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Opportunity Costs of Growing Space – an Essential Driver of Economical Single-tree Harvest Decisions

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Abstract

Controlling the growing space available to trees is essential for silvicultural management. For an efficient, i.e. economical, allocation of the scarce growing space, a qualitative and quantitative knowledge of all drivers of harvest decisions is required. The fundamental Faustmann-Pressler-Ohlin-Theorem reveals these drivers at the stand level: In the economical optimum, the stand's future value increment is equal to the interest of its value plus the land rent of the following stand. However, with increasing availability of single-tree data and single-tree-oriented management of heterogeneous stands, the need to transfer these fundamental economic relationships to the single-tree level arises. While several studies already focus on this problem, approaches using practice-related growth and harvest simulations that omit assumptions on the optimal thinning type are still somewhat rare. Our study seeks to provide a deeper understanding of basic economic principles underlying single-

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tree harvests. We thus aim to contribute to the methodological improvement of decision support systems regarding the implementation of silvicultural-economic linkages. We present a simulation-optimization model to analyze the importance of opportunity costs of growing space for economical harvests of even-aged single-trees under varying production goals and individual tree characteristics. Here, we show that controlling the competition-based growing space efficiency should guide harvest decisions at a young age, whereas with age the focus should shift to possible investment alternatives for the financial resources fixed in a tree. Our analyses of economical harvest decisions indicate that the importance of individual tree characteristics rises with increasing heterogeneity. From a silvicultural perspective, we found some surprising economically optimal harvest sequences in heterogeneous groups of trees, which underlines the high potential of our model to inform practical decision making at the single-tree level. By implementing economic theory in marteloscopes, our approach could enable an improved training of forest managers to face complex silvicultural decisions. In an environment shaped by scarcities, the derived principles are not limited to timber production itself and can be applied to various ecosystem services.

Keywords: Managing Tree Competition, Thinning, Incremental Analysis, Economic Optimization

1. Introduction

An essential task in forest management is the control of biological production (Möhring, 2010). Once a stand is established, the dominant measure to control its future growth is the alteration of the competitive stand structure through the removal of individual trees. In such thinning operations, forest managers periodically weigh the incremental benefits and costs of each possible single-tree harvest decision. To contribute to the understanding of these silvicultural-economic decisions, investment theory provides us a framework in which to analyze economically efficient solutions (cf. e.g. Coordes, 2014; Gong and Löfgren, 2010; Möhring, 2001, 2009).

The investment character of planting a tree is clear – disbursement at the beginning followed by subsequent timber deposits. In contrast, harvesting a tree is a highly complex investment situation (cf. Coordes, 2014, p. 146 ff.). On the one hand, postponing the harvest of a tree (keeping it as a means of production) is an investment in its higher value at the time of its future realization as a product (cf. Möhring, 2010). On the other hand, harvesting the tree is an alternative investment in the future value increment of the surrounding or following trees. For forest managers, the question of the optimal allocation of financial resources and land (or more specifically the growing space) to the trees of a stand arises (cf. Möhring, 2009, for stand-level decisions). This question can be classified in the neoclassical economic theory (Pertz, 1983, in connection with Samuelson, 1976). An investment where

23 the benefits of incremental¹ expansion are greater than the (opportunity)
24 costs will be gradually expanded until, at the optimum, the incremental ben-
25 efits equal the incremental costs (cf. e.g. Chang, 1984; Möhring, 1994; Yin
26 et al., 1998). The most common stand-level application of incremental anal-
27 yses with respect to time is the Pressler (1860; 1995) Indicator Percent (cf.
28 Chang and Deegen, 2011; Viitala, 2016), while a profit function approach has
29 been proposed by Li et al. (2020), Yin and Newman (1997), and Yin et al.
30 (1998) for forest-level applications. Pressler’s approach provides the concept
31 for the determination of the economically optimal rotation age in the frame-
32 work of the Faustmann-Pressler-Ohlin-Theorem (FPO) (cf. Johansson and
33 Löfgren, 1985, p. 74 ff.). The extension of this theorem to thinning is more
34 complex, as thinning age, thinning type, and thinning intensity have to be
35 determined simultaneously (cf. Hyytiäinen and Tahvonen, 2002; Klemperer,
36 1996, p. 242 ff.). Several studies have addressed this question. For example
37 Näslund (1969) examined the economically optimal stand volume, and Clark
38 and de Pree (1979) classified the determination of the optimal thinning in-
39 tensity to the more general question of the optimal use of natural resources.
40 Möhring (2010) determined optimal stand densities under financial restric-
41 tions and showed parallels between derived economic principles and practical
42 silvicultural concepts. Halbritter and Deegen (2015) extended the problem
43 in their analytical approach to the optimal planting density and the corre-
44 sponding interactions with thinning, rotation age and the exogenous factors

¹In contrast to e.g. Chang (1984), we use a discrete approach with single-tree harvest decisions in annual time steps instead of continuous harvest volumes in continuous time. We thus use the term ‘incremental’ instead of ‘marginal’.

45 of timber price and interest rate.

46 These approaches at the stand level (comparable to Faustmann) cannot
47 be directly applied to stands of high horizontal (e.g. tree quality or species)
48 and vertical (e.g. tree vitality or age) diversity. As Heshmatol Vaezin et al.
49 (2009) pointed out, the area occupied by a growing tree changes over time,
50 and thus a Faustmann maximization of the Land Expectation Value lacks a
51 reference area. When developing models closer to continuous cover forests,
52 more recent studies circumvented this issue, for instance, by composing a
53 more diverse forest of several age cohorts (cf. e.g. Jacobsen et al., 2018;
54 Messerer et al., 2020; Tahvonen, 2004) or through the application of matrix
55 models (cf. e.g. Rämö and Tahvonen, 2017; Roessiger et al., 2016). In con-
56 trast, Coordes (2014), Foppert (2020), Härtl et al. (2010) as well as Meilby
57 and Nord-Larsen (2012) analyzed the economics of harvest decisions on the
58 smallest forest management unit, the single tree. A detailed literature review
59 of the historical developments in the research field of suitable approaches re-
60 lated to neighborhood dynamics is provided by Foppert (2020).

61 Nevertheless, there are few practice-related simulation models which fo-
62 cus on single trees while analyzing not only a specific development phase,
63 but also deriving economically efficient harvest decisions without assuming
64 a specific thinning type. Our study aims to contribute here by providing
65 a simulation-optimization approach, which is sufficiently complex to derive
66 practical-relevant silvicultural implications, but at the same time, remains
67 numerically manageable. Therewith the framework seeks to advance the im-
68 plementation of economic theory in single-tree harvest decision support sys-
69 tems (DSS) or silvicultural training programs, such as marteloscopes (Soucy

70 et al., 2016).

71 We illustrate the economic principles behind economical harvest decisions
72 at the single-tree level based on a group of trees in a Central European
73 age-class forest of Norway spruce (*Picea abies* (L.) KARST). Therefore, we
74 quantify and compare the three *drivers* of each single-tree harvest: (i) The
75 future value increment of the tree, (ii) the opportunity costs of capital and
76 (iii) the opportunity costs of growing space – i.e. the incremental benefits (i)
77 and costs (ii + iii) of postponing the harvest of a tree for one year.

78 Quantifying the tree’s value increment and its opportunity costs of the
79 possible alternative use of the capital fixed in the tree is straightforward and
80 comparable to the final-harvest decision rule according to Pressler (1860; 1995,
81 cf. Möhring, 2009). In contrast, quantifying the opportunity costs of the
82 alternative land use is more complex. The land shortage is of particular im-
83 portance here, since trees do not grow independently (cf. e.g. Coordes, 2014,
84 p. 9 f.; Möhring, 2010; Pretzsch, 2005), and their growth is characterized by
85 the competitive structure in the stand. It can be assumed that this competi-
86 tive structure (due to light, water and nutrient availability) closely correlates
87 with the available upper as well as underground growing space of a tree (cf.
88 Pretzsch, 2009, chapter 8; Röhrig et al., 2006, p. 210 ff.). Therefore, we refer
89 to a three-dimensional understanding of space by using the term, “growing
90 space”, instead of “land”.

91 We hypothesize that the relative importance of the drivers depends on
92 silvicultural-economic *conditions* that affect the forest production. Revealing
93 and illustrating the influence of these conditions on the drivers of economi-
94 cally optimal single-tree harvests is a missing link between forest economic

95 theory and silvicultural measures at the operational level. In our study, we
96 analyze the influence of four different conditions:

97 *Capital scarcity* refers to the capital that is fixed in the trees as a
98 means of production; alternative uses of this capital can be related
99 to investments outside of forest production but also other silvicultural
100 measures such as planting.

101 Our *production goals* differentiate between forest owners who produce
102 one homogeneous roundwood product, such as pulpwood, and those
103 who aim to produce several products with different price levels, such
104 as pulpwood and sawtimber assortments.

105 *Quality* refers to the subsequent timber utilization potential of the trees,
106 i.e. whether they have less branches or a straight growth.

107 *Vitality* refers to the volume growth potential of the trees.

108 Aiming to shed new light on the drivers and the silvicultural-economic
109 conditions determining the economical single-tree harvest decision, our anal-
110 ysis is guided by two questions:

- 111 1. To what extent do the opportunity costs of growing space, apart from
112 value increment and opportunity costs of capital, drive economical
113 single-tree harvest decisions?
- 114 2. Under which circumstances are tree quality and vitality relevant con-
115 ditions which influence the drivers of economical single-tree harvest
116 decisions?

117 In order to contribute to the solution of these questions, we analyze the
118 economic drivers of optimal single-tree harvest decisions based on a single-
119 tree growth and harvest simulation. We compare the quantified drivers for
120 different scenarios as combinations of the silvicultural-economic conditions.
121 In addition, we found some surprising optimal sequences of single-tree har-
122 vests that may improve the understanding of these complex silvicultural-
123 economic decisions. Since forest management increasingly focuses on single
124 trees and the availability of single-tree data rises, our approach provides an
125 important contribution to incorporating various scarcity-related challenges
126 of forest management into operational single-tree harvest decisions.

127 **2. Model and Methods**

128 We developed a bioeconomic simulation-optimization model to quantify
 129 and compare incremental benefits and costs as drivers of efficient single-
 130 tree harvest decisions. These decisions are dependent on the silvicultural-
 131 economic conditions of capital scarcity, production goals, vitality and quality
 132 (Fig. 1).

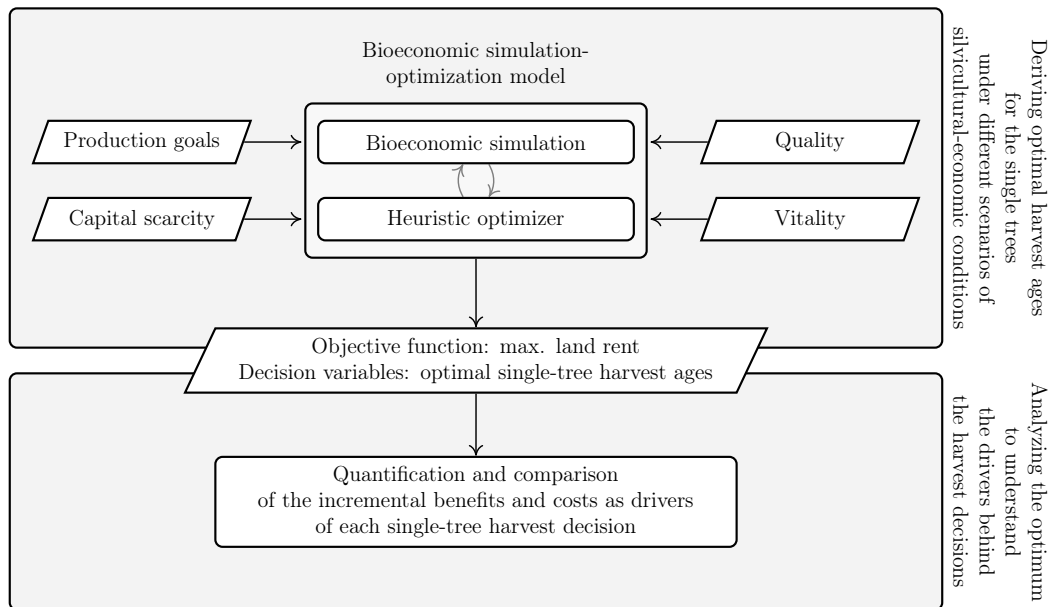


Figure 1: Overview of the applied methods and their linkages. First, a bioeconomic simulation-optimization model selects the harvest ages of a group of single trees that maximize the land rent under different scenarios defined by silvicultural-economic conditions. For each scenario, the heuristic optimizer varies harvest ages and reruns the bioeconomic simulation in an iterative process. Afterwards, the derived optimum is analyzed quantitatively regarding the drivers of the harvest decisions. Parallelograms represent inputs and outputs of the simulation-optimization model, rectangles are model or analysis functions, and arrows indicate information flows.

133 The bioeconomic simulation is based on a growth model for Norway
 134 spruce (*Picea abies* (L.) KARST). It simulates a group of 20 single trees,

135 which interact in a spatially non-explicit competitive environment (Sec. 2.1).
136 The simulation model is the basis for our optimization. The decision vari-
137 ables are the harvest ages of the trees, which are changed to optimize the land
138 rent as the objective function (Sec. 2.2). We optimized the harvest ages for
139 different scenarios of silvicultural-economic conditions (Tab. 1). We analyzed
140 the influence of production goals and capital scarcity (scenarios 1.1 - 1.4), as
141 well as tree vitality and quality (scenarios 2.1 - 2.4). This was done through
142 the comparison of the optimal harvest decisions in distinct groups of trees,
143 which were homogeneous with respect to vitality and quality. Contrasting
144 this, in scenario 3, we simulated four interacting tree cohorts, differing in vi-
145 tality and quality. Afterwards, we analyzed the optimal harvest sequences in
146 order to better understand the economic drivers behind the harvest decisions.
147 For this purpose, we built a calculation framework which allows for a quan-
148 titative comparison of the incremental benefits and costs of each single-tree
149 harvest (Sec. 2.3).

150 *2.1. Bioeconomic Simulation and Scenarios*

151 The simply constructed, time-discrete bioeconomic single-tree growth and
152 harvest simulation model contains two parts: a tree growth and harvest sim-
153 ulation in annual time steps², and an economic valuation (for a flow chart
154 see Supplementary Methods). The software R (R Core Team, 2019) was used
155 to transfer the stand-level simulation-optimization model by Möhring (2010)
156 to the single-tree level. We extended the model by considering the vitality

²In our model, and the analyses based on it, we consistently use annual steps as the smallest time unit relevant for silvicultural management of forests with seasonal growth dynamics.

157 (growth potential) and quality (subsequent timber utilization potential) as
158 characteristics of the single trees, which allowed us to simulate four interact-
159 ing cohorts that were heterogeneous in this regard. The growth simulation is
160 carried out for the entire group – as the sum of the single trees – considering
161 the actual competitive situation (stand density). The derived annual volume
162 increment of the entire group is distributed among the trees according to
163 their individual growth potential (vitality) as specified in the Supplementary
164 Methods. In contrast to the stand-level model by Möhring (2010), where
165 thinning takes place by a steadily determinable extraction of a volume frac-
166 tion, our model applies discrete harvests of one or more trees. With respect
167 to the single-tree oriented forestry of Central Europe, we interpret the group
168 of 20 single trees as a management unit. We did not consider edge effects,
169 since we assumed that this group is part of a stand with similar characteris-
170 tics and management. Simulating 20 trees also limited the complexity of the
171 computationally-demanding integer optimization.

172 The simulation is based on the reference growth of a Norway spruce stand,
173 which is described using functions of Smaltschinski (2001) based on estab-
174 lished yield tables by Wiedemann (1936/42, quoted in Schober, 1995). These
175 age-dependent functions provide the gross volume yield (Fig. 2a: dashed
176 line), the standing volume (Fig. 2a: solid line), the annual volume increment
177 (temporal difference quotient of the gross volume yield, Fig. 2b) and the
178 mean tree height (not shown).

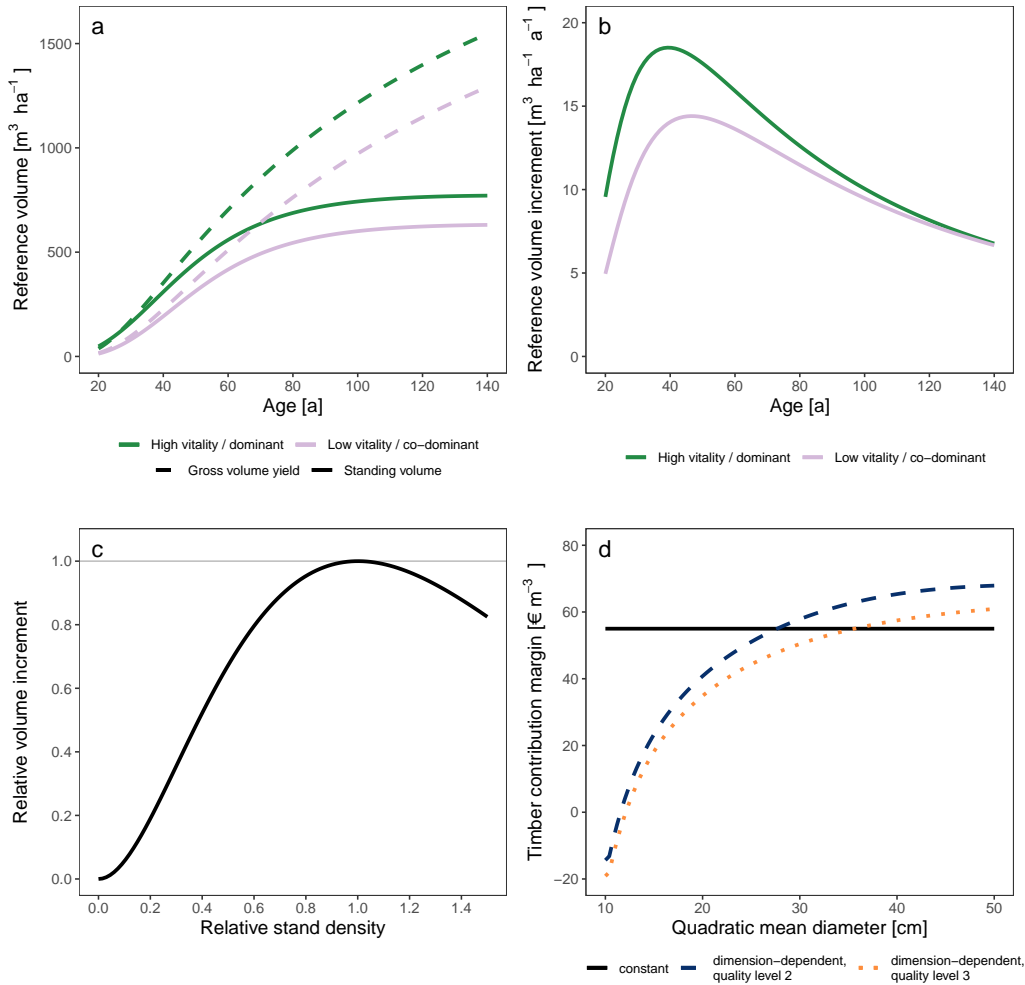


Figure 2: Basic functions of the bioeconomic single-tree simulation model. a: Reference gross volume yield and standing volume taken from Smaltschinski (2001) based on yield tables according to Wiedemann (1936/42, quoted in Schober, 1995). b: Relative volume increment according to Smaltschinski (2001) corresponding to yield table values from Wiedemann (1936/42, quoted in Schober, 1995); the two vitality levels refer to different site indices. c: Volume increment reduction function (actual volume increment relative to reference volume increment) according to Möhring (2010). d: Constant and dimension-dependent timber contribution margin based on the harvest costs and timber revenue functions of Bodelschwingh (2018); the two quality levels of the dimension-dependent timber contribution margin represent high (2) or low (3) quality.

179 We aimed to analyze the influence of the tree *vitality*, i.e. growth po-
180 tential, on single-tree harvest decisions. We thus varied the reference growth
181 (Fig. 2a,b) in scenarios 1.1 to 2.4 with two different site indices ($H_{100}(100) =$
182 35.1 m and $H_{100}(100) = 31.2$ m, see Tab. 1). In scenario 3, we assumed that
183 tree cohorts, which are heterogeneous with respect to their growth potential,
184 interact. Here, we followed the classifications of Kraft (1884, see Pretzsch,
185 2009, p. 154), and refer to the vitality levels as *dominant* and *co-dominant*
186 trees.

187 However, the actual volume increment depends on the competitive struc-
188 ture, which is influenced by the individual harvest ages of the interacting
189 single trees. Since the yield tables assume a reference stand density, we
190 used a volume increment reduction function (Fig. 2c) adapted from Möhring
191 (2010). This was used to derive the actual volume increment in relation to
192 the reference volume increment in the yield tables (Fig. 2b). For the detailed
193 calculation of the volume increment of the single-trees under consideration of
194 the individual growth potential and the competitive structure, we refer the
195 reader to the Supplementary Methods.

196 For the economic valuation, we calculated cash flows based on the growth
197 and harvest simulation. The net timber revenues (contribution margin) of
198 a harvested and marketable timber volume unit are the difference of timber
199 proceeds and harvest costs. In order to analyze the influence of different *pro-*
200 *duction goals*, we simulated scenarios (Tab. 1) with a constant contribution
201 margin of 55 €/m^3 , representing one homogeneous product (e.g. pulpwood),
202 and scenarios with a diameter-dependent contribution margin (Fig. 2d; for
203 the derivation of the required diameters see Supplementary Methods). The

204 latter assumes that several products, such as pulpwood and different saw
205 timber assortments, are produced and that, given a specific quality level,
206 the share of high-value assortments increases with increasing tree diameters.
207 We derived the timber proceeds using the model of Bodelschwingh (2018),
208 which allowed us to simulate scenarios with different *quality* levels (see Of-
209 fer and Staupendahl, 2008, 2009). These quality levels represent different
210 compositions of assortments dependent on the trees' timber characteristics,
211 such as stem shape, number of branches, or rot. We used level 2 for high
212 and level 3 for low quality trees (Tab. 1). In the scenarios 2.1 to 2.4, we
213 analyzed the differences in harvest ages between homogeneous stands of high
214 and low quality. In contrast, in scenario 3, we focused on the interactions
215 between tree cohorts which were heterogeneous with respect to quality. We
216 used dimension-dependent harvest costs according to Bodelschwingh (2018),
217 which were parameterized based on harvest data of single-tree oriented man-
218 agement in public forests of the Federal State of Hesse in Germany. This takes
219 into account both increased management costs of harvesting single trees in a
220 stand and also that the harvest of higher single-tree volumes results in lower
221 harvest costs per unit volume.

222 Since our growth and harvest simulation started at age 20, we further
223 considered establishment costs ($c_0 = 2000 \text{ €}/\text{ha}$) and pre-commercial spac-
224 ing costs ($c_{10} = 400 \text{ €}/\text{ha}$) at age 10. The costs were allocated proportion-
225 ally to the cash flows of the tree group. Based on these cash flows, we
226 derived the land rent as the annuity of the Land Expectation Value (Faust-
227 mann, 1849; 1995), and thus derived the annuity of perpetual forest rotations.
228 Thereby, we assumed that regeneration occurs as planting immediately after

229 the harvest of the last tree. We analyzed the influence of *capital scarcity* by
230 comparing scenarios with two different interest rates: 0.000 000 1 %³ for the
231 case of unlimited, cost-free capital availability, and 2 % for including oppor-
232 tunity costs of capital in a magnitude often assumed for internal investment
233 alternatives in Central European forest enterprises (e.g. Clasen et al., 2011;
234 Hahn et al., 2014). With these constant interest rates (see discussion in
235 Knoke et al., 2017; Price, 2011), we assumed a perfect capital market (see
236 discussion in Wildberg and Möhring, 2021), which is in line with the classical
237 FPO-Theorem (cf. Johansson and Löfgren, 1985; Samuelson, 1976).

³Using a 0 % interest rate in equation 1 would lead to a denominator of 0. Möhring (1994) as well as Möhring and Dieter (2020) showed, applying L'Hospital's rule to the annuity factor, that for $r \rightarrow 0\%$ the land rent equals the forest rent according to the Theory of Highest Revenue.

Table 1: Simulated scenarios defined by the assumptions on and parametrization of the silvicultural-economic conditions that influence the drivers of single-tree harvest decisions. The last column refers to the corresponding figure in the results.

Scenario	Stand structure	Production goal ¹⁾	Capital scarcity ²⁾	Vitality ³⁾	Quality ⁴⁾	Result Figure
1.1	homogeneous	homogeneous product	without	high	high	Fig. 3: top left
1.2	homogeneous	homogeneous product	with	high	high	Fig. 3: top right
1.3	homogeneous	several products	without	high	high	Fig. 3: bottom left
1.4	homogeneous	several products	with	high	high	Fig. 3: bottom right
2.1	homogeneous	several products	with	low	low	Fig. 4: top left
2.2	homogeneous	several products	with	low	high	Fig. 4: top right
2.3	homogeneous	several products	with	high	low	Fig. 4: bottom left
2.4		<i>see scenario 1.4</i>				Fig. 4: bottom right
3	heterogeneous: cohort 1 cohort 2 cohort 3 cohort 4	several products	with	co-dominant co-dominant dominant dominant	low high low high	Fig. 5: top left top right bottom left bottom right

¹⁾ see Fig. 2d: constant timber contribution margin for only one homogeneous product or dimension-dependent timber contribution margin for varying shares of several products

²⁾ referring to interest rates:

without opportunity costs of capital: $r = 0.000\,000\,1\%$, or with opportunity costs of capital: $r = 2\%$

³⁾ see Fig. 2a and 2b, growth potential based on top height at age 100 ($H_{100}(100)$):

high resp. dominant: $H_{100}(100) = 35.1\text{ m}$; low resp. co-dominant: $H_{100}(100) = 31.2\text{ m}$

⁴⁾ see Fig. 2d, referring to the quality levels in Bodelschwingh (2018)

238 *2.2. Heuristic Optimization*

239 In order to quantify the drivers of thinning decisions, the economically
 240 optimal harvest sequence for 20 trees was derived by a heuristic integer opti-
 241 mization. The management is characterized by the harvest ages t_j of all
 242 single trees j ($j = 1, \dots, 20$) as our decision variables. The rotation age
 243 $T = \max(t_1, \dots, t_{20})$ was determined by the harvest of the last tree – no
 244 explicit, additional decision variable was needed. As the objective function
 245 of a rational decision maker (*homo oeconomicus*), we maximized the land
 246 rent a (annuity) of the tree group (as in Möhring, 2010), which is in line with
 247 maximizing the Land Expectation Value (Chang, 1984; Möhring, 2009):

$$\max_{t_1, \dots, t_{20}} a = \left(\sum_{j=1}^{20} V_j(t_j) \cdot (1+r)^{T-t_j} - c_0 \cdot (1+r)^T - c_{10} \cdot (1+r)^{T-10} \right) \cdot \frac{r}{(1+r)^T - 1} \quad (1)$$

248 with respect to

$$20 \text{ a} \leq t_j \leq 100 \text{ a.} \quad (2)$$

249 Apart from the harvest ages $t_j = t_1, \dots, t_{20}$ and the resulting rotation age
 250 T , the land rent depends on the trees' net harvest value $V_j(t_j)$, the interest
 251 rate r , the establishment costs c_0 , and the pre-commercial spacing costs c_{10} .

252 Solving the described non-linear integer optimization program with 20 de-
 253 cision variables is highly demanding since the resulting number of possible
 254 harvest period variations in annual steps is very high. We solved the pro-
 255 gram using the heuristic black-box optimization algorithm NOMAD (R-package
 256 `crs` by Racine et al., 2018). However, to ensure that the identified optimum
 257 is at least close to the global optimum, we additionally chose a multi-stage
 258 approach. We derived the required starting values based on a simplified

259 enumeration (for further details see Supplementary Methods).

260 2.3. Quantification and Comparison of the Drivers Behind Harvest Decisions

261 Following the determination of the optima we analyzed the harvest deci-
262 sions for each scenario to understand the underlying drivers. We developed
263 a calculation framework by transferring the Pressler Decision Rule (Pressler,
264 1860; 1995, cf. Möhring, 2009), which contains the drivers of harvest deci-
265 sions at the stand level, to the single-tree level.

266 According to Pressler (1860; 1995, cf. Möhring, 2009), for a stand's opti-
267 mal final-harvest age T , its annual value increment $i_V(T, T + 1)$ is equal to
268 the sum of the opportunity costs of capital, i.e. the interest of the harvest
269 value $V(T) \cdot r$, and land, i.e. the annuity of the following stands a :

$$i_V(T, T + 1) = V(T) \cdot r + a. \quad (3)$$

270 Applied to a single tree j , value increment and harvest value can be simply
271 derived in our bioeconomic simulation model. In contrast, quantifying the
272 opportunity cost of occupied land, or more specifically the three dimensional
273 growing space, is much more challenging at the single-tree level. Here, the
274 effects of a postponed single-tree harvest on the current neighbouring trees
275 are taken into account. The opportunity costs thus arise due to spatial intra-
276 instead of temporal inter-stand effects. This considers, for example, the
277 future potentially reduced volume growth, lower timber proceeds, or higher
278 harvest costs per unit volume of the influenced trees.

279 In the following, we refer to these costs of postponing the harvest of tree
280 j for one year as the opportunity costs of growing space o_j . This considers

281 that the harvest of tree j at the age $t_j + 1$ (instead of harvesting it at t_j) leads
 282 to a change in the harvest values ΔV of all influenced trees $k \in \Phi_j$ at their
 283 respective time of realization (harvest) t_k . Since all trees k are harvested at
 284 different future points in time t_k , and given the potential long time period
 285 between the harvest of tree j and the harvests of the trees $k \in \Phi_j$, these
 286 changes in value are discounted with the interest rate r . We calculated these
 287 opportunity costs of growing space,

$$o_j = \sum_{k \in \Phi_j} \frac{\Delta V_{k,j}(t_k)}{(1+r)^{(t_k-(t_j+1))}}, \quad (4)$$

288 for each single-tree harvest based on the difference of the cash flows resulting
 289 from two alternative runs of our bioeconomic simulation model – one where
 290 the tree j was harvested at t_j and one with the postponed harvest at $t_j + 1$.

291 Analogous to Pressler at the stand level (Pressler, 1860; 1995, cf. Möhring,
 292 2009), one obtains the single-tree harvest decision rule with tree j 's value in-
 293 crement $i_{V,j}(t_j, t_j + 1)$, the interest on its harvest value $V_j(t_j) \cdot r$ and the
 294 opportunity cost of growing space (Eq. 4) as:

$$i_{V,j}(t_j, t_j + 1) = V_j(t_j) \cdot r + \sum_{k \in \Phi_j} \frac{\Delta V_{k,j}(t_k)}{(1+r)^{(t_k-(t_j+1))}}. \quad (5)$$

295 This is in line with the optimality condition for single tree harvests according
 296 to Coordes (2014, p. 61), who derived it directly from the full optimization
 297 problem within the Faustmann approach. While this condition has to hold
 298 true for every single-tree harvest, it is, due to the intertemporal interactions
 299 in the opportunity costs of growing space (Eq. 4), not suitable to solve the

300 simultaneous optimization problem of all 20 single-tree harvests. One should
301 consider that, due to these intertemporal interactions, the formulation based
302 on the FPO-theorem does not satisfy some properties required in classical
303 profit function approaches (see Li et al., 2020). Thus, we solved the simulta-
304 neous optimization problem with the heuristic approach (Sec. 2.2) and used
305 equation 5 only to analyze the drivers of each single-tree harvest decision in
306 the context of the optimal harvest sequence.

307 **3. Results**

308 Even in our simplest scenario, where the trees were assumed to be ho-
309 mogeneous with respect to vitality and quality, harvesting single trees out of
310 the group before reaching the final harvest proved to be economical since the
311 trees compete for growing space. If capital costs, fixed in the standing trees,
312 are not considered, the optimal harvest age is determined by the trees' value
313 increment and opportunity costs of growing space. In the optimum, whenever
314 the incremental benefit of letting a tree grow for another year is surpassed
315 by the negative effects of the higher competition on the surrounding trees
316 (lines touch in Fig. 3, Scenario 1.1), one tree is harvested⁴. Since harvesting
317 one tree increases the other trees' future growth, the now improved ratio of
318 incremental costs and benefits of the remaining trees justifies maintaining
319 them.

320 Considering capital scarcity fundamentally changed the relationship of
321 the drivers of the single-tree harvest decisions. Now, the opportunity costs
322 of maintaining the tree are driven by both the financial resources fixed in the
323 standing tree as well as its competitive effect on the surrounding trees (Fig. 3,
324 Scenario 1.2). The sum of the opportunity costs as well as the value increment
325 maintain their increasing trend. At age 60 the value increment of each tree
326 is 57% higher than in the scenario without any capital scarcity: 9 instead of
327 15 trees provide a rather similar value increment at group-level (21.96 € a^{-1}
328 resp. 23.25 € a^{-1}). Initially, the harvest decision is mainly driven by the

⁴The amplification in the differences between opportunity costs and value increment after harvests with higher ages are model immanent. The share of the tree group the model can harvest in the next step becomes larger if a tree is harvested, successively highlighting the discrete approach.

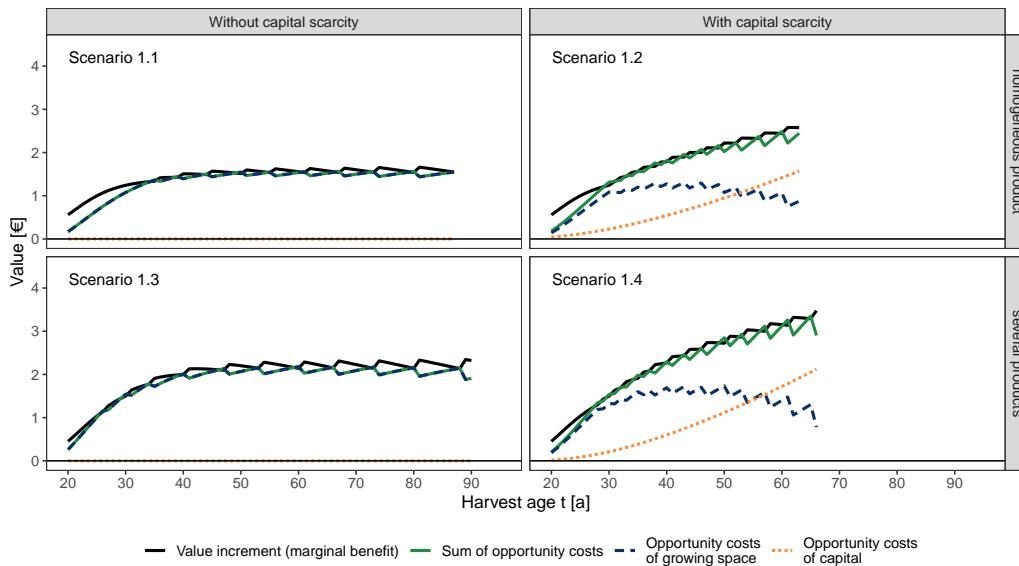


Figure 3: Incremental benefits and costs of letting the tree, which would otherwise be harvested next according to the optimization result, grow for an additional year. For comparison, both benefits and costs are expressed as positive values per tree. Whenever incremental benefits and costs converge, a tree is harvested. The panels (scenarios, see Tab. 1) demonstrate how the developments depend on the assumptions on capital scarcity (left vs. right) and the production goal (top vs. bottom).

329 opportunity costs of growing space. With the increasing value of the trees,
 330 the opportunity costs of capital become more relevant – trees are harvested
 331 earlier as their value increment has to surpass not only the effect on other
 332 trees but also the capital costs. Consequently, the stand density is lower
 333 in this scenario, which even leads to declining opportunity costs of growing
 334 space after the age of 43. Above the age of 53 the importance of competition
 335 for harvest decisions starts to become even lower than that of capital, and
 336 one year before the final harvest of the remaining trees it accounts for just
 337 36 % of the opportunity costs.

338 Introducing a production goal aiming at the production of different timber

339 assortments leads to dimension-dependent contribution margins. This did
 340 not fundamentally alter the development of incremental benefits and costs,
 341 which is illustrated by the comparison of the top and bottom subgraphs of
 342 Fig. 3. Without capital scarcity (Fig. 3, Scenario 1.3), the model already
 343 suggested the harvest of 3 trees before age 34. This focuses the growth on
 344 fewer single trees, whose resulting higher dimensions lead to higher timber
 345 contribution margins (Fig. 2d). Additionally, the extension of the rotation
 346 period allows for the exploitation of the effect for a longer time (age 91 vs. age
 347 88). Both effects are also valid under capital scarcity (Fig. 3, Scenario 1.4),
 348 but are less pronounced.

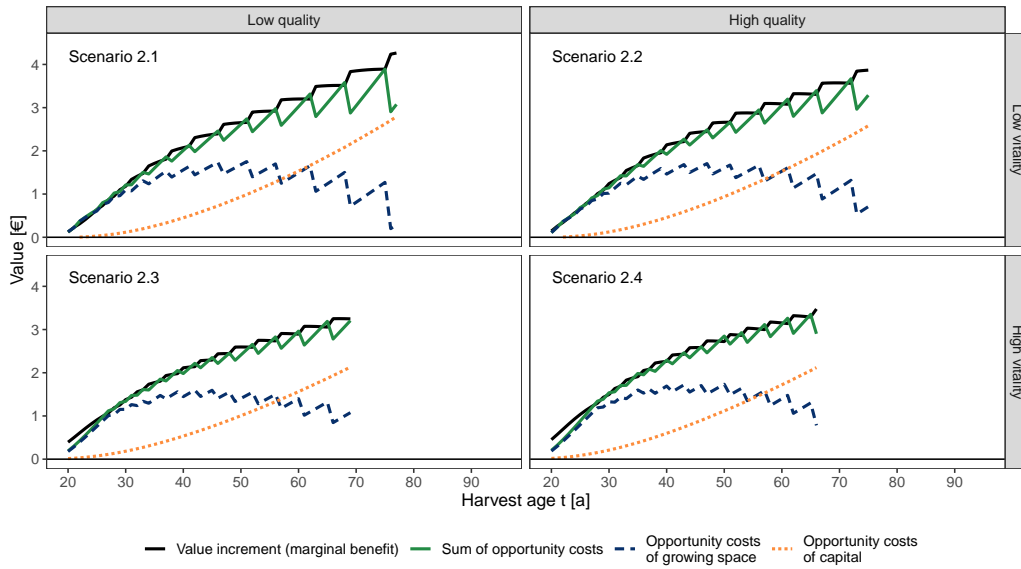


Figure 4: Incremental benefits and costs of letting the tree, which would otherwise be harvested next according to the optimization result, grow for an additional year. For comparison, both benefits and costs are expressed as positive values per tree. Whenever incremental benefits and costs converge, a tree is harvested. The panels (scenarios, see Tab. 1) demonstrate how the developments depend on tree quality (left vs. right) and vitality (top vs. bottom).

349 To quantify the influence of quality and vitality on the drivers of single-
350 tree harvest decisions, we first analyzed groups of trees, which are homo-
351 geneous with respect to quality and vitality. These scenarios are based on
352 Scenario 1.4 with capital scarcity (interest rate 2%) and the goal of pro-
353 ducing several products (dimension-dependent timber contribution margin).
354 Here we showed that under our assumptions, the influences of quality and
355 vitality on the optimal harvest sequence are rather small (Fig. 4 in compari-
356 son to Fig. 3). The most important consequence is a shorter optimal rotation
357 period in tree groups of high vitality, however the effects on previous har-
358 vests are small. The culmination points of the opportunity costs of growing
359 space as well as the intersections of both opportunity costs are similar in all
360 simulated cases.

361 In contrast, in the group of heterogeneous trees (Scenario 2, see Tab. 1),
362 their different qualities and vitalities essentially influenced the harvest se-
363 quence. Here, under capital scarcity and aiming at several products, co-
364 dominant trees (lower vitality) are harvested at younger ages to promote the
365 growth of the dominant trees – low quality (age 26 to 30, Cohort 1) before
366 high quality (age 32 to 36, Cohort 2). 5 dominant trees form the final-harvest
367 group as promoted target trees harvested at the age of 70. But contrary to
368 intuition, it is not optimal to hold all dominant trees of high quality until
369 the final-harvest age. At first, similar to the co-dominant trees, 3 low quality
370 trees are harvested at ages 46, 50 and 55. However, the last two thinning
371 trees are of high quality (ages 60 and 66). To interpret this, Fig. 5 shows
372 the incremental costs and benefits in bars equalizing in value at the single
373 trees' optimal harvest ages. Within the dominant trees, the importance of

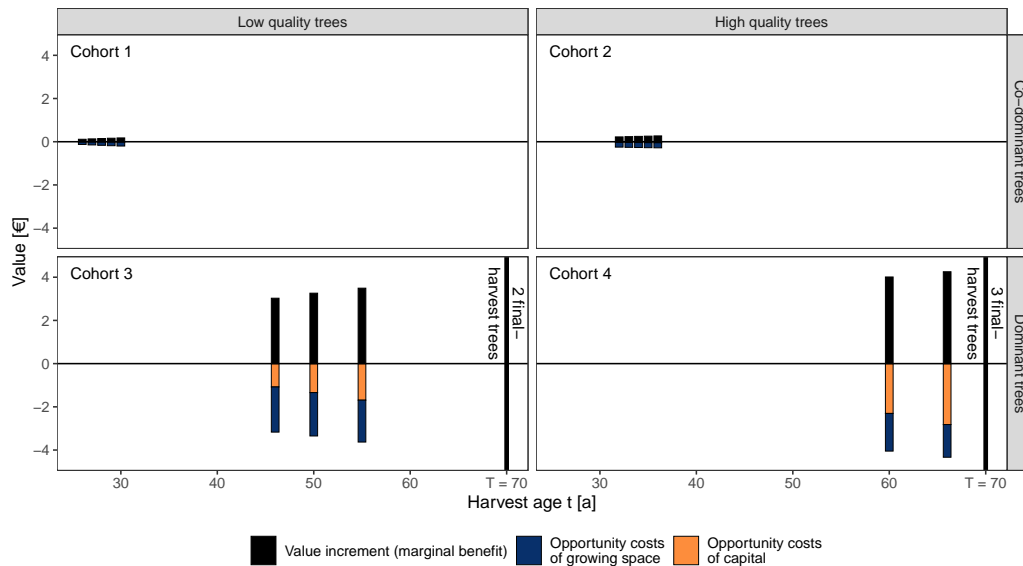


Figure 5: Incremental benefits and costs of letting the tree, which would otherwise be harvested next according to the optimization result, grow for an additional year. The group of 20 heterogeneous trees splits into 4 cohorts (5 trees each, the different panels). Each cohort is defined by quality (low and high quality trees) and vitality (dominant for high and co-dominant for low vitality trees). Each bar indicates one tree at its optimal harvest age and the bar's colors provide the benefits and opportunity costs of the alternative decision to let this tree grow for another year. 5 dominant trees, 2 of low and 3 of high quality, are harvested at the end of the rotation (age 70), which is illustrated by the vertical lines. The opportunity costs of growing space for letting these trees grow another year are the land rent of the next stand. Since these strongly exceed the opportunity costs of single thinning trees and our study mainly focuses on the latter, incremental benefits and costs are not shown here.

374 harvest drivers differs between low quality (Cohort 3) and high quality (Co-
 375 hort 4) trees. At the harvest ages of the low quality trees, the opportunity
 376 costs of growing space are dominant (53 to 66% of the opportunity costs) –
 377 growth competition drives the harvest decision. At the harvest ages of the
 378 high quality trees, however, the opportunity costs of capital exceed those of
 379 growing space (57 to 65% of the opportunity costs) – capital scarcity drives
 380 the harvest decision. Thus, the time span where the relative importance of

381 both drivers changes (between ages 55 and 60), indicates an important point
382 in time for economical single-tree harvest sequences.

383 4. Discussion

384 Our approach of combining a bioeconomic simulation of interacting single-
385 trees with a heuristic harvest-sequence optimization contributes to a deeper
386 understanding of the economic principles underlying single-tree harvest deci-
387 sions. Referring to our first research question, Fig. 3 reveals that opportunity
388 costs of growing space, apart from value increment and opportunity costs of
389 capital, drive single-tree harvest decisions to a decisive extent. While the de-
390 cisions are driven only by the competitive situation when financial resources
391 are not scarce, assuming any time preference reduces the impact of growing
392 space with increasing age until, at advanced development stages, the harvest
393 decision is primarily driven by the opportunity costs of capital. Referring to
394 our second question, our simulations indicate that vitality and quality are of
395 minor importance when managing homogeneous tree groups (Fig. 4), while
396 they are of high importance for scheduling single-tree harvests in heteroge-
397 neous, i.e. more complex, structures (Fig. 5). The absolute values should be
398 interpreted with care and are not intended to directly guide practical deci-
399 sion making. This is because our simulation model uses functions based on
400 different data sources and also simplifies relationships. This resulted in, for
401 example, relatively low optimal stand densities in young stand ages. How-
402 ever, the functional relationships appear plausible and are sufficient to guide
403 our analysis.

404 *4.1. Opportunity Costs of Growing Space as a Driver of Single-Tree Harvest*
405 *Decisions*

406 Without the assumption of capital scarcity, harvest decisions are, apart
407 from value increment, only driven by the opportunity costs of growing space
408 (Scenario 1.1, Fig. 3). In line with Rämö and Tahvonen (2017), a rising time
409 preference led to a lower optimal number of remaining trees and thus lower
410 financial resources fixed (Scenario 1.2, Fig. 3). Consequently, the competitive
411 pressure decreased with age and the importance of the opportunity costs of
412 growing space decreased. For practical forest management this implies that
413 single-tree harvest decisions in young forest stands should be driven by a
414 tree's effects on its neighbouring trees, whereas in older stands the alterna-
415 tive use of financial resources becomes more important (see investment vs.
416 divestment in Coordes, 2014, p. 146 ff.). This result underlines that being
417 aware of the actual magnitude of capital scarcity is essential for efficient har-
418 vest decisions. Since forest enterprises are usually not financed externally
419 (Wildberg and Möhring, 2021, in connection with Tahvonen et al., 2001),
420 alternative uses for capital within the enterprise, for example, alternative sil-
421 vicultural measures, should be considered (e.g. Möhring, 2014). Such internal
422 interest rates, based on observed harvest decisions, have been estimated to
423 be about 1.5 % for data from the state forest administration of Lower-Saxony
424 in Central Germany (Möhring, 2001). They ranged between 1.6 % and 3.1 %
425 based on data from the German NFI, depending on the forest ownership
426 (Husmann et al., 2019).

427 Under the assumption that timber is a homogeneous good (e.g. fuelwood
428 or pulp) and financial resources are not scarce (Scenario 1.1, Fig. 3), a for-

429 est manager should aim to maintain a tree for as long as its volume growth
430 cannot be compensated for by the surrounding trees (maximized mean an-
431 nual volume increment, see Koster, 2020, p. 38 ff., 93 f.). The so called
432 stand density effect (cf. Halbritter and Deegen, 2015) describes the (par-
433 tial) compensation of the harvested tree’s volume growth by the promoted
434 growth of neighboring trees – the extraction of the single tree (reduction of
435 the stand density) then under-proportionally reduces the growth of the stand
436 (e.g. Pretzsch, 2005, Fig. 2c).

437 With the rejection of the assumption of a homogeneous product (Sce-
438 nario 1.3, Fig. 3), we assumed an increasing timber contribution margin per
439 unit volume with higher tree diameters (cf. e.g. Bodelschwingh, 2018). Al-
440 though our results confirm the findings of Halbritter and Deegen (2015) that
441 a decreasing price growth increases the harvest intensity, the motivation for
442 this differs. In Halbritter and Deegen (2015), with age-dependent prices,
443 higher harvest intensities reduce the fixed capital. In addition, our model,
444 with dimension-dependent timber contribution margins, considered the ef-
445 fect that harvesting an additional tree can be interpreted as an investment
446 in an increased diameter growth of the influenced trees. Thus, especially for
447 younger ages, the opportunity costs of growing space increase and the har-
448 vest of more trees becomes rational. The additional volume growth (density
449 effect) is realized on fewer, higher dimensioned trees and thus increases the
450 trees’ value over-proportionally (see dimension effect in Koster, 2020, p. 57
451 f.). The opportunity costs of growing space are now determined by both the
452 value of the promoted trees’ additional volume and the value increment of
453 the volume which exists independently of the analyzed tree’s harvest.

454 Under the assumption of time preference, financial resources fixed in a
455 tree increasingly drive the harvest decision with increasing age (Fig. 3: right).
456 Consequently, with decreasing competitive pressure with age, single-tree har-
457 vest decisions in young forest stands should be driven by a tree's effects on
458 its neighbouring trees, whereas in old-growth stands, the alternative use of
459 financial resources becomes more important. The tipping point arising at
460 earlier ages for stronger capital scarcities underlines the importance of exter-
461 nal as well as internal investment alternatives (e.g. Möhring, 2014), such as
462 pre-commercial spacing or pruning, for single-tree harvest decisions.

463 *4.2. Economic Relevance of Individual Tree Characteristics Increases with* 464 *Increasing Heterogeneity*

465 Our results indicate that homogeneous groups of trees rarely differ in
466 their optimal harvest sequence independent of their vitality and quality lev-
467 els (Fig. 4). The reduction in stand density can be interpreted as systematic
468 tree selection. In contrast, in groups composed of interacting trees differing
469 in vitality and quality levels, harvest decisions strongly depend on individual
470 tree characteristics (Fig. 5). This is in line with today's practical silvicult-
471 tural guidelines in Central Europe (see a.o. BaySF, 2009), which put vitality,
472 stability, quality and spatial arrangement of promoted target trees and their
473 promotion by harvesting competitors in the focus of silvicultural decisions.
474 In line with the matrix approach by Roessiger et al. (2016), the initial har-
475 vests in our simulation, which are mainly driven by the opportunity costs
476 of growing space, consistently promote the most vital members of the tree
477 group. The growing space created by the harvest of co-dominant trees en-
478 ables a more efficient exploitation by dominant trees. In continuation of this

479 concept, one would expect the cohort of dominant high quality trees as tar-
480 get trees (final-harvest trees). Surprisingly, in our simulation, the optimal
481 target trees were 2 of low and 3 of high quality. Omitting the specification
482 of the target trees is thus a particular strength of our approach, which, in
483 contrast to e.g. Foppert (2020) and Härtl et al. (2010), allows us to study
484 a wide range of potentially unexpected but economical harvest sequences.
485 The reason for the heterogeneous composition of target trees can be found in
486 the changing importance of drivers of the harvest decision over age, i.e. the
487 increasing importance of the opportunity costs of capital. Liquidating the
488 comparably high amount of capital fixed in high quality trees becomes more
489 important than promoting their future growth. However, our findings could
490 clearly differ if the contribution margin for the high quality trees increased
491 more strongly at higher diameters (high valuable sawtimber; e.g. oak cf.
492 Bodelschwingh, 2018). In this case, the higher value increment of the high
493 quality trees would likely make maintaining them advantageous. The often
494 ambiguous results of analytical approaches for such complex questions (cf.
495 Coordes, 2014, p. 144) underline the importance of the further development
496 of simulation-based decision support models to inform practical management.

497 *4.3. Limitations*

498 In line with recent silvicultural management concepts, which increasingly
499 aim at a higher diversity (e.g. Puettmann et al., 2015), our results highlight
500 the relevance of individual tree characteristics. This justifies our choice of a
501 single-tree approach, which significantly increases the model complexity com-
502 pared to stand-level approaches, such as in Möhring (2010). As compared to
503 cohort models, such as Messerer et al. (2020), simulating single trees further

504 allowed us to incorporate not only interactions between several cohorts but
505 also within them. However, the resulting large computational problem (cf.
506 e.g. Foppert, 2020, in connection with Meilby and Nord-Larsen, 2012) was
507 reduced by some simplifying assumptions:

508 We did not consider spatially explicit competition such as, for example,
509 Meilby and Nord-Larsen (2012). Coupling our model with advanced forest
510 growth simulators such as TreeGrOSS (Hansen and Nagel, 2014; Nagel, 1996)
511 or SILVA (Kahn and Pretzsch, 1997) would allow us to study more detailed
512 competitive situations, e.g. clustered arrangements of trees with varying
513 distances between the trees. However, the general effects derived in our
514 model would probably only be amplified or diminished depending on the
515 trees' actual distances.

516 Simulating a group of even-aged trees strongly reduced the complexity,
517 as effects between cohorts of different age (cf. e.g. Messerer et al., 2020)
518 and assumptions on the influences of the canopy on the regeneration (cf.
519 e.g. Jacobsen et al., 2018) are omitted. While our calculation framework
520 would still be applicable when relaxing this assumption, the relevance of the
521 opportunity costs of growing space would increase. Not only the neighboring
522 trees of the same age, but also younger and future tree generations would be
523 influenced by every single-tree harvest decision.

524 In contrast to e.g. Härtl et al. (2010), the volume growth in our sim-
525 ulations responds immediately to a change in density due to tree harvests,
526 which likely overestimates the growth dynamics.

527 Allowing the model to harvest in subsequent years is unrealistic in practi-
528 cal forest management since even low fixed harvest costs considerably reduce

529 the harvest frequency (Coordes, 2014, p. 118 ff.; Koster, 2020, p. 69 ff.; Rämö
530 and Tahvonen, 2017). However, the possibility of high harvest frequencies,
531 i.e. lower harvest intensities, enabled a more continuous management of the
532 competitive structure in our discrete approach.

533 We abstained from the integration of risks such as, for example, Halbrit-
534 ter et al. (2020), Möllmann and Möhring (2017) or Staupendahl and Möhring
535 (2011) who integrated mortality risks in stand-level optimizations, or Messerer
536 et al. (2020), who integrated market risks in a cohort model. Assuming a
537 risk-neutral decision maker, the drivers of value increment and opportunity
538 costs of growing space, which depend on realizations in a now uncertain fu-
539 ture, would become expectation values (cf. Koster, 2020, Eq. 2-56). Due to
540 the simultaneous influence on both incremental benefits and costs, the effect
541 of risk implementation on harvest decisions is ambiguous.

542 5. Conclusions and Outlook

543 By revealing the relevance of the opportunity costs of growing space, our
544 results underline the impact of spatial as well as temporal tree interactions
545 on efficient harvest decisions. For each single-tree harvest decision, a for-
546 est manager is confronted with the challenge of assessing the tree's current
547 value, its future value development, and its impact on neighbouring trees.
548 This is particularly demanding when structural heterogeneity increases as
549 single-tree characteristics gain in importance. Our approach contributes to
550 the illustration of the underlying economic principles of harvest decisions
551 in a scarcity-driven environment at the operational single-tree level. In an
552 environment of increasing societal demands (e.g. carbon sequestration) on
553 limited forest resources (MEA, 2005) and accelerating climate change (IPCC,
554 2014), forest managers face an extended silvicultural trade-off between the
555 effects of an immediate tree use and future effects of postponing the harvest.
556 Here, our approach could assist forest managers if applied in marteloscopes
557 for training and decision support systems for daily forest management. We
558 expect such combinations of forest economic theory, focusing on the conse-
559 quences of scarcity, with silvicultural measures at the operational level to be
560 a fruitful field of further research.

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Figure and Table Captions

Fig. 1: Overview of the applied methods and their linkages. First, a bioeconomic simulation-optimization model selects the harvest ages of a group of single trees that maximize the land rent under different scenarios defined by silvicultural-economic conditions. For each scenario, the heuristic optimizer varies harvest ages and reruns the bioeconomic simulation in an iterative process. Afterwards, the derived optimum is analyzed quantitatively regarding the drivers of the harvest decisions. Parallelograms represent inputs and outputs of the simulation-optimization model, rectangles are model or analysis functions, and arrows indicate information flows.

Fig. 2: Basic functions of the bioeconomic single-tree simulation model. a: Reference gross volume yield and standing volume taken from Smaltschinski (2001) based on yield tables according to Wiedemann (1936/42, quoted in Schober, 1995). b: Relative volume increment according to Smaltschinski (2001) corresponding to yield table values from Wiedemann (1936/42, quoted in Schober, 1995); the two vitality levels refer to different site indices. c: Volume increment reduction function (actual volume increment relative to reference volume increment) according to Möhring (2010). d: Constant and dimension-dependent timber contribution margin based on the harvest costs and timber revenue functions of Bodelschwingh (2018); the two quality levels of the dimension-dependent timber contribution margin represent high (2) or low (3) quality.

Fig. 3: Incremental benefits and costs of letting the tree, which would otherwise be harvested next according to the optimization result, grow for an additional year. For comparison, both benefits and costs are expressed as positive values per tree. Whenever incremental benefits and costs converge, a tree is harvested. The panels (scenarios, see Tab. 1) demonstrate how the developments depend on the assumptions on capital scarcity (left vs. right) and the production goal (top vs. bottom).

Fig. 4: Incremental benefits and costs of letting the tree, which would otherwise be harvested next according to the optimization result, grow for an additional year. For comparison, both benefits and costs are expressed as positive values per tree. Whenever incremental benefits and costs converge, a tree is harvested. The panels (scenarios, see Tab. 1) demonstrate how the developments depend on tree quality (left vs. right) and vitality (top vs. bottom).

Fig. 5: Incremental benefits and costs of letting the tree, which would otherwise be harvested next according to the optimization result, grow for an additional year. The group of 20 heterogeneous trees splits into 4 cohorts (5 trees each, the different panels). Each cohort is defined by quality (low and high quality trees) and vitality (dominant for high and co-dominant for low vitality trees). Each bar indicates one tree at its optimal harvest age and the bar's colors provide the benefits and opportunity costs of the alternative decision to let this tree grow for another year. 5 dominant trees, 2 of low and 3 of high quality, are harvested at the end of the rotation (age 70), which is illustrated by

the vertical lines. The opportunity costs of growing space for letting these trees grow another year are the land rent of the next stand. Since these strongly exceed the opportunity costs of single thinning trees and our study mainly focuses on the latter, incremental benefits and costs are not shown here.

Tab. 1: Simulated scenarios defined by the assumptions on and parametrization of the silvicultural-economic conditions that influence the drivers of single-tree harvest decisions. The last column refers to the corresponding figure in the results.

Online supplement

Supplementary Methods to
*Opportunity Costs of Growing Space – an
Essential Driver of Economical Single-tree
Harvest Decisions*

A Model Flow Chart

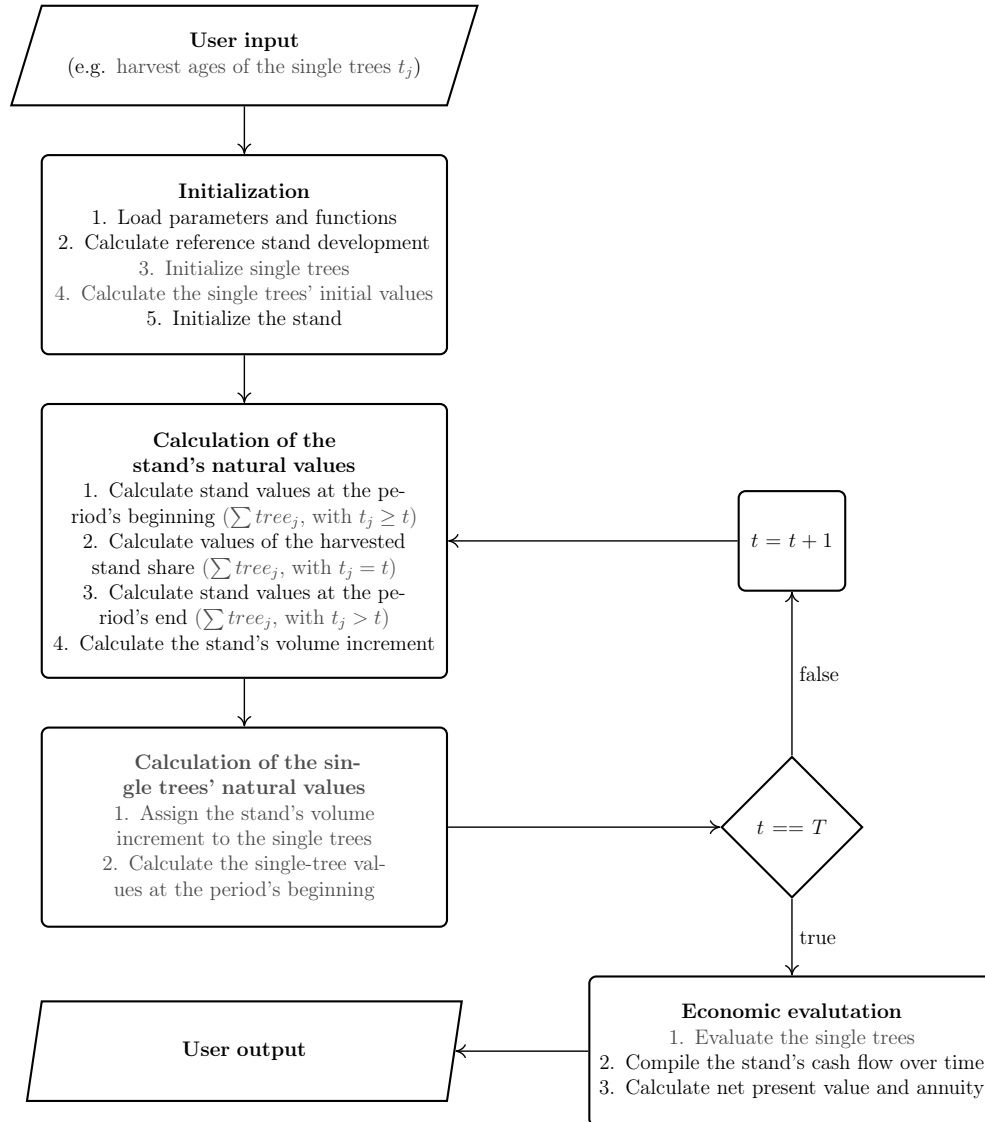


Figure 1: Model flow chart. Parallelograms: user interfaces, rectangles: simulation modules, rhombuses: tests, grey: single-tree level. t : age of the tree group, t_j : harvest age of tree j , T : rotation period.

B Details on the Growth Simulation

B.1 Derivation of the Single-Trees' Volume Increment

The interaction between the cohorts' trees is implemented in the calculation of the actual volume increment. This increment in solid volume $i_{S,c}(t)$ for a cohort c depends on the cohort-specific stand density $D_c(t)$ at time t . In order to derive the stand density, the total volume of all cohorts $S(t) = S_1(t) + S_2(t) + S_3(t) + S_4(t)$ is set in relation to the reference volume $S_{c,ref}(t)$ (main text, Fig. 2a) of the respective cohort c . This reference volume (main text, Fig. 2a) as well as the reference volume increment (main text, Fig. 2b) are downscaled to the growing area of the entire group of 20 trees. The cohort-specific stand density is calculated as:

$$D_c(t) = \frac{S(t)}{S_{c,ref}(t)}. \quad (1)$$

The actual increment in solid volume $i_{S,c}(t)$ of cohort c is then derived by multiplying its reference increment in solid volume $i_{S,c,ref}(t)$ (main text, Fig. 2b) by the density-dependent volume increment reduction function $f(D_c(t))$ (main text, Fig. 2c):

$$i_{S,c}(t) = i_{S,c,ref}(t) \cdot f(D_c(t)). \quad (2)$$

Thus, one more cubic meter of wood in the group of 20 trees has a different effect on dominant (high vitality) than on co-dominant (low vitality) trees, which implements their different potential to occupy additional growing space or to deal with limited resource availability.

B.2 Derivation of Diameters

For the dimension-dependent timber revenues and harvest costs, the trees' diameters were required. Since these diameters should be sensitive to the silvicultural management, rather than assuming a reference development we applied a form factor function according to Bergel (1987) to derive diameters based on the single-tree volume. Since the form factor function of Bergel (1987) is also diameter-dependent, we replaced it here by the diameter-height relationship according to Petterson (1955, quoted in Pretzsch, 2009); the parameters were determined using the yield tables (Wiedemann, 1936/42, quoted in Schober, 1995) under consideration of the adjustments according to Wollborn and Böckmann (1998).

C Details on the Heuristic Optimization

Since the number of possible harvest period variations for 20 trees in annual steps (age 20 to 100) is very high, we took a multi-stage approach to increase the probability of finding the global optimum. Therefore, we first derived the global optimum for 5 trees. Here, after a selection of variants (pruning), a complete enumeration was possible in an acceptable period of time for the homogeneous stand since this assumption reduces the combinatorial problem from a variation (ordered sample) with repetition to a combination (disordered sample). To accomplish the remaining and still computationally intensive enumeration, we used parallel computations applying the R-package `multidplyr` (Wickham et al., 2017) and ran it on a high-performance cluster. This enumeration result was used as the initial solution for a heuristic black-box optimization with 20 trees applying the NOMAD algorithm as implemented in the R-package `crs` (Racine et al., 2018). We first conducted a multi-start optimization with limited iterations and chose the best solution thereof as the initial solution for the last optimization with up to 10 000 iterations. For the heterogeneous stand, we had to reduce the first enumeration to 5 year steps, since the problem was much more complex. We then invested more repetitions in the following steps. This elaborate procedure should ensure that the identified optimum is at least close to the global optimum and was found to derive stable solutions when repeated.

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