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1 Economics of mixed-species forestry with ecosystem services

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17 Abstract

18 Specifying the economics of forest value besides raw material production following the Faustmann-
19 Hartman setup is widely established, but criticized as restrictive in capturing diversity values. We show
20 that extending the model to cover diversity attributes, i.e. including mixed species and internal
21 heterogeneity within species is not enough to overcome the restrictions. Additionally, it is necessary to
22 extend forest harvesting regimes to cover thinning (partial harvesting), continuous cover forestry, and
23 the management of commercially useless trees. Restrictions in the Faustmann-Hartman setup are first
24 shown analytically with optimized thinning, but without tree size structures. The empirical significance
25 of these findings is shown by a model with four tree species, tree size structures, an extended set of forest
26 management activities, a detailed description of harvesting costs, and a measure for stand diversity as a
27 key factor behind ecosystem services. We show how optimal harvesting regime, net revenues, wood
28 output, and stand diversity depend on model flexibility, economic parameters and on the valuation of
29 ecosystem services. In a setup allowing flexible management regimes, the costs of reaching a specified
30 level of ecosystem services are negligible compared to the Faustmann-Hartman specification.

31

32 Keywords: Hartman model, Faustmann model, forest amenities, ecosystem services, continuous cover
33 forestry, forest policy, dynamic mixed-integer optimization, optimal harvesting

34

35

36

37 1 Introduction

38 Forests represent a prime example of extractive natural resources that are highly valuable besides their
39 contribution as a source of raw materials. In the economics of forest resources, this was perhaps first
40 formalized in Hartman (1976), who included the value of a standing forest into the generic Faustmann
41 (1849) and Samuelson (1976) optimal rotation model. Since then, numerous studies have followed the
42 Hartmann extension. However, despite this success, a recent review by Amacher (2015) comes to the
43 conclusion that albeit the economic modeling of amenities as a function of stand age may be justified as
44 a first hypothesis, it remains very basic. The uniformity of the large number of models presented after
45 Hartmann (1976) is also found restrictive. According to Amacher (2015), forest economics has so far
46 been unable to merge conservation biology, which identifies links between key habitats and species
47 diversity attributes in economic optimization models of forest resources.

48 Our study aims to proceed from the Faustmann-Hartman setup by a model for mixed-species forests.
49 This extension together with the inclusion of tree size structure enables us to formalize both species and
50 intraspecies diversity. We show that extending the diversity attributes in the amenity or ecosystem
51 services (ES) valuation is not enough as such. In addition, it is necessary to extend the set of forest
52 management activities and proceed beyond Faustmann-Hartman rotation forestry regime based on
53 harvesting stands by clearcuts only.¹

54 Existing literature largely suggests a strong connection between forest structural diversity, species
55 diversity, ES, and productivity. Structural diversity in forests originates from two main sources, i.e. from
56 horizontal diversity including structural differences among tree species and from vertical variation
57 among tree strata. The ‘habitat heterogeneity hypothesis’ in ecology (MacArthur & Wilson 1967)

¹ It is seldom noticed that in his famous formula for the bare land value, Faustmann (1849) includes the present value of revenues from thinning (partial cuttings).

58 postulates that structurally (horizontally and/or vertically) complex habitats provide more niches and
59 diverse ways of exploiting environmental resources and thus imply higher species diversity and
60 productivity. Liang et al. (2016) study the biodiversity-productivity relationship using a global dataset,
61 and find a positive concave relationship between species richness and tree volume productivity. Ongoing
62 species loss in forests is found a threat to forest productivity, and benefits from the transition of
63 monocultures to mixed-species stands are emphasized. Gamfelt et al. (2013) study boreal forests, and
64 find either a monotonically increasing positive, or a single-peaked relationship between tree species
65 richness and the supply of ES such as soil carbon storage, deadwood, and berry and game production.
66 Zhou (2017) applies hedonic valuation and finds stand structural diversity and the density of large pine
67 trees as key determinants for preserving amenities among forest owners in the U.S. southern pine region.

68 Another line of research has studied the connection between management measures and forest
69 diversity characteristics. Bose et al. (2013) review expanding Canadian experiments on forests thinning
70 and continuous cover forestry that aim to balance economic and ecological objectives. Avoiding clearcuts
71 contributes to maintaining the natural characteristics of forest landscapes and more favorable habitat
72 attributes for birds, insects, vertebrates, and vegetation. As constraints to continuous cover forestry, they
73 mention the threat of short-sighted high-grading, i.e. “harvest the best, leave the rest”. Conceptual and
74 simulation models for synthesizing empirical knowledge are proposed as the most promising way ahead.
75 In a review on Canadian field experiments Ruel et al. (2013) find that many attributes of old-growth
76 forests can be preserved with thinning, and diversity indices for partially harvested stands remain similar
77 or very close to uncut forests. They obtained a result that avoiding clearcuts causes a short-term decrease
78 in profitability, while the long-term outcome may be the reverse (no optimization applied). Martin et al.
79 (2018) emphasize less intensive management treatments as a main method for maintaining the diversity
80 of Canadian boreal forests, but expect that economic viability will restrict broader developments of the

81 alternatives for clearcutting. For Nordic boreal forests the diversity of management methods have been
82 emphasized in Peura et al. (2018).

83 Thus, existing forest ecological and management research supports the view that while longer
84 rotation periods are favorable for amenities and ES, the role of lower impact harvesting methods, such
85 as thinning and continuous cover management, may be more important when the aim is to maintain forest
86 diversity, ES, and a balance with wood production. This background strongly suggests extending the
87 economic analysis of harvesting methods² and diversity attributes beyond the Faustmann-Hartman setup.

88 In this study, we first develop a model with thinning in Clark (1976, p. 62) extended to include ES,
89 multiple tree species, and continuous cover forestry. This Lotka-Volterra type of model reveals the
90 restrictions of the Faustmann-Hartman setup compared to a model with a wider set of harvesting options,
91 and supports studying the significance of the theoretical findings by an empirically detailed model.

92 Our empirical extension is a detailed size-structured model³ for stand growth and for any number
93 of tree species. The detailed structure enables describing stand diversity with the available ecological
94 measures. The model allows three different types of harvesting activities: clearcut, thinning, and felling
95 (noncommercial) trees without hauling from the site and optimization between rotation and continuous
96 cover forestry. Revenues are separate for sawlogs and pulpwood, and market prices are species-specific.
97 A detailed harvesting cost model recognizes various tree species and is separate for clearcuts, and
98 thinning and felling trees without commercial value. Each harvest operation includes a fixed cost
99 (transporting the harvester to the site). Thus, we optimize a vector of binary variables determining
100 whether to harvest at the given period in addition to optimizing the harvested number of trees over the
101 size classes and species. Natural regeneration implies that it is possible to continue thinning instead of

² Nordic forest management practices typically include 2-3 thinnings before the clearcut but unlike rotation, thinnings are not optimized. Management based solely on thinning, i.e. continuous cover forestry has not been favored by Nordic forest experts due to the view that it does not maximize sustainable yield.

³ The size-structured model is investigated analytically in Tahvonen (2015) but for one species and without ES.

102 clearcutting followed by costly artificial regeneration. Excluding ES values and their dependence on
103 diversity, all features and model parameters are based on empirical data valid in the Nordic context.

104 If thinning is ruled out, the number of tree species and intraspecies diversity has negligible effect
105 on optimal rotation. Diversity valuation lengthens rotation and with very high valuation, yields an
106 infinitely long rotation, i.e. abandon of forestry. This is in line with the Faustmann-Hartman setup.

107 Adding the possibility of thinning more than doubles rotation length, increases bare land value by
108 20–70%, and yields higher stand diversity compared to rotation forestry, but produces lower levels of
109 wood. Even without ES preferences, thinning (or partial cutting) implies developments of tree and size
110 structures that are not possible within the Faustmann-Hartman model. Including the preferences for ES
111 into the objective shows that a much lower level of their valuation is enough to abandon clearcuts
112 compared to similar outcome within the Faustmann-Hartman model. ES preferences support continuous
113 cover forestry, increases the share of birch, pine, and noncommercial broadleaves, large tree size classes
114 and lengthens the continuous cover steady-state harvesting interval. Including thinning into the model
115 cuts the cost of increasing ES production to a negligible level compared to the Faustmann-Hartman
116 specification. Stand diversity appears to be higher in the continuous cover steady state compared to an
117 unharvested stand, even without including ES into the model objective.

118 Similar previous results in forest economics do not exist, and our results strongly suggest that
119 proceeding beyond the Faustmann-Hartman setup is necessary to better understand the economics of
120 forestry with preferences to ecosystem services and biodiversity. In existing literature, Buongiorno et al.
121 (1994) include a diversity index into a model for continuous cover forestry, but use a static one species
122 model. Lin et al. (1996) include mixed species, but no optimization. Haight and Getz (1987) (1989)
123 Haight and Monserud (1990a,b) and Getz and Haight (1989) develop the approach for optimizing mixed
124 species continuous cover management for Northern California forests, but without ES. Wikström and
125 Erikson (2000) specify a one-rotation model for a two species forest, measure diversity with the Shannon

126 index, but concentrate on the technical solution procedure. The background model in the hedonic price
 127 analysis of Zhou (2017) describes continuous cover forestry, stand diversity is measured with the
 128 Shannon index, but no forest management details are analyzed. Rämö and Tahvonen (2015) study Nordic
 129 mixed species forests but exclude ecosystem services, optimal choice between rotation and continuous
 130 cover forestry and assume fixed harvesting intervals, i.e. apply several restrictions that are generalized
 131 in our study.

132 Next in this paper, we specify the analytical model and results. Then, we proceed to empirical
 133 model specifications and optimization methods. The results are first presented for the Faustmann-
 134 Hartman specification and then for the extension. Finally, we offer some conclusions.

135

136 2 Ecosystem services and thinning in mixed species model without size structure

137 Let $x_j(t), j = 1, 2$ denote the volume of tree species j per land unit and $h_j(t), j = 1, 2$ the rate of thinning
 138 respectively and write $\mathbf{x} = [x_1, x_2]$. Volume growth per tree species is $g_j(t)f_j(\mathbf{x})$, where g_j are aging
 139 functions and f_j growth functions with biological density dependence. ES values are $y(t)A(\mathbf{x})$, where
 140 function y denotes the dependence on stand age and function A the dependence on species volumes.
 141 Letting r denote the rate of interest, w the cost of artificial regeneration, $p_j, j = 1, 2$ the stumpage prices
 142 and assuming quasi-linear preferences as in Hartman (1976) the model with thinning, clearcuts and ES
 143 valuation becomes

$$144 \max_{\{h_j, x_j(T), T \in [0, \infty), j=1, 2\}} J = \frac{-w + \int_0^T [p_1 h_1 + p_2 h_2 + y(t)A(\mathbf{x})] e^{-rt} dt + [p_1 x_1(T) + p_2 x_2(T)] e^{-rT}}{1 - e^{-rT}} \quad (1)$$

$$145 \text{ s.t. } \dot{x}_j = g_j(t)f_j(\mathbf{x}) - h_j, x_j(0) = x_{j0}, j = 1, 2, \quad (2)$$

$$146 0 \leq h_j \leq h_{j\max}, j = 1, 2. \quad (3)$$

147 The ES valuation and growth functions are continuous and continuously differentiable and satisfy

148 $y(t) > 0,$ (A1)

149 $A_{x_j} > 0$ for $\gamma_1 x_1 + \gamma_2 x_2 < \tilde{x}$, and $A_{x_j} < 0$ for $\gamma_1 x_1 + \gamma_2 x_2 > \tilde{x}$, $\gamma_j > 0$, $A_{x_j x_j} < 0$, $j = 1, 2,$ (A2)

150 $g_j(0) > 0, g'_j < 0, g''_j > 0, g'_j \rightarrow \bar{g}_j \geq 0$ when $t \rightarrow \infty, j = 1, 2,$ (A3)

151 $f_{j x_i} < 0, f_{j x_j} < 0, j = 1, 2, i = 1, 2, i \neq j$ and for each $\mu_i x_i$ there exists $\hat{x}_j \geq 0$ such that
 $f_{j x_j} > 0$ for $x_j < \hat{x}_j$ and $f_{j x_j} < 0$ for $x_j > \hat{x}_j$, where $f_{j x_j}(\hat{x}_j, \mu_i x_i) = 0$ and $\mu_i \geq 0, i = 1, 2.$ (A4)

152 Additionally, functions A and $f_j, j = 1, 2$ are assumed to be concave. By (A2) the ES valuation function
 153 A increases in the volume of both species, but only if total stand volume is not too high. Aging has a
 154 negative growth effect on both species in (A3), but growth may remain positive if natural regeneration
 155 occurs (the case $\bar{g}_j > 0$). The density of species i decreases the growth of species j and marginal growth
 156 is negative ($f_{j x_j} < 0$) if the volumes of species are high enough (A4). Examples of these functions are

157 $A(\mathbf{x}_t) = \alpha_1 x_1 + \alpha_2 x_2 - \eta_0 (\eta_1 x_1 + \eta_2 x_2)^\tau, \alpha_j > 0, \eta_0, \eta_j > 0, j = 1, 2, \tau > 1.$

158 $f_j(\mathbf{x}_t) = x_j r_j \left(1 - \frac{x_j}{K_j - \mu_i x_i} \right), r_j > 0, K_j > 0, \mu_i \geq 0, j, i = 1, 2, j \neq i.$ ⁴

159 Our two species stand and the inclusion of ES values extends Clark (1976, p. 63) and Tahvonen (2016).
 160 In contrast to the plantation forestry in Clark (1976, p. 63-) where $\bar{g}_j = 0$, optimal rotation in our model
 161 may be finite or infinite, i.e. the model includes optimal choice between continuous cover and rotation
 162 forestry. As in Clark (1976, p. 63-) problem (1)–(3) can be solved by first optimizing thinning and
 163 assuming a fixed rotation period, and next optimizing the rotation period given optimized thinning. Thus,

⁴ The denominator in f_j remains strictly positive when the initial levels of $x_{j0}, j = 1, 2$ are low. The specification is close to that in Beckage and Gross (2006) but is concave in the admissible region.

164 for any rotation period $T > 0$ and costate variables $\phi_j, j=1, \dots, n$, the Hamiltonian and necessary
 165 optimality conditions are (2), (3) and

$$166 \quad H = p_1 h_1 + p_2 x_2 + y(t) A(x_1, x_2) + \phi_1 [g_1(t) f_1(x_1, x_2) - h_1] + \phi_2 [g_2(t) f_2(x_2, x_1) - h_1],$$

$$167 \quad p_j - \phi_j < 0 \Rightarrow h_j = 0, \quad j = 1, 2, \quad (4)$$

$$168 \quad p_j - \phi_j = 0 \Rightarrow 0 \leq h_j \leq h_{j \max}, \quad j = 1, 2, \quad (5)$$

$$169 \quad p_j - \phi_j > 0 \Rightarrow h_j = h_{j \max}, \quad j = 1, 2, \quad (6)$$

$$170 \quad \dot{\phi}_j = -A_{x_j} + \phi_j [r - g_j f_{j x_j}] - \phi_i g_i f_{i x_j}, \quad j, i = 1, 2, \quad j \neq i, \quad (7)$$

$$171 \quad \phi_j - p_j \geq 0, x_j(T) \geq 0, (\phi_j - p_j) x_j(T) = 0, \quad j = 1, 2. \quad (8)$$

172 Given one tree species only, $A \equiv 0$ and x_0 low, it is first optimal to let the stand grow without thinning
 173 until a switch to thinning regime where $p = \phi$ and $r = g f_x$. Given $r < \bar{g} f_x(0)$, $\bar{g} > 0$, and conditions
 174 (8), thinning continues until the end of rotation, where the remaining stand volume is clearcut if optimal
 175 rotation is finite. In the other case the optimal rotation is infinitely long and the solution represent
 176 continuous cover forestry and thinning continues without clearcuts (Tahvonen 2016, cf. Clark 1976).

177 Assuming ES values and two species we analyze a similar regime combination: wait, thin and
 178 possibly clearcut at $T \in (0, \infty)$. Denote a solution satisfying the necessary optimality conditions (2), (3),
 179 (4)–(6), (7) and (8) as $h_j^*(t)$, and $x_j^*(T^*)$, $j = 1, 2$. Maximizing (1) w.r.t. T yields the condition for the
 180 solutions with finite optimal rotation T^* :

$$181 \quad e^{-rT^*} (1 - e^{-rT^*})^{-1} q(T^*) = 0, \quad (9)$$

182 where

$$183 \quad q(T^*) = p_1 h_1^*(T^*) + p_2 h_2^*(T^*) + y(T^*) A[\mathbf{x}(T^*)] + p_1 x_1'(T^*) + p_2 x_2'(T^*) + r [p_1 x_1^*(T^*) + p_2 x_2^*(T^*) + J(T^*)] = 0. \quad (10)$$

184 At T^* the optimal regime is singular, i.e. $p_j - \phi_j = 0, \dot{\phi}_j = 0, j = 1, 2$ implying that differentiating (10)

185 and simplifying by (7) and $\dot{\phi}_j = 0, j = 1, 2$ yields

$$186 \quad q'(T^*) = y'A + \sum_{j=1}^2 p_j g'_j f_j. \quad (11)$$

187 In (11) the term $g' < 0$, but we have left the sign of y' unrestricted. Thus, without ES, optimal rotation

188 is unique but with ES valuation multiple locally optimal rotations can be ruled out only if

189 $y'(T^*)A(T^*)$ is negative or does not dominate the sum in (11). Write equation (10) as

$$190 \quad J_F(T) + J_A(T) = 0, \quad (12)$$

191 where

$$192 \quad J_F(T) = \sum_{j=1}^2 p_j x'_j(T^*) - r \sum_{j=1}^2 p_j x_j^*(T^*) + \sum_{j=1}^2 p_j h_j^*(T^*) - r \frac{-w + \int_0^T \sum_{j=1}^2 p_j h_j e^{-rt} dt + \sum_{j=1}^2 p_j x_j^*(T^*)}{1 - e^{-rT}} \quad (13)$$

$$193 \quad J_A(T) = y(T^*)A[\mathbf{x}(T^*)] - \frac{r \int_0^{T^*} y(t)A[\mathbf{x}(t)]e^{-rt} dt}{1 - e^{-rT^*}}. \quad (14)$$

194 With no ES values (14) is zero and the following terms in (13)

$$195 \quad \sum_{j=1}^2 p_j x'_j(T^*) - r \sum_{j=1}^2 p_j x_j^*(T^*) + \sum_{j=1}^2 p_j h_j^* > 0 \quad (15)$$

196 i.e. obtain positive value by the concavity of f , $f_{ix_j} < 0, i \neq j$, conditions (7) and $\dot{\phi}_j = 0$. Given $\bar{g}_j > 0$

197 and $r < \bar{g} f_{jx_j}(0)$, $j = 1, 2$ the positive sign in (15) holds even when $t \rightarrow \infty$. Thus, given natural

198 regeneration and a bare land value (in 13) low enough for all $T \in [0, \infty)$, no finite rotation satisfying (9)

199 exist implying that optimal rotation is infinite, i.e. it is optimal to continue thinning without clearcut and

200 continuous cover forestry is optimal. Accordingly, if $\bar{g}_j = 0, j = 1, \dots, n$, the RHS of (13) is negative when

201 $t \rightarrow \infty$, implying unique finite rotation satisfying (9). Thus, if growth ceases independently on stand
202 density as in Clark (1976, p.63-), the optimal rotation is finite and clearcuts are always optimal.

203 ES values lengthen (shorten) optimal rotation if $J_A(T^*) > 0$ ($<$) in (14). The former (latter) case
204 follows e.g. if $d(yA)/dt > 0$ ($<$) for all $0 < t < T$. When $J_A(T) > 0$ as $t \rightarrow \infty$, ES values may cause a
205 regime switch from rotation forestry to continuous cover regime given rotation forestry happens to be
206 optimal without ES values. When $J_A(T) < 0$ as $t \rightarrow \infty$, ES values may cause a switch from continuous
207 cover forestry to rotation forestry. Neglecting thinning and setting $h_j \equiv 0, j = 1, 2$ in (13) implies that the
208 solution collapses into the Faustmann-Hartman model for mixed stands. Compared to this, thinning
209 expands the set of stand development alternatives. We demonstrate this by the aim of a phase diagram
210 and numerical examples computed by AMPL/Knitro optimization software.

211
212 Figure 1.

213
214 With two species the Faustmann model becomes a Lotka-Volterra system with somewhat
215 unconventional harvesting alternatives. When long run coexistence of the (unharvested) species is
216 possible as in Figure 1, an unharvested stand develops from an initial point A toward a stable steady state
217 at B (via a point such as C). Within the Faustmann-Hartman setup, the choice set includes stopping this
218 development at any point between A and B , for example at point C and repeating the rotation from the
219 origin or abandoning clearcut and approaching point B . After including thinning all such choices are
220 available, but since now the admissible steady states are defined by
221 $\bar{g}_j f_j(x_j, x_i) - h_j = 0, h_j \geq 0, j, i = 1, 2, j \neq i$, the whole region under both of the isoclines represents the set
222 of admissible steady states. This reveals the restrictive nature of the Faustmann-Hartman model that
223 neglects this wider set of harvesting alternatives.

224 Assume the growth specification given in Figure 1 and

225 $y(t)A(x_1, x_2) = 0.12(1 - e^{-0.06t}) \left[10x_1 + 20x_2 + 0.25(x_1 + x_2)^2 \right], p_1 = 50, p_2 = 100, w = 400, r = 0.01.$ (16)

226 The optimal discrete time approximation for the Faustmann-Hartman model solution is a 27-periods
 227 rotation cycle $A, C, 0, A$. Without ES the rotation is 22 periods. With thinning and ES the optimal solution
 228 is the path A, D, E , i.e. a continuous cover solution, and without ES the solution is somewhat similar, but
 229 includes a clearcut at the age of 90 periods. Next assume

230 $y(t)A(x_1, x_2) = 0.13(1 - e^{-0.06t}) \left[40x_1 + 10x_2 + 0.25(x_1 + x_2)^2 \right], p_1 = 100, p_2 = 50, w = 400, r = 0.02,$ (17)

231 i.e. a case where the essential change is the increase in the relative value of the species in the horizontal
 232 axes. The Faustmann-Hartman solution is unchanged (cycle $A, C, 0, A$), but the solution with thinning
 233 reacts sensitively to this change and is A, F, G . Given specification (16), the Faustmann-Hartman objective
 234 values are 367 and 1054 with and without ES, while the objective values are much higher with thinning,
 235 i.e. 1184 and 2092 respectively.

236 This theoretical model and analysis strongly suggest that the inclusion of intermediate cuttings or
 237 thinning may greatly alter forest management solutions and increase the economic objective values in a
 238 model with multiple tree species and ES values. We turn to examine to what extent these findings are
 239 realized in an empirically realistic model for mixed-species boreal forests.

240

241 3 A model for mixed species size-structured stands with thinning and ecosystem services

242 We apply a nonlinear size-structured model for mixed stands that allows direct application of empirically
 243 estimated ecological and economic models and parameters along with indices for biodiversity. For this
 244 end, let $\mathbf{x}_{jt} = (x_{j1t}, \dots, x_{jnt})$ denote the number of trees of species $j = 1, \dots, l$ in size classes $1, \dots, n$ at the
 245 beginning of period t and \mathbf{x}_t a matrix for the number of trees in different species and size classes

246 respectively.⁵ The fraction $\alpha_{js}(\mathbf{x}_t)$, $j = 1, \dots, l$, $s = 1, \dots, n$ of size class s trees of species j move to size
 247 class $s + 1$ at the end of each period and the fraction $\mu_{js}(\mathbf{x}_t)$ of trees dies. Natural regeneration is
 248 $\phi_j(\mathbf{x}_t)$, $j = 1, \dots, l$. Given h_{jst} denotes (commercially) harvested and k_{jst} , $j = 1, \dots, l$, $s = 1, \dots, n$, $t = t_0, \dots, T$
 249 felled trees (i.e. trees left on the site), the development of the mixed species stand can be written as

$$250 \quad x_{j1,t+1} = \phi_j(\mathbf{x}_t) + [1 - \alpha_{j1}(\mathbf{x}_t) - \mu_{j1}(\mathbf{x}_t)]x_{j1t} - h_{j1t} - k_{j1t}, \quad j = 1, \dots, l, \quad t = t_0, \dots, T, \quad (18)$$

$$251 \quad x_{j,s+1,t+1} = \alpha_{js}(\mathbf{x}_t)x_{jst} + [1 - \alpha_{j,s+1}(\mathbf{x}_t) - \mu_{j,s+1}(\mathbf{x}_t)]x_{j,s+1,t} - h_{j,s+1,t} - k_{j,s+1,t}, \quad j = 1, \dots, l, \quad s = 1, \dots, n-1, \quad t = t_0, \dots, T, \quad (19)$$

$$252 \quad x_{jst_0} \text{ given}, \quad j = 1, \dots, l, \quad s = 1, \dots, n. \quad (20)$$

253 Cuttings may not occur every period and are restricted by the constraints

$$254 \quad h_{jst} = \delta_t h_{jst}, \quad j = 1, \dots, l, \quad s = 1, \dots, n, \quad t = t_1, \dots, T, \quad (21)$$

$$255 \quad k_{jst} = \delta_t k_{jst}, \quad j = 1, \dots, l, \quad s = 1, \dots, n, \quad t = t_1, \dots, T, \quad (22)$$

256 where $\delta_t: Z \in [0,1]$, $t = t_0, t_0 + 1, \dots$ are binaries and specify the periods with positive cuttings ($\delta_t = 1$).

257 The stand is established at $t = 0$ ($< t_0$) with a fixed cost w . Gross harvesting revenues are $R(\mathbf{h}_t)$ and
 258 the variable harvesting costs for thinnings and clearcuts $C_{th}(\mathbf{h}_t, \mathbf{k}_t)$ and $C_{cl}(\mathbf{h}_t, \mathbf{k}_t)$ respectively. Wood
 259 value and harvesting costs will depend of species, tree size and the quantity of wood harvested.

260 Based on Gamfelt (2013) we postulate that a higher level of biological diversity implies a higher
 261 level of valuable (nontimber) ES. This is specified by a functional relationship between a biodiversity
 262 measure d_t and the value of nontimber ES given as $\tilde{A}\{E[d(\mathbf{x}_t)]\}$, where d measures biodiversity as a
 263 function of stand state \mathbf{x} , function E the dependence of ES on biodiversity, and function \tilde{A} the

⁵ The fact the in section 2 x_j , $j=1, \dots, n$, and \mathbf{x} denoted volumes but here the number of trees should not cause any confusion.

264 willingness to pay for nontimber ES. Given C^f denotes fixed harvesting cost, b the per annum discount
 265 factor and Δ the period length, we write the objective functional as

$$266 \quad \max_{\{\mathbf{h}_t, \mathbf{k}_t, \delta_t, i=1, \dots, J, T \in [t_0, \infty)\}} \frac{-w + \sum_{t=t_0}^{T-1} \left\{ R(\mathbf{h}_t) - C_{th}(\mathbf{h}_t, \mathbf{k}_t) - \delta_t C^f + \tilde{A} \{ E[d(\mathbf{x}_t)] \} \right\} b^{\Delta(t+1)} + \left\{ R(\mathbf{h}_T) - C_{cl}(\mathbf{h}_T, \mathbf{k}_T) - \delta_T C^f + \tilde{A} \{ E[d(\mathbf{x}_T)] \} \right\} b^{\Delta(T+1)}}{1 - b^{\Delta(T+1)}}. \quad (23)$$

267 When the rotation period $T \in [t_0, \infty)$ is finite the solution is a rotation forestry and when it is infinitely
 268 long it represents continuous cover forestry. The latter becomes possible when trees regenerate naturally
 269 and thinning can be continued without clearcuts. In specification (23) land is initially bare but this can
 270 be extended to optimize cuttings from any initial stand state (Tahvonen 2015). Notice that by removing
 271 thinning the specification falls back to optimizing the rotation length only similarly as model (1)-(3).

272

273 4 Empirical specifications and data

274 The equations for stand growth take the form

$$275 \quad \phi_j(\mathbf{x}) = \frac{\phi_{j1} \beta_i(\mathbf{x})^{\phi_{j2}} S^{\phi_{j3}} [\beta(\mathbf{x}) + \phi_{i4}]^{\phi_{j5}}}{1 + e^{-[\phi_{j6} + \phi_{j7} \beta(\mathbf{x}) + \phi_{j8} S + \phi_{j9} \beta_j(\mathbf{x})]}}, \quad j = 1, \dots, l, \quad (24)$$

$$276 \quad \alpha_{sj}(\mathbf{x}) = \frac{1}{\alpha_{j1}} \left[\alpha_{j2} + \alpha_{j3} d_s + \alpha_{j4} d_s^2 + \alpha_{j5} d_s^3 + \alpha_{j6} \beta_s(\mathbf{x}) + \alpha_{j7} \beta(\mathbf{x}) + \alpha_{j8} S + \alpha_{j9} L \right], \quad j = 1, \dots, l, s = 1, \dots, n, \quad (25)$$

$$277 \quad \mu_{sj}(\mathbf{x}) = \left\{ 1 + e^{-[\mu_{j1} + \mu_{j2} d_2 + \mu_{j3} d_s^2 + \mu_{j4} \beta(\mathbf{x})]} \right\}^{-1}, \quad j = 1, \dots, l, s = 1, \dots, n, \quad (26)$$

278 where $d_s, s = 1, \dots, n$ is tree diameter (cm) at a height of 130 cm, S denotes site index, L latitude and β ,
 279 and β_s stand basal area and basal area (m^2) for trees with diameter larger than in size class s ,
 280 respectively (Bollandsås et al. 2008). The parameter values for ϕ_{ji}, μ_{ji} and $\alpha_{ji}, j = 1, \dots, l, i = 1, \dots, 7$ and
 281 details for the site index and latitude are given in Appendix 1, Table 1.

282
283 Figure 2.
284

285 Based on this growth model and the data Figure 2a shows undisturbed volume development for a
286 Norway spruce and birch mixture comparable with Figure 1. Figure 2a includes all four species. In all
287 cases, the trajectories of undisturbed stands converge toward Norway spruce-dominated steady states, a
288 prediction that makes perfect sense in the case of a boreal average-productivity site without natural and
289 human disturbances (cf. Bollandsås 2008).

290 The tree diameters and diameter-specific pulp and sawtimber volumes are given in Table 2 and are
291 based on Heinonen (1994). The per period gross revenues and variable harvesting costs are given as

$$292 \quad R(\mathbf{h}) = \sum_{j=1}^l \sum_{s=1}^n (p_{1j} v_{1sj} + p_{2j} v_{2sj}) h_{sj}, \quad (27)$$

$$293 \quad C_v(\mathbf{h}, \mathbf{k}) =$$

$$294 \quad \sum_{j=1}^l \gamma_{ju0} \gamma_{ju1} \sum_{s=1}^n h_{js} (\gamma_{ju2} + \gamma_{ju3} v_{js} + \gamma_{ju4} v_{js}^2) + \quad (28a)$$

$$295 \quad \gamma_{u5} \sum_{j=1}^l \sum_{s=1}^n h_{js} v_{js} + \gamma_{u6} \left(\sum_{j=1}^l \sum_{s=1}^n h_{js} v_{js} \right)^{0.7} + \quad (28b)$$

$$296 \quad \sum_{j=1}^l \sum_{s=1}^n k_{js} (\gamma_{u7} + \gamma_{u8} v_{js}), \quad u = th, cl, \quad (28c)$$

297

298 where p_{1j} and p_{2j} are sawtimber and pulpwood prices, v_{1sj} and v_{2sj} sawtimber and pulpwood volumes
299 per tree, v_{js} is the total tree volume, and γ_{juk} , $j = 1, \dots, l, u = th, cl, k = 1, \dots, 9$ are parameters (Appendix
300 1, Table 3). This specification is based on detained empirical logging experiments by Nurminen et al
301 (2006), and it includes cutting (28a), hauling (28b), and felling (28c) costs separately. The cutting cost
302 per tree is higher for thinning compared to clearcut ($\gamma_{jth1} > \gamma_{jcl1}, j = 1, \dots, l$). Variable harvesting costs

303 increase with total harvested volume but decrease with tree volume. In computing the hauling cost (28b)
 304 there is no need to separate the tree species. The prices for sawtimber and pulpwood are given in
 305 Appendix 1, Table 4. Fixed cost C^f equals €500 and refers to moving the harvester to the site.

306 Biodiversity is measured with the Simpson (1949) (or Herfindahl 1950) diversity index. Site
 307 diversity may depend on both on species and tree sizes (Eggers 2018, Duncker 2012, O’Hara 2014), and
 308 we take each size class and each tree species as “species”. Thus, trees in each size class are different
 309 “species” and the maximum number of species equals $l \times n$. The Simpson index is defined as

$$310 \quad d(\mathbf{x}) = 1 - \frac{\sum_{j=1}^l \sum_{s=1}^n x_{js} (x_{js} - 1)}{\sum_{j=1}^l \sum_{s=1}^n x_{is} \left(\sum_{j=1}^l \sum_{s=1}^n x_{js} - 1 \right)}, \quad d(\mathbf{x}) \in [0, 1]. \quad (29)$$

311 The value of Simpson index is high when the stand carrying capacity is evenly allocated across tree
 312 species and size classes. Because of the lack of empirical data, it is assumed that the value ES depend
 313 linearly on the diversity measure, i.e. $\tilde{A}\{E[d(x)]\} = Ad(x)$, where A is a constant. The value of A will
 314 be varied widely to reveal the effects of ES valuation on wood production and cuttings.

315

316 *Optimization method and algorithms*

317 The optimization problem (18)–(29) is a dynamic discrete-time problem. Complications arise from
 318 nonlinearities, potential nonconvexities, many state variables (44–48), and the mixed-integer feature of
 319 the optimized variables. We search for optimal solutions by applying a tri-level computational structure.
 320 At the upper level, we optimize the rotation period; at the middle level, the timing and number of
 321 thinnings; and at the lowest level (given the rotation length and timing of thinnings), the number of trees
 322 harvested from each size classes and species. As the number of trees is considered a continuous variable,

323 the lowest level problem is solved using gradient-based methods and AMPL/Knitro optimization
324 software (version 10.2), which enables the use of four state-of-the-art interior-point and active-set
325 methods. The 44–48 state variable problems with 80–180 time periods can be computed within a couple
326 of seconds. Potential nonconvexities are handled with a multi-start procedure. The middle level problem
327 is to optimize the 0-1 binary variables for thinning timing. This is performed using hill climbing and
328 genetic algorithms. In addition, the functioning of these algorithms is spot-checked by computing the
329 outcomes of all conceivable timing combinations. To find the optimal rotation length, the middle and
330 lower level optimization is repeated for rotation periods between 80 and 180 years by applying a five-
331 year period length. Parallel computation is utilized whenever possible. When 180-years rotation yields
332 the highest bare land value, we additionally compute an approximation for the optimal infinite horizon
333 solution. This computation includes up to seven optimized harvests (both timing and number of trees
334 harvested) before reaching a steady state harvesting cycle with an optimized interval length between the
335 harvests. Using an Intel (R) Xeon (R) E5-2643 v3 @3.40GHZ, 24 logical processor computer, solving
336 the infinite horizon approximation takes 50–120 hours. More details for these procedures are explained
337 for the case of single-tree species model in Sinha et al. (2017).

338

339 5 Results

340 *The Faustmann-Hartman model with varying number of tree species*

341 Figure 3a shows the volume developments of unharvested (average-fertility sites) and that adding tree
342 species has a surprisingly small effect on the total stand volume, which reaches a maximum of $500m^3$
343 at the age of 100 years. Figure 3b reveals that the mixed stand is dominated by Norway spruce. In Table
344 1, the maximized bare land value increases with the number of commercial species while adding
345 noncommercial other broadleaves decreases the bare land value. Optimal rotation varies between 60 and

346 50 years and the rotation for single-species Norway spruce is in line with earlier studies (Niinimäki et al
347 2012). Annual yield and the discounted level of ES increases with the number of tree species.

348 The diversity of unharvested stands reach a maximum at stand ages between 100 and 110 years
349 (Figure 3c), because the number of trees in various size classes is highest at these ages and at greater
350 ages the stand becomes dominated by Norway spruce. Including ES values (mixed stand with all four
351 species) lengthens rotation to 110 years (Figure 3d). When $A = 6460$, this rotation is locally optimal
352 simultaneously with abandoning the clearcut. Given $A > 6460$, the latter becomes globally optimal. This
353 value of parameter A will be used as a benchmark in analyzing the effects of ES preferences for the
354 generalized model with thinning.

355
356 Figure 3. Table 1.

357
358 *Stand management with optimized thinning and rotation but without preferences for ecosystem services*
359 Figures 4a, b show bare land values as functions of rotation lengths given optimized thinning timing and
360 the harvested number of trees from different size classes and species. Assuming no regeneration cost, the
361 rotation periods maximizing the bare land values are finite and vary between 100 and 120 years, i.e. are
362 approximately twice as long as without thinning. The rotation periods become infinitely long under a
363 positive regeneration cost (Figure 4b) of €1500, implying the optimality of continuous cover forestry.

364 Comparing Tables 1 and 2 shows that including thinning increases the bare land values c.a. 20%
365 when regeneration cost are zero, and c.a. 70% with a positive regeneration cost and when the inclusion
366 of thinning causes a switch from rotation forestry to continuous cover forestry. Note that average annual
367 wood output decreases ca. 20% simultaneously when the optimized thinning and continuous cover
368 forestry cause the 70% increase in bare land value, thus demonstrating the misleading nature of wood
369 output as a guiding objective in forestry. Comparing the present value of ES between the solutions for

370 the Faustmann-Hartman model and the model with thinning shows that both thinning with longer
371 rotations and the continuous cover solution increases stand diversity and ES without exceptions.

372 Figures 4c and d compare the rotation and continuous cover solutions. They are both dominated by
373 Norway spruce albeit the fraction of birch is ca. 24% in the continuous cover steady-state solution (with
374 an optimal 15-year harvesting period). The fraction of pine is kept negligible because of low natural
375 regeneration in a relatively dense spruce dominated stand. Other noncommercial other broadleaves are
376 felled (but left to the site) at the harvesting dates in both type of solutions. If noncommercial broadleaves
377 are left growing in the continuous cover solution, our computation shows that they will take over the
378 stand and the fraction of valuable species and their harvesting decreases toward zero.⁶

379

380 Figure 4. Table 2.

381

382 *Stand management with optimized thinning and preferences for ecosystem services*

383 Including preferences for ES lengthens optimal rotation (Figure 5a,b) as in the model without thinning.
384 With optimized thinning an ecosystem preference parameter equal to ca. $A = 600$ is enough to imply
385 infinite rotation and a switch to continuous cover forestry. Note that within the Faustmann-Hartman
386 model the same level of ES valuation produces 57-year rotation (Figure 3d) and the rotation does not
387 become infinitely long until $A = 6460$.

388

389 Figure 5.

390

391 Comparing Figures 6a and 4d shows that ES increase overall stand density from ca. $100m^3ha^{-1}$
392 to $116m^3ha^{-1}$ and the steady-state harvesting interval from 15 to 20 years. Additionally, the standing
393 volumes of birch and noncommercial other broadleaves increase, while the relative volume of Norway

⁶ The outcome is called "high grading", i.e. "take the best, leave the rest". We note that high grading is not economically valid argument against continuous cover forestry albeit it may occur in open access situations.

394 spruce decreases from 0.7 to 0.56. Figure 6b shows the development of the main economic variables over
395 time. Harvesting costs are ca. 20% of the harvesting revenues. A drop occurs in the Simpson index at the
396 dates of harvesting, as harvesting decreases the number of large size classes for each species. This
397 “thinning from above” can be seen from Figures 6c-f along with how including ES changes the stand-
398 steady state size structure and harvest of each species. Including ES decreases the number of trees in
399 small size classes, while the number of trees in large size classes increases. Postponing tree harvest to
400 larger trees becomes optimal for all tree species. This is most clear for noncommercial other broadleaves.

401
402 Figure 6. Figure 7.

403
404
405 Another perspective to the effects of valuing ES can be obtained by depicting optimal solutions for
406 a two-species mixture (cf. Figures 1 and 2a). Given the Faustmann-Hartman model and no ES preferences
407 the optimal rotation period equals 55 years and the solution cycles from bare land to point *B* via *A* and
408 back to bare land. If ES preferences are high enough, clearcut is abandoned in the Faustmann-Hartman
409 model and an unharvested stand develops toward the steady state at point *C*. In contrast with optimized
410 thinning clearcut is abandoned both with and without ES preferences. In the former case, the solution
411 proceeds without harvest to state *D* and then converges toward a 20-year continuous cover cycle. With
412 ES preferences the solution proceeds further without harvest (state *E*) and converges toward a 30-year
413 continuous cover cycle, where the average volumes of both species are higher.

414 Increasing the value of ES decreases the net revenues from harvesting. In Figure 8a these costs are
415 much higher in the Faustmann-Hartman model, and the cost of reaching the maximum level of ES is only
416 ca. 95% lower when thinning and the continuous cover solution are applied. This is partly explained by
417 the fact that continuous cover harvesting allows maintaining higher (species) diversity compared to the
418 no-harvesting solution, where the stand develops toward a Norway spruce-dominated state (Figure 8b).

419

420 Figure 8.

421

422 6 Conclusions

423 Our study shows that while it is important to proceed beyond the widely cited Faustmann-Hartman setup
424 to richer descriptions of forests amenity values and ecosystem services, it is equally important to expand
425 the set of forest harvesting activities from clearcutting to various forms of partial harvesting or thinning.
426 Both simplified theoretical and empirically detailed models show that by restricting economic analysis
427 to optimizing the rotation period only is overly limited especially in the presence of heterogeneous mixed
428 species forests and preferences for ecosystem services. A wider set of management alternatives allows
429 adjusting the mixture of naturally regenerating tree species during the rotation as well as maintaining
430 harvest revenues albeit abandoning clearcuts. As a consequence both net revenues from harvesting and
431 the value of ecosystem services tend to increase. Increasing the level of ecosystem services and stand
432 diversity from the outcome based on wood production decreases revenues but this cost is much lower
433 under extended management alternatives compared to the Faustmann-Hartman setup.

434 Several features of our model are very different compared to earlier-mixed species forest economic
435 studies, making the comparison of their results difficult. For example, no earlier study presents results
436 for mixed-species stands and optimization between rotation forestry with clearcuts and continuous cover
437 forestry. Additionally, optimization results in earlier studies are not based on optimizing harvest timing
438 in mixed-species continuous cover forests. Earlier models with ecosystem values have not included the
439 management of naturally regenerating noncommercial species that may have ES value.

440 Our results can be compared to certain earlier views on the management of mixed-species forests.
441 Filyushkina et al. (2018) write that while intensive management, such as clearcuts or frequent thinning,
442 decreases forest ecosystem value, certain management may be beneficial. Our results are clearly in line
443 with this view or more generally with the widely studied “intermediate disturbance hypothesis” stating

444 that highest species diversity occurs in species communities with medium scale disturbances (Connell
445 1978). For example, Raymond et al (2018) found in their gradient experiments that tree species diversity
446 increases with selection cuts in temperate mixed stands. For Swedish forests similar result is obtained in
447 Widenfalk and Weslien (2009). Using a large set of global data, Liang et al. (2016) show that tree species
448 richness increases wood production and emphasize the re-evaluation of forest management strategies and
449 the potential benefits from the transition of monocultures to mixed-species stands. These views obtain
450 support from our results (Tables 1 and 2, Figure 8a,b). Finally, we note that coming economic studies
451 should still proceed in generalizing the description of forest amenity and ES values and in re-evaluating
452 forest management alternatives using various ecological models for mixed-species forests estimated for
453 various forest environments.

454

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530

531 Tables

532

533

534 Table 1. Optimal solutions within the Faustmann-Hartman model

535

Species mixture	Bare land value € ha ⁻¹		Rotation years		Annual yield m ³ ha ⁻¹		Discounted ES with $A=I$	
	w=0	w=1500	w=0	w=1500	w=0	w=1500	w=0	w=1500
Spruce	3377	1513	55	60	6.2	6.4	1.22	1.36
Spruce, birch	3407	1540	55	55	6.8	6.8	1.79	1.79
Spruce, birch, pine	3650	1767	50	55	7.1	7.1	1.78	1.96
Spruce, birch, pine, other bl	3426	1551	50	55	6.8*	6.8*	1.89	2.07

536 Note: w=regeneration cost (€), ES=ecosystem services bl=broadleaves, interest rate 3%, initial state at

537 $t_0 = 20$: spruce 1750, birch 1000, pine 500, other broadleaves 500, *does not include other broadleaves

538

539 Table 2. Optimal solutions for harvesting net revenues maximization with thinning

Species mixture	Bare land value € ha ⁻¹		Rotation years		Annual yield m ³ ha ⁻¹		Discounted ES with $A=I$	
	w=0	w=1500	w=0	w=1500	w=0	w=1500	w=0	w=1500
Spruce	4148	2644	120	∞	6.4	4.7**	1.90	2.00
Spruce, birch	4132	2610	110	∞	7	5.2**	2.50	2.65
Spruce, birch, pine	4457	2917	110	∞	7.2	5.1**	2.67	2.82
Spruce, birch, pine, other bl	4274	2739	100	∞	7.2*	5.1**)*	2.72	2.91

540 Note: w= regeneration cost, ES=ecosystem services, interest rate 3%, initial state as in Table 1.

541 *Does not include other broadleaves, **Steady state yield.

542

543

544

545 Figure captions

546

547 Figure 1. Comparison of admissible and optimal solutions with and without thinning.

548 Note: $g(t)f(x) = (10 + 12e^{-0.02t})x_j 0.01 \left(1 - \frac{x_j}{K_j - 0.9x_i}\right)$, $j = 1, 2, i = 1, 2, j \neq i, x_{10} = 0.5, x_{20} = 0.1$.

549 Figure 2, a,b. Stand development without harvest

550 a) Spruce, birch mixture

551 b) Four species, the development of Scots pine ($x_{20} = 100$) not shown.

552 Figure 3a-d. Stand development and rotation within the Faustmann-Hartman model

553 Note: a) and c) different mixtures, b) and d) mixed stands with spruce, birch, pine other
554 broadleaves, d) interest rate 3%, $w=0$, initial state see Table 1.

555

556 Figure 4a–d. Rotation vs continuous cover forestry without ecosystem services

557 a), c) Regeneration cost zero, a), c) Regeneration cost €1500, b), d): Interest rate 3%.

558

559 Figure 5a,b. The effects of ecosystem services on optimal rotation

560 Note: regeneration cost zero, interest rate 3%, initial state as in Table 1.

561

562 Figure 6a-f. Optimal solution with preferences for ecosystem services

563 Note: Interest rate 3%, all four tree species.

564

565 Figure 7. Solutions for a Norway spruce birch mixture.

566 Note: Interest rate 3%, $A=0$ or $A=6460$.

567

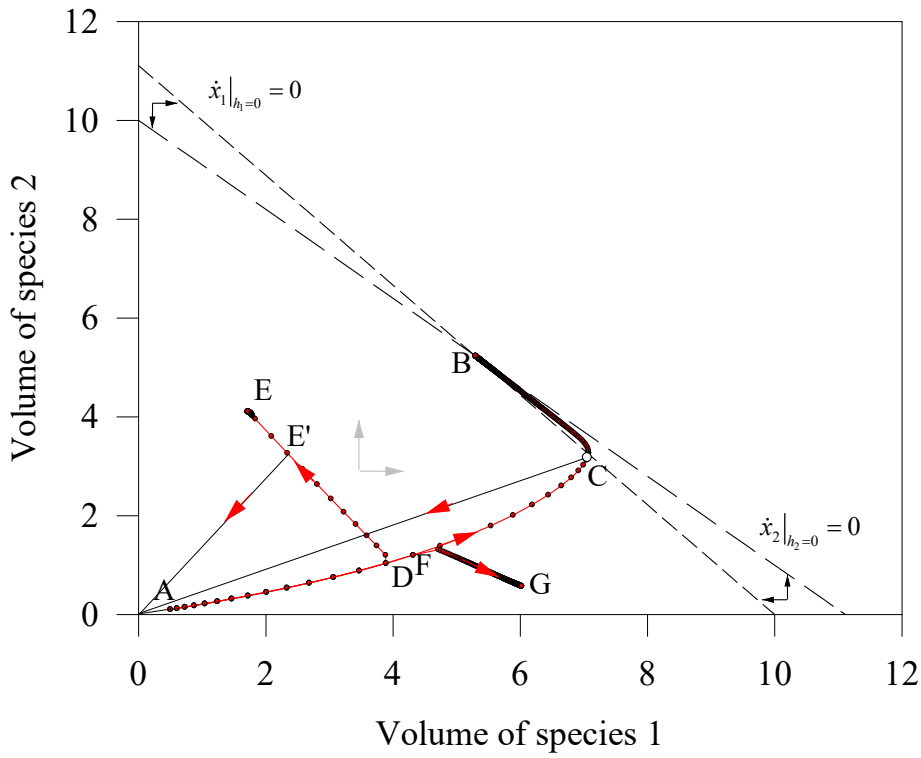
568 Figure 8a,b. Costs and production of ecosystem services

569 Notes: Interest rate 3%, regeneration cost 1500€, all four tree species included.

570

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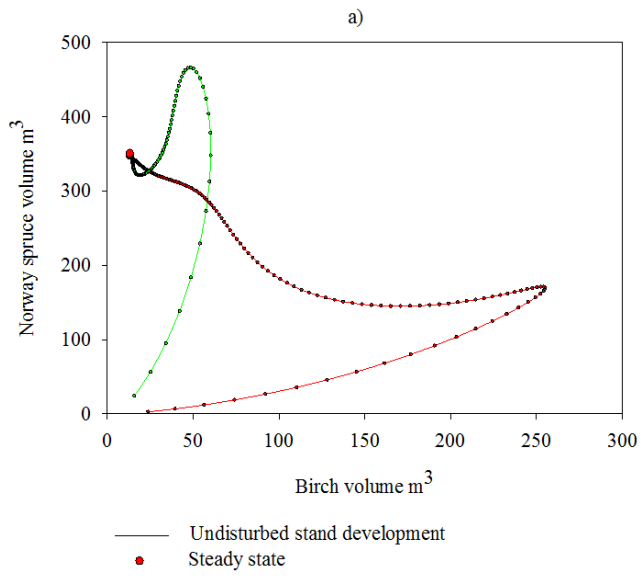
574 Figure 1. Comparison of admissible and optimal solutions with and without thinning

575 Note: $g(t)f(x) = (10 + 12e^{-0.02t})x_j 0.01 \left(1 - \frac{x_j}{K_j - 0.9x_i}\right)$, $j = 1, 2, i = 1, 2, j \neq i, x_{10} = 0.5, x_{20} = 0.1$.

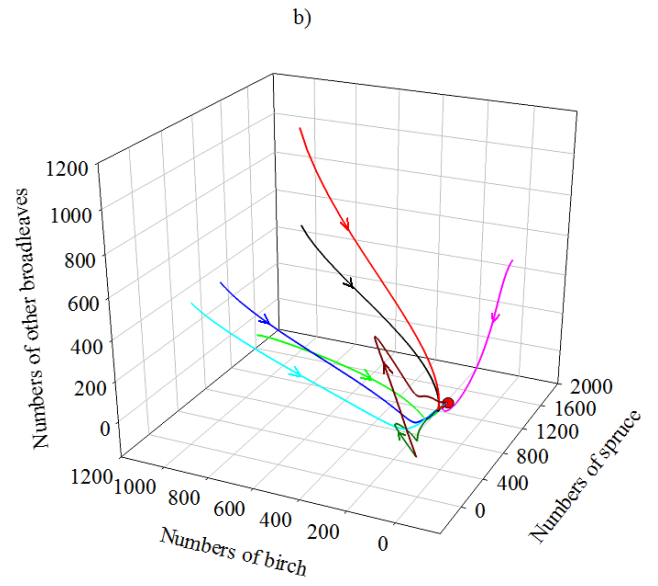
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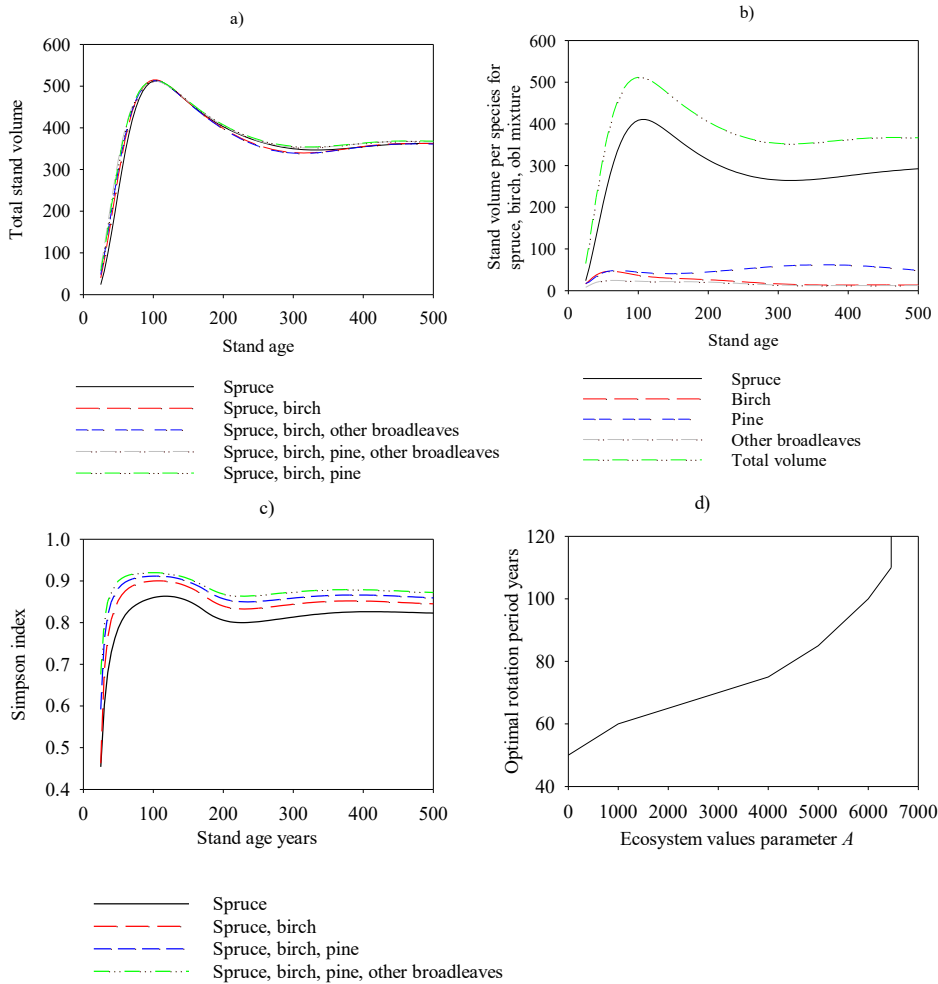
580 Figure 2, a,b. Stand development without harvest

581 a) Spruce, birch mixture

582 b) Four species, the development of Scots pine ($x_{20} = 100$) not shown

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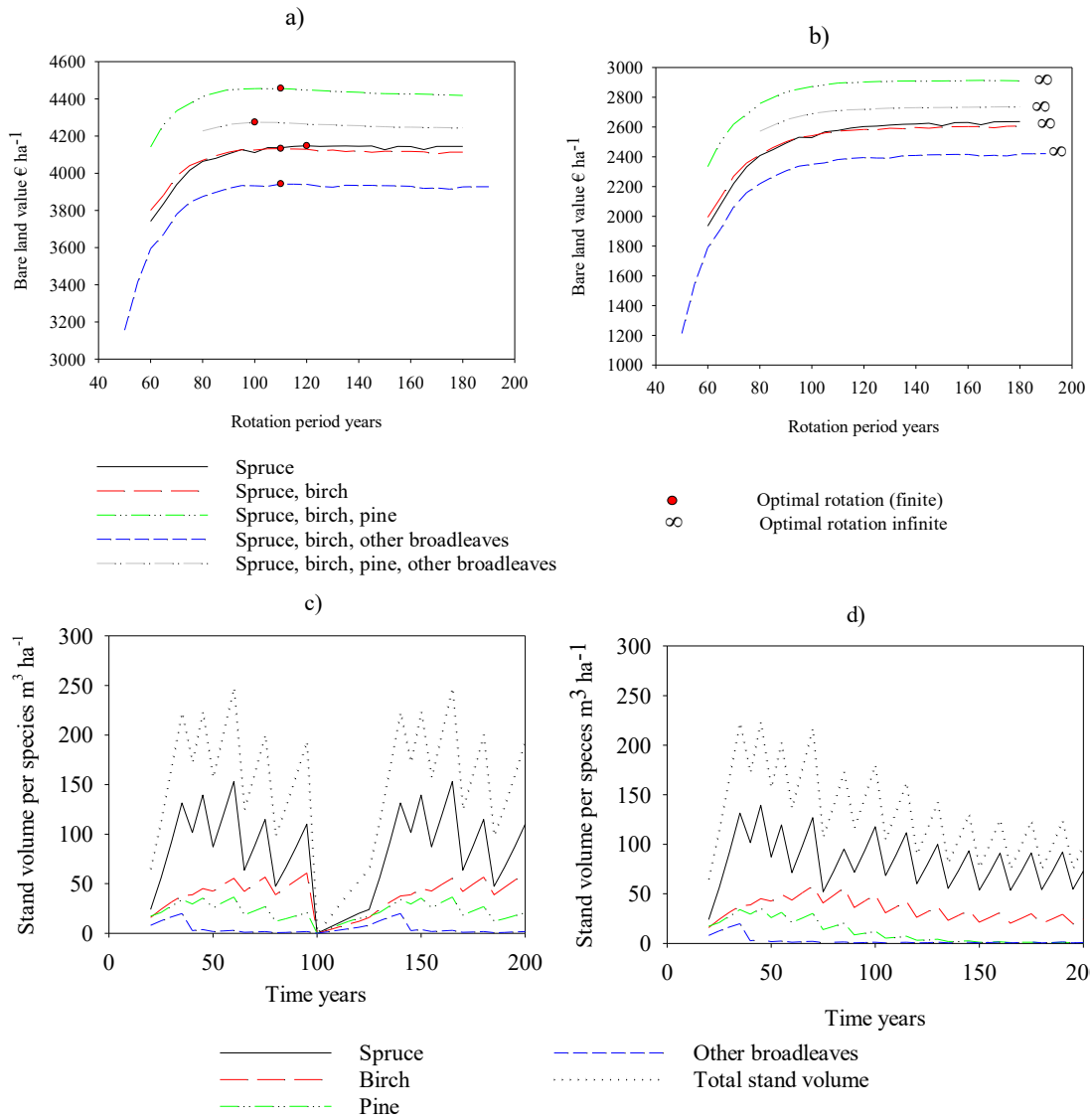


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586 Figure 3a-d. Stand development and rotation within the Faustmann-Hartman model

587 Note: a) and c) different mixtures, b) and d) mixed stands with spruce, birch, pine other
 588 broadleaves, d) interest rate 3%, $w=0$, initial state see Table 1.

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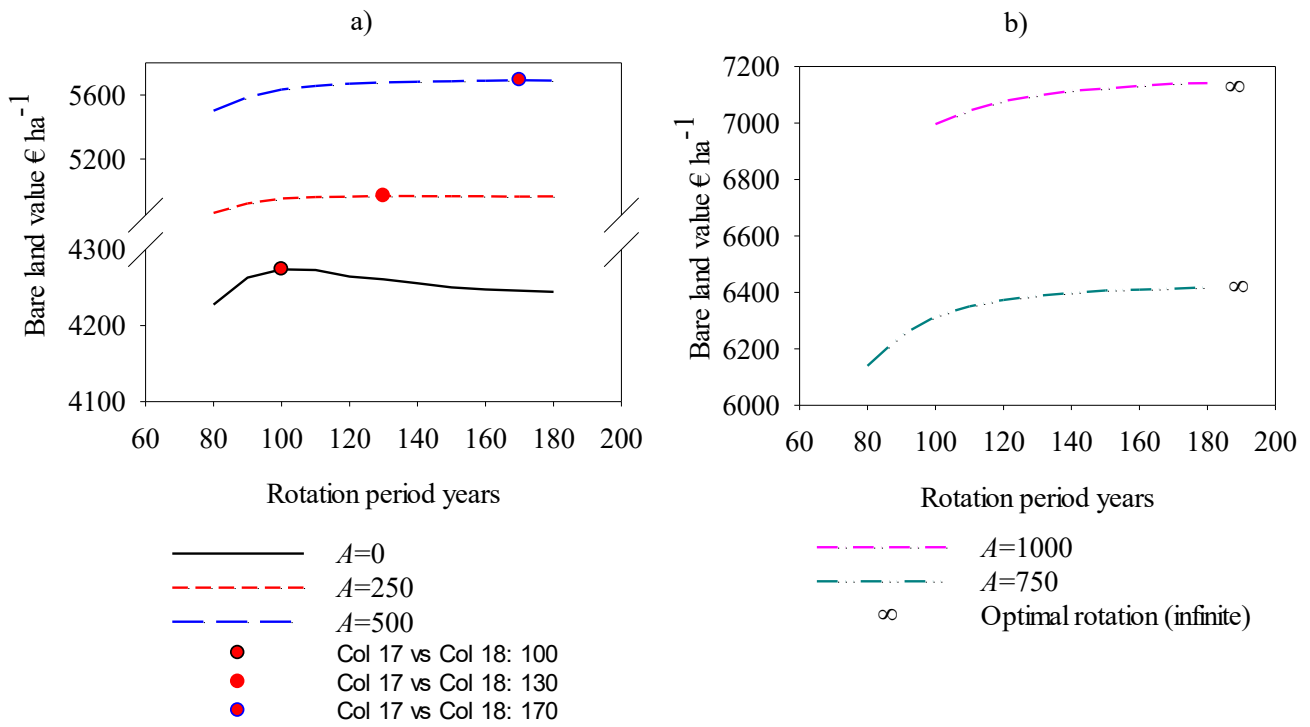


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591 Figure 4a–d. Rotation vs continuous cover forestry without ecosystem services

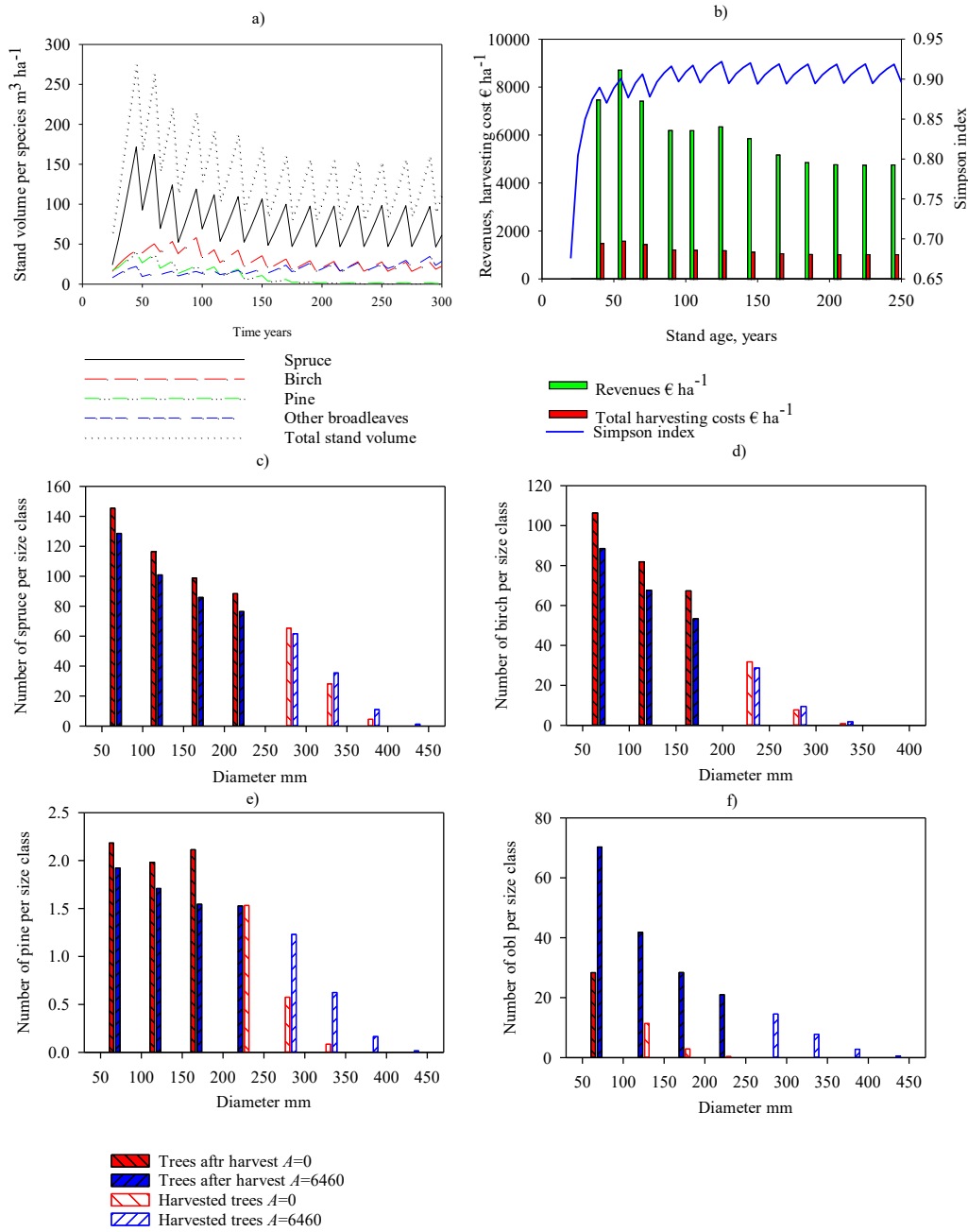
592 a), c) Regeneration cost zero, a), c) Regeneration cost €1500, b), d): Interest rate 3%

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Figure 5a,b. The effects of ecosystem services on optimal rotation
Note: regeneration cost zero, interest rate 3%, initial state as in Table 1.



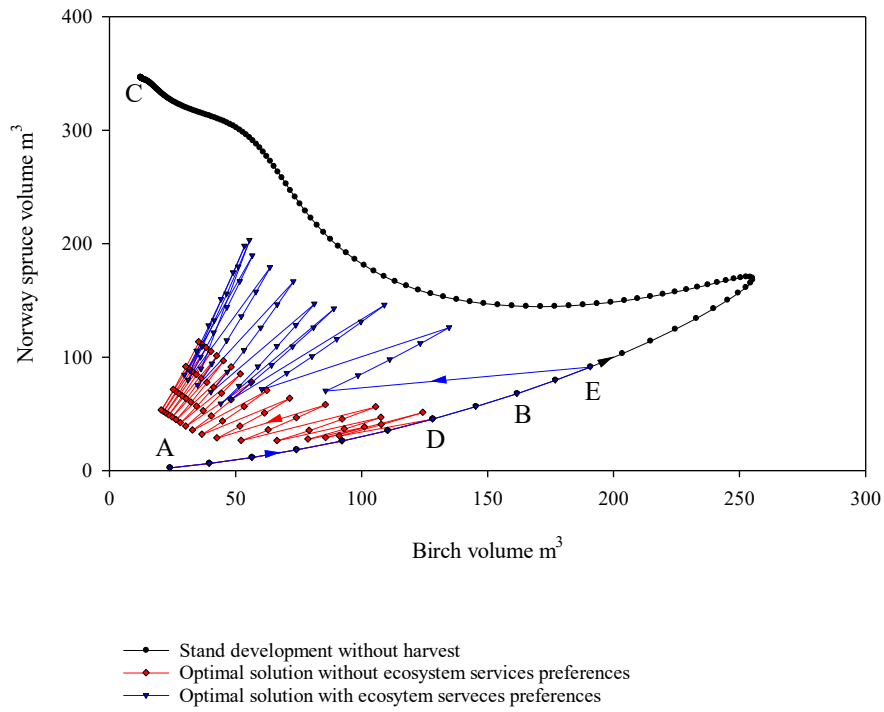
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599 Figure 6a-f. Optimal solution with preferences for ecosystem services

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Note: Interest rate 3%, all four tree species

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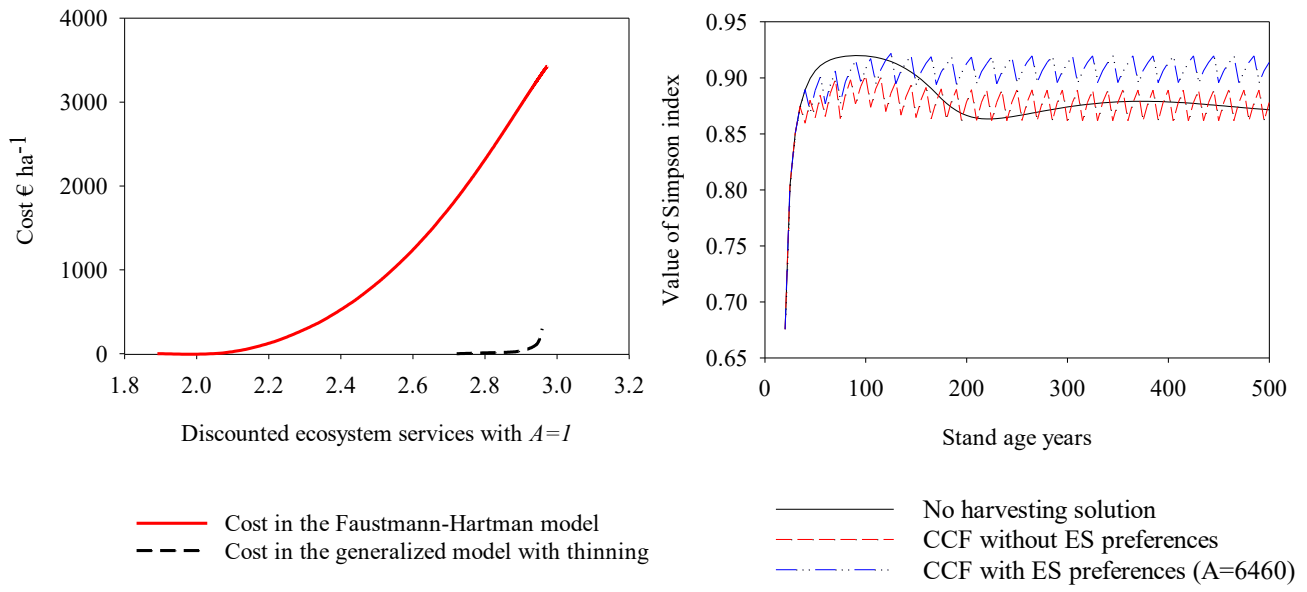
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603 Figure 7. Solutions for a Norway spruce birch mixture.

604 Note: Interest rate 3%, $A=0$ or $A=6460$

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608 Figure 8a,b. Costs and production of ecosystem services

609 Notes: Interest rate 3%, regeneration cost 1500€, all four tree species included

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611 Appendix 1. Parameters for regeneration, transition and mortality functions

612 Table A1. Parameters for equations (24)–(26) (Bollandsås (2008)).

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	Norway spruce	Scots pine	Birch	Other broadleaves
ϕ_1	43.142	67.152	64.943	3.438
ϕ_2	0.051	0	0.104	0.193
ϕ_3	0.368	0	0.143	0.442
ϕ_4	0.741	1.205	1.205	1.205
ϕ_5	-0.157	-0.076	-0.161	0.170
ϕ_6	-2.291	-3.552	-0.904	-3.438
ϕ_7	0.018	-0.062	-0.037	-0.029
ϕ_8	0.066	0	0	0.123
ϕ_9	0.019	0.08	0.016	0.048
α_1	0.02	0.02	0.02	0.02
α_2	17.839	25.543	11.808	2.204
α_3	0.0476	0.0251		0.063
α_4	-11.585×10^{-5}	-5.660×10^{-5}	9.616×10^{-5}	-8.320×10^{-5}
α_5	0	0	-9.585×10^{-8}	0
α_6	-0.3412	-0.216	0	0
α_7	-0.024	-0.123	-0.152	-0.177
α_8	0.906	0.698	0.519	0.359
α_9	-0.268	-0.336	-0.161	0
μ_1	-2.492	-1.808	2.188	-1.551
μ_2	-0.020	-0.027	0.016	-0.011
μ_3	3.200×10^{-5}	3.300×10^{-5}	2.700×10^{-5}	1.400×10^{-5}
μ_4	0.031	0.055	0.030	0.016

615 Note: We set the latitude parameter equal to $L = 61.9$ and assume an
 616 average fertility site (S_{15}) where the height of 100 dominant trees equal 15m.

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623 Table A2. Sawlog and pulpwood volumes $v_{1js}, v_{2js}, j = 1, \dots, L, s = 1, \dots, n$ (m^3) per tree.

Size class	Diameter cm	Norway spruce		Scots pine		Birch and other broadleaves	
		Pulp	Saw log	Pulpwood	Saw log	Pulpwood	Saw log
1	7.5	0.01374	0	0.03458	0	0.01591	0
2	12.5	0.06664	0	0.06659	0	0.07464	0
3	17.5	0.1669	0	0.10166	0.09764	0.18005	0
4	22.5	0.0808	0.23419	0.03905	0.27034	0.07854	0.25137
5	27.5	0.06482	0.44578	0.03001	0.48515	0.06655	0.45137
6	32.5	0.05975	0.68392	0.02750	0.74205	0.05827	0.69732
7	37.5	0.04978	0.96304	0.02647	1.04106	0.04978	0.96304
8	42.5	0.05039	1.25313	0.02596	1.38216	0.04865	1.24859
9	47.5	0.04324	1.57421	0.02567	1.76537	0.04463	1.55035
10	52.5	0.03925	1.89981	0.02549	2.29067	0.03891	1.86531
11	57.5	0.03317	2.21442	0.02537	2.65807	0.03685	2.18117
12	62.5	0.03073	2.56544	0.02529	3.16758	0.03268	2.49693

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625 Table A3. Prices for saw timber and pulpwood, p_{1i}, p_{2i} .

	Norway spruce	Scots pine	Birch	Other broadleaves
Saw timber	58.44	58.64	49.73	0
Pulpwood	34.07	30.51	30.50	0

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627 Table A4: Parameter values for the harvesting cost functions

Species	u	γ_{ju0}	γ_{ju1}	γ_{ju2}	γ_{ju3}	γ_{ju4}	γ_{ju5}	γ_{ju6}	γ_{ju7}	γ_{ju8}
Norway spruce	th	2.100	1.150	0.412	0.758	-0.180	2.272	0.535	0.826	0.244
	cl	2.100	1.000	0.412	0.758	-0.180	1.376	0.393	0.6132	0.2982
Scots pine	th	2.100	1.150	0.547	0.196	0.308	2.272	0.535	0.826	0.244
	cl	2.100	1.000	0.532	0.196	0.308	1.376	0.393	0.6132	0.2982
Birch	th	2.100	1.150	0.420	0.797	0.174	2.272	0.535	0.826	0.244
	cl	2.100	1.000	0.430	0.756	0.174	1.376	0.393	0.6132	0.2982
Other broadleaves	th	2.100	1.150	0.342	0.101	0	2.272	0.535	0.826	0.244
	cl	2.100	1.000	0.342	0.101	0	1.376	0.393	0.6132	0.2982

628 Note: Symbols, see equation (7).

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