impact on the strip harvesting design.

The strip harvesting model developed in this study can be applied to different initial conditions, site types and locations on drained boreal peatlands. This is a good property, as numerical results will depend on initial conditions, geographical locations, and site types. For example, Ahtikoski et al. (2022b) show that in more northern locations than in our study and with wide strips, strip harvesting becomes a more profitable option than even-aged management. A notable limitation of our study is that we assumed fixed strip areas after the first harvest. This simplification is a special case of a general model in which strips can be selected in each harvest. Such a model should, however, include a more specific description of the relationship between WTL and strip size or width. It should also be noted that it may not be reasonable to harvest many strips at different periods in operational forestry because harvesting costs increase with an increasing number of strips. Furthermore, there are challenges in strip harvesting regarding how to maintain the desirable WTL in the middle of the harvested strips (Stenberg et al. 2022). Our study assumed no spatial variation in the water table within the strip-harvested stand and is thus a simplification of the true WTL variation.

There are many interesting avenues for further research. An important task is to strengthen the biological basis of strip harvesting, especially the estimates of tree growth and natural regeneration in the strips. Another fundamental task is to assess uncertainties concerning the evapotranspiration capacity of tree stands and other vegetation and the spatial variation in the water table in the harvested and unharvested strips. We assumed in our calculations that DNM is not a necessary operation in strip harvesting, but it may become necessary in areas with poor drainage network conditions and low tree evapotranspiration capacity due to, for example, deficiency of key nutrients, specifically potassium, which may be a common situation in drained peatland forests. Extending the numerical models to include fixed harvesting costs is an important future research topic that would further increase the reliability of optimization results (see e.g., Tahvonen and Rämö 2016). It would also be interesting to examine at what level the constraint would be set according to the socially optimal solution where marginal nutrient damages are derived from valuation studies.

Data availability

Data generated or analyzed during this study are available from the corresponding author upon reasonable request.

Competing interests

The authors declare there are no competing interests.

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Appendix A. Maximization problem of even-aged forestry with clear-cutting and DNM in drained peatland forestry

The employed even-aged model is a modification of Miettinen et al. (2020a). It provides a framework of boreal drained peatland forestry including both nutrient and sediment load damage functions and water protection costs. We apply the model not using the social damage valuation functions, and assume that water protection costs are included in DNM costs. The age of the initial stand is a, the stand age at the first harvest of the initial stand is t_1, and DNM effort is n. Thus, the stand growth function is $f(t_1 - a; n)$. The unit cost of DNM is w, timber price is p, regeneration costs are c and the real interest rate is denoted by r. The net present value of harvest revenues in the steady state is defined as $LEV = [pf(T; n)e^{-rT} - c - wn](1 - e^{-rT})^{-1}$. The forest manager maximizes the net present value of harvest revenues for both the initial stand, denoted by V, and the steady state, denoted by LEV:

$$V = pf(t_1 - a; n)e^{-r(t_1 - a)} - wn + e^{-r(t_1 - a)}LEV \qquad \text{(A.1)}$$

Appendix B

Table B1. Shadow prices of strip harvesting (€/cm) in southern Finland when the water table level (WTL) is 37 cm below the soil surface. Partial sensitivity analysis: timber prices and real interest rate.

	Transitional harvests				Steady-state harvests	
	λ1	λ2	λ3	λ4	µ1	µ2
Basic run	109	338	788	254	1007	149
Sensitivity analysis						
Price of Scots pine, sawlog/pulpwood (€ m^{-3})						
-20%	87	271	630	203	805	119
+20%	130	406	945	305	1209	179
Real interest rate, %						
2	59	301	690	246	874	123
3	140	377	888	266	1141	178

Table B2. Timber yields of strip harvesting in southern Finland when the water table level (WTL) is 37 cm below the soil surface. Partial sensitivity analysis: timber prices and real interest rate.

	Transitional harvests				Steady-state harvests		Total timber yield (m^3 ha^{-1})
	Timber yield (m^3), first harvest at t_1	Timber yield (m^3), second harvest at t_2	Timber yield (m^3), third harvest at t_3	Timber yield (m^3), fourth harvest at t_4	Timber yield (m^3), steady-state harvest at T_1	Timber yield (m^3), steady-state harvest at T_2	
Basic run	170	101	206	92	238	90	897
Sensitivity analysis							
Price of Scots pine, sawlog/pulpwood (€ m^{-3})							
-20%	170	101	206	92	238	90	897
+20%	170	101	206	92	238	90	897
Real interest rate (%)							
2	172	100	207	91	239	90	899
3	168	101	205	93	237	91	896

Table B3. Shadow prices of strip harvesting (€/cm) in southern Finland when the water table level (WTL) is 35 cm below the soil surface. Partial sensitivity analysis: timber prices and real interest rate.

	Transitional harvests				Steady-state harvests	
	λ1	λ2	λ3	λ4	µ1	µ2
Basic run	50	232	769	168	962	84
Sensitivity analysis						
Price of Scots pine, sawlog/pulpwood (€ m^{-3})						
-20%	40	186	615	135	769	67
+20%	60	279	923	202	1154	101
Real interest rate, %						
2	-3.2	211	686	171	853	70
3	85	255	858	170	1076	99

Table B4. Timber yields of strip harvesting in southern Finland when the water table level (WTL) is 35 cm below the soil surface. Partial sensitivity analysis: timber prices and real interest rate.

	Transitional harvests				Steady-state harvests		Total timber yield (m^3 ha^{-1})
	Timber yield (m^3), first harvest at t_1	Timber yield (m^3), second harvest at t_2	Timber yield (m^3), third harvest at t_3	Timber yield (m^3), fourth harvest at t_4	Timber yield (m^3), steady-state harvest at T_1	Timber yield (m^3), steady-state harvest at T_2	
Basic run	182	79	208	69	242	70	851
Sensitivity analysis							
Price of Scots pine, sawlog/pulpwood (€ m^{-3})							
-20%	182	79	208	69	242	70	851
+20%	182	79	208	69	242	70	851
Real interest rate (%)							
2	185	79	209	69	243	69	854
3	180	80	207	70	241	70	848

Appendix C. Optimal harvesting decisions, harvest cycles and timber yields of strip harvesting are shown in Figures C1 and C2. In both figures, the x-axis refers to stand/rotation ages (t_i, T_i) and the y-axis refers to stand volumes ($f_i(t)$ and $g_i(t)$) and timber yields in each harvest (marked in orange/blue). Under a binding constraint on the water table level, the stand must reach the minimum volume before the next harvest. The stand volume always stays above the minimum stand volume described by the horizontal line. The harvest cycle reaches the steady-state cycle after the fourth harvest.

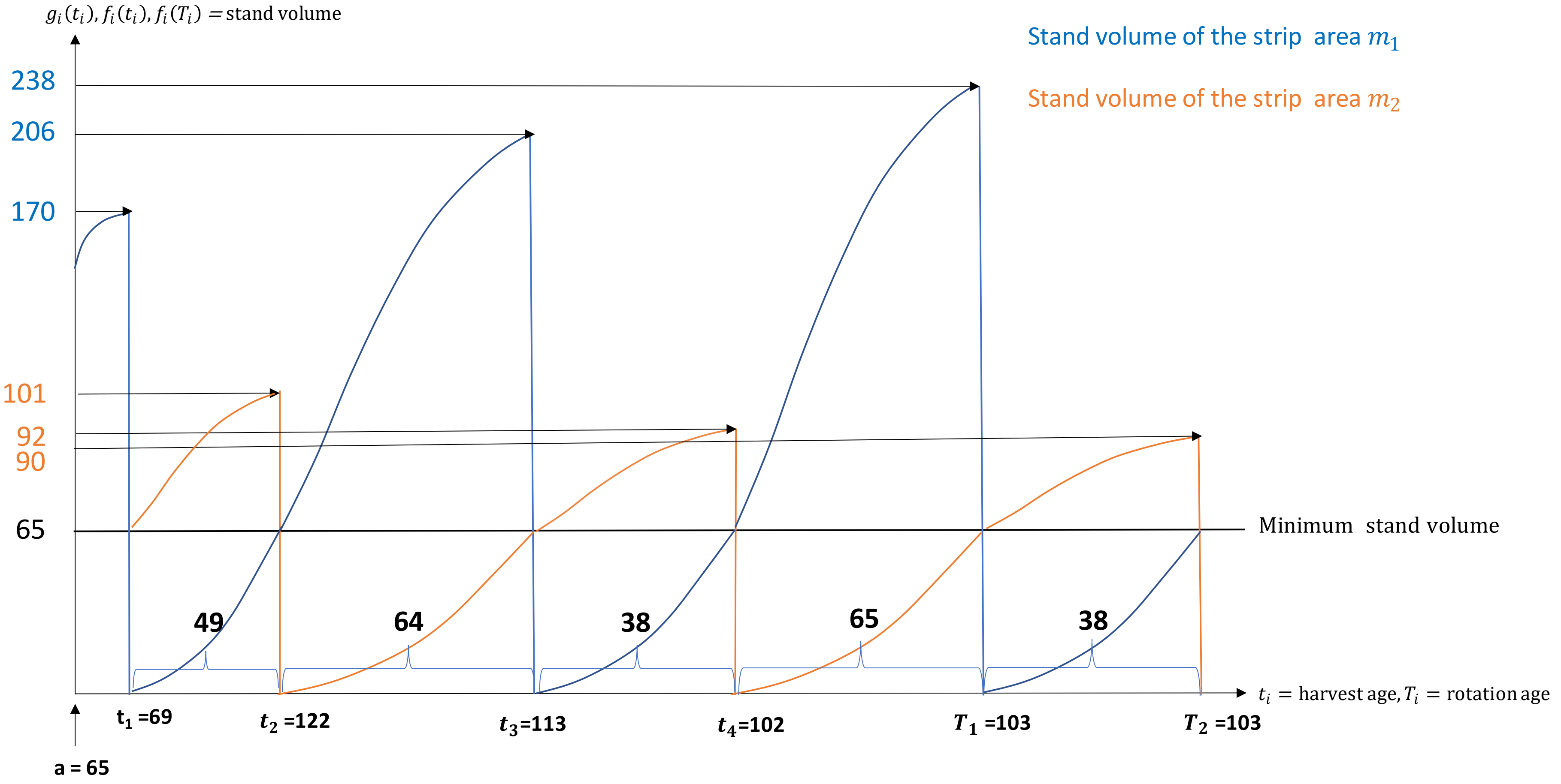

Figure C1. Optimal harvesting decisions, harvest cycles and timber yields of strip harvesting in southern Finland when the water table level is 37 cm below the soil surface.

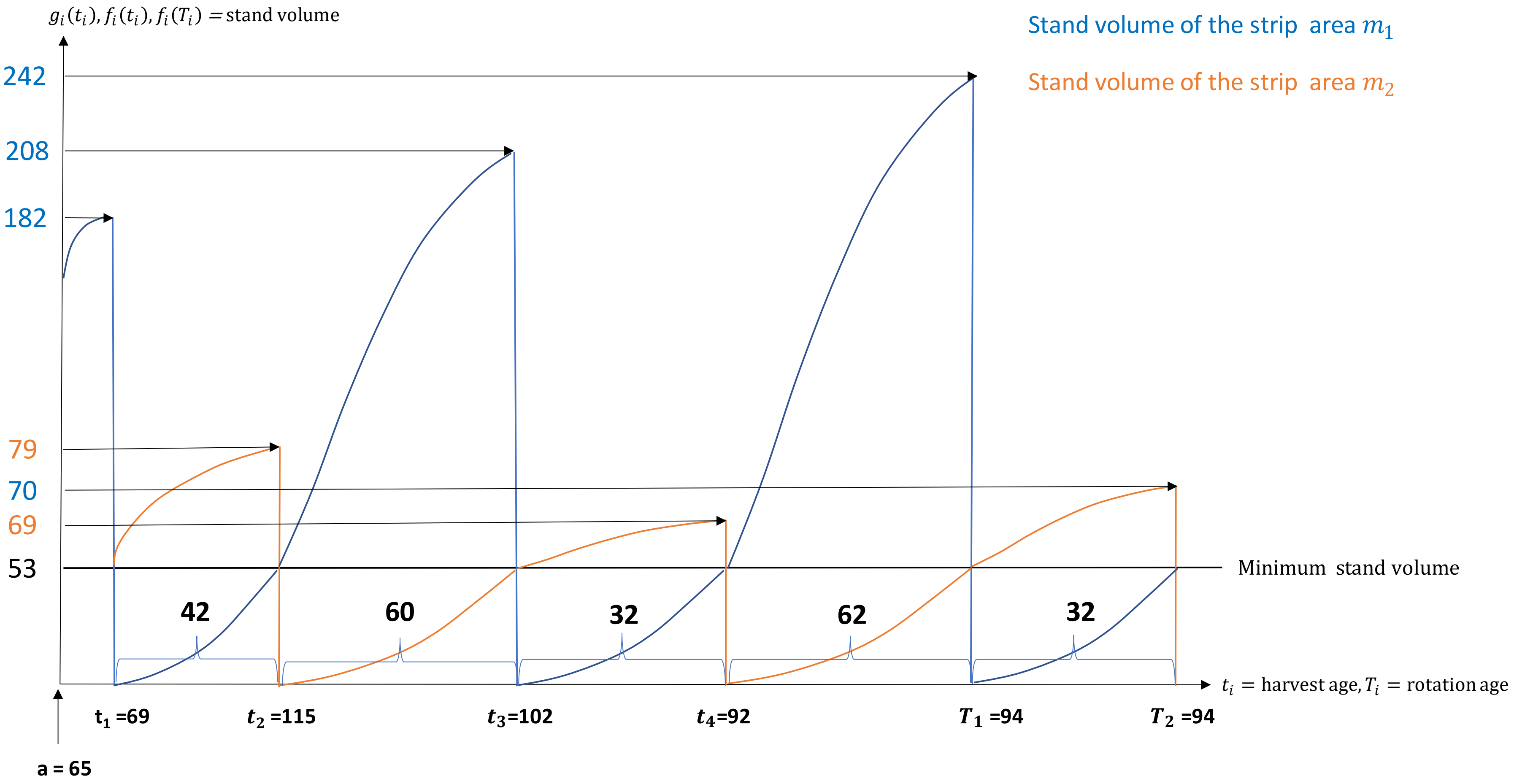

Figure C2. Optimal harvesting decisions, harvest cycles and timber yields of strip harvesting in southern Finland when the water table level is 35 cm below the soil surface.

Appendix D

Table D1. Optimal harvesting decisions, timber yields and profitability of strip harvesting in southern Finland. Partial sensitivity analysis: timber prices.

	m_1 (% of the total area)	m_2 (% of the total area)	Transitional harvests				Steady-state harvests		NPV (€ ha^{-1})	Timber yield steady state (m^3 ha^{-1})
			t_1 (years)	t_2 (years)	t_3 (years)	t_4 (years)	T_1 (years)	T_2 (years)		
WTL = 37 cm										
Basic run	72.5	27.5	69	122	113	102	103	103	6513	328
Sensitivity analysis										
Price of Scots pine, sawlog/pulpwood (€ m^{-3})										
-20%	72.5	27.5	69	122	113	102	103	103	5209	328
+20%	72.5	27.5	69	122	113	102	103	103	7815	328
WTL =35 cm										
Basic run	77.6	22.4	69	115	102	92	94	94	6883	312
Sensitivity analysis										
Price of Scots pine, sawlog/pulpwood (€ m^{-3})										
-20%	77.6	22.4	69	115	102	92	94	94	5505	312
+20%	77.6	22.4	69	115	102	92	94	94	8259	312

WTL, water table level; m_1, share of area harvested in the first harvest cycle; m_2, share of area harvested in the second harvest cycle; t_1, stand age at first transitional harvest; t_2, stand age at second transitional harvest; t_3, rotation age at third transitional harvest; t_4, rotation age at fourth transitional harvest; T_1, steady-state rotation age of the first area harvested; T_2, steady-state rotation age of the second area harvested; NPV, net present value