

Article

The Value of Hybrid Aspen Coppice Investment under Different Discount Rate, Price and Management Scenarios: A Case Study of Estonia

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Abstract: Hybrid aspen is one of the most promising tree species for short-rotation forestry in Northern Europe. After the clearcutting of hybrid aspen plantation, the next generation arises from root and stump sprouts. The economic feasibility of different management strategies of hybrid aspen coppice stands has not yet been comprehensively evaluated in Northern Europe. We compared the land expectation values (LEVs) of hybrid aspen coppice stands managed according to four scenarios: three early thinning methods (corridor, cross-corridor and single-tree) followed by conventional management and intensive bioenergy production (repeated harvests in 5-year rotations) over a 25-year period in hemiboreal Estonia. We considered the historic price volatility of aspen wood assortments under various discount rates (1–20%). We found that the 25-year rotation with different early thinning methods was more profitable than short bioenergy cycles in the case of low discount rates (<5%). The LEV of short coppice cycles for only bioenergy production became more profitable in comparison with those by thinning methods, when higher discount rates (>10%) were applied. Hybrid aspen coppice stands can be managed profitably, but more risks are taken when the management strategy focuses only on bioenergy production.



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1. Introduction

The European Union has set a strategy to become climate-neutral by 2050, but at the same time maintaining the competitiveness of the economy [1]. Such an ambitious goal can be achieved under the sustainable bioeconomy development [2], where the usage of renewable energy sources must be significantly increased in comparison with the current level [3]. Forests and woody biomass play an important role in those strategies by substituting fossil fuels as well as absorbing the atmospheric CO₂ [4]. However, forests have several other functions (biodiversity, soil protection, recreation, etc.) that must not be reduced under future bioeconomies [4]. Therefore, the afforestation of new areas is recommended to ensure sustainable biomass supply and increase CO₂ sequestration [5,6]. In Nordic and Baltic countries, considerable effort to substitute fossil fuels with bioenergy has been made, and future projections foresee increasing usage of wood-based biofuels [7]. Besides the traditional forest-related biofuel resources (logging and timber processing residues and low-quality wood), short-rotation forests with deciduous trees are considered as a suitable option for this purpose in the region by the afforestation of abandoned agricultural lands [8].

Hybrid aspen (*Populus tremula* L. × *P. tremuloides* Michx.) has become one of the most planted tree species on former agricultural lands to practice short-rotation forestry in the Northern Europe region [9–11]. Moreover, hybrid aspen plantations can make a significant contribution to climate change mitigation by intensive CO₂ uptake [12,13] and the improvement of the biodiversity value in landscape [14,15]. Historically, hybrid aspen stands were established to produce timber for the match industry, while the current purpose is the combined production of pulp and energy wood and logs [16].

Recently, second-generation hybrid aspen coppice stands have received more attention because of the advantage of being more environmentally friendly compared to being intensively fertilised willow coppice systems [17]. For example, unfertilised short-rotation hybrid aspen coppice forests can be very productive in Northern Europe and provide mean annual increments of 6–12 t DM ha⁻¹ year⁻¹ during the early stages [10,18,19]. In addition to short-rotation coppice cycles (5-years) for bioenergy purposes, second-generation hybrid aspen offers management flexibility where longer-rotation cycles (25-years) can be applied for a combined production of logs, pulpwood and energy wood [9,16].

Such flexibility means that different management regimes can be chosen for hybrid aspen [18,20], where intensive early thinnings (more costly) can provide more valuable wood assortments after a longer period compared to low-value biomass production in short cycles. The early thinning in a dense hybrid aspen coppice stand can be applied as systematic corridor thinning [20] or single-tree selection [19,21]. Systematic corridor thinning (synonym: strip thinning; in a broader sense: geometric thinning) has been proposed as a cost-efficient method for young and dense stands to optimise early management cost [22,23] and provide additional biomass for energy [20,21]. Although single-tree selection in a dense forest stand has higher cost than corridor methods [24], it might offer more revenues in later harvest stages from greater volumes of valuable wood assortments [25]. Therefore, the selection of an optimal management plan for hybrid aspen coppice stand providing the maximum land expectation value (LEV) is a challenging task where various aspects such as the costs of management activities, wood price volatility and discount rate scenarios need to be considered.

The aim of tree plantations is to maximise wood production per land area and also profitability [26,27]. For example, it has been shown that tree plantations can offer higher rates of return than agricultural crops [26,28]. However, the financial feasibility of tree plantations could depend on multiple factors, especially when the aim is to produce only bioenergy [29]. In Northern Europe, the economic feasibility has been proven for birch stands managed with relatively short cycles (23–26-years) for biomass production when considering discount rates up to 5% [30]. At the same time, thinning does not always provide higher profitability over unmanaged birch stand [25]. Hybrid aspen has been shown to be profitable on former agricultural soils in the first-generation planted stands providing IRR of 4.4–7.3% and positive LEVs with 1–5% discount rates [16], but the profitability of coppicing followed by different thinning treatments has not been comprehensively evaluated. The investment to establish hybrid aspen plantation is higher than for traditional tree species (pine, spruce and birch) due to high cost of clonal planting materials [16]. Considering the volatility of wood prices and the length of rotation cycles [30,31], the LEVs under various forest thinning strategies, price fluctuations and variation in discount rates need to be clarified for hybrid aspen. As thinning of a dense hybrid aspen coppice stand can provide additional wood supply, the economic feasibility of such silvicultural practices needs to be evaluated before large-scale applications. For example, the realisation of timber from thinning as energy wood can be more profitable than as pulpwood in the region [32].

The aim of this study was to estimate and compare the LEVs resulting from different forest thinning strategies recommended for hybrid aspen coppice stands. For achieving the aim, longitudinal assortment price volatility and discount rate variation were also taken into account in the scenarios built.

2. Materials and Methods

2.1. Forest Management Strategies for Hybrid Aspen Coppice Stands

The present study was based on the second-rotation hybrid aspen thinning trial in South-Eastern Estonia ($58^{\circ}19'40''$ N, $26^{\circ}33'16''$ E). The aim of the experiment was to compare tree growth and stand yield dynamics after applying four different management scenarios in vegetatively resprouted hybrid aspen 2 years after clearcutting:

1. Energy wood coppicing with repeated 5-year cycles without thinning;
2. Corridor thinning (2 m wide corridors were cut systematically, leaving 1 m wide uncut strips of trees, where an initial density ($94,000 \text{ trees ha}^{-1}$) was reduced by about 67%);
3. Cross-corridor thinning (2 m wide corridors were cut systematically in two perpendicular directions systematically, leaving $1 \text{ m} \times 1 \text{ m}$ uncut patches, with an initial density reduction by about 89%);
4. single-tree thinning (selective cutting with an initial density reduction by about 97%).

Methods 2–4 are aimed to manage hybrid aspen by a longer rotation cycle (25-years) with multiple thinning operations to produce primarily aspen logs and pulpwood; meanwhile, method 1 aims to manage hybrid aspen with very short repeated coppice cycles (5-years) to produce only energy wood [18–20]. The more detailed description of the thinning trial and early growth results are presented by Hepner et al. [19].

2.2. Growths and Assortment Volumes in Case of Different Management Scenarios

For the “energy wood coppicing” management scenario, we calculated the above-ground biomass volume by multiplying the measured oven-dried biomasses [19] with an average density of hybrid aspen stems (wood + bark) of 0.35 t m^{-3} [33]. To obtain the chopped wood volume, we applied the default conversion coefficient of 2.78.

The growth data of the first-rotation hybrid aspen stands from the same site (Table 1) were used to model the further growth of the second-rotation hybrid aspen coppice stands that were aimed to be managed in longer cycles. First, the annual increments of the stand basal area and height were calculated by Equations (1) and (2), respectively:

$$Z_G = G_2 - G_1, \quad (1)$$

$$Z_H = H_2 - H_1, \quad (2)$$

where Z_G is the increment of the stand basal areal ($\text{m}^3 \text{ ha}^{-1} \text{ year}^{-1}$), Z_H is the average height increment (m year^{-1}), and subscript numbers 1 and 2 denote the given and the following years, respectively.

Table 1 shows the growth data of the first-rotation (planted) hybrid aspen stands.

To model the further growth of coppice stands, where different thinning regimes were applied, we relied on relationships of the stand basal area and the mean tree height with their increments (Figure 1). Hence, the regression analysis was used to fit the following models to the data [34]:

$$Z_G = e^{(a_0 + a_1 \cdot \ln G + a_2 \cdot (\ln G)^2 + a_3 \cdot (\ln G)^3)}, \quad (3)$$

$$Z_H = e^{(a_0 + a_1 \cdot \ln H + a_2 \cdot (\ln H)^2 + a_3 \cdot (\ln H)^3)}, \quad (4)$$

which were converted into the linear form:

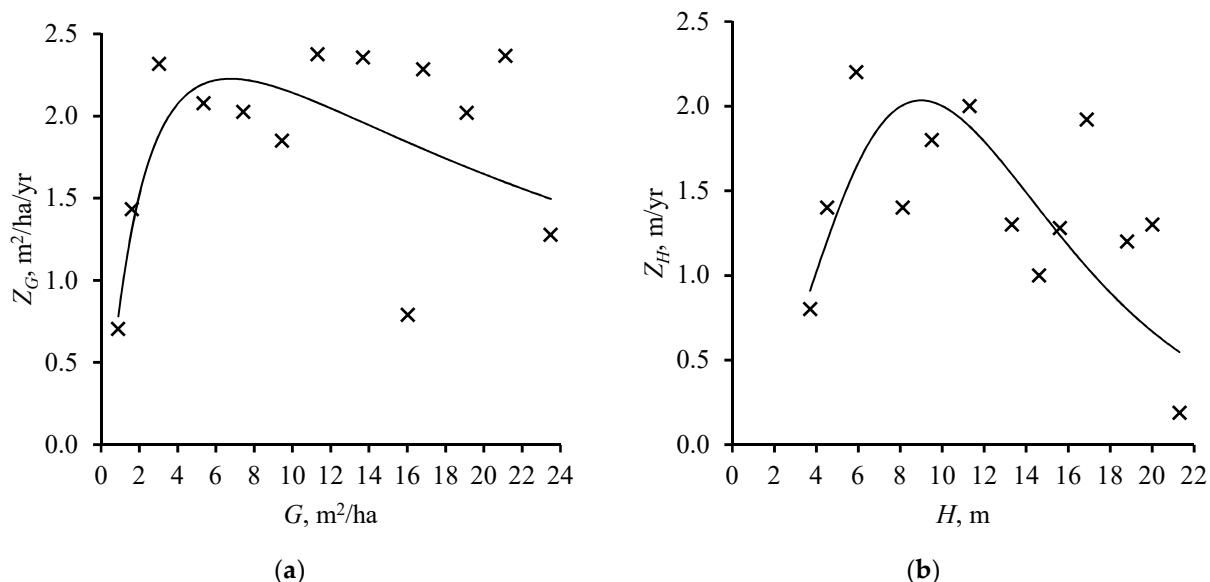
$$\ln Z_G = a_0 + a_1 \cdot \ln G + a_2 \cdot (\ln G)^2 + a_3 \cdot (\ln G)^3 + \varepsilon, \quad (5)$$

$$\ln Z_H = a_0 + a_1 \cdot \ln H + a_2 \cdot (\ln H)^2 + a_3 \cdot (\ln H)^3 + \varepsilon, \quad (6)$$

where Z_G is the annual increment of the stand basal area ($\text{m}^3 \text{ ha}^{-1} \text{ year}^{-1}$), Z_H is the average height increment (m year^{-1}), G is the stand basal area ($\text{m}^3 \text{ ha}^{-1}$), H is the average stand height (m), and a_0, a_1, a_2 and a_3 are regression coefficients (Table 2).

Table 1. First-rotation (planted) hybrid aspen stand growth data.

Age (year)	Stand Basal Area (m^2/ha)	Stand Basal Area Increment ($\text{m}^2 \text{ ha}^{-1} \text{ year}^{-1}$)	Average Height (m)	Average Height Increment (m year^{-1})
5	0.90	0.70	3.7	0.8
6	1.61	1.43	4.5	1.4
7	3.04	2.32	5.9	2.2
8	5.36	2.08	8.1	1.4
9	7.44	2.02	9.5	1.8
10	9.46	1.85	11.3	2.0
11	11.31	2.37	13.3	1.3
12	13.68	2.36	14.6	1.0
13	16.04	0.79	15.6	1.3
14	16.83	2.28	16.9	1.9
15	19.11	2.02	18.8	1.2
16	21.13	2.37	20.0	1.3
17	23.50	1.28	21.3	0.2
18	24.77		21.5	

**Figure 1.** Regression curves between the increment of stand basal area (Z_G) and the stand basal area (G) (a) and between the average height increment (Z_H) and the height (H) (b). The parameter estimates of the regression models are presented in Table 2.**Table 2.** Parameter estimates for Equations (3)–(6).

Growth characteristic	Equation No.	Parameter	Parameter Estimate
Z_G	3 & 5	a_0	-0.1402
		a_1	0.9836
		a_2	-0.2571
		a_3	0
		R^2	0.459
		p -value	0.046
Z_H	4 & 6	a_0	-1.5369
		a_1	0
		a_2	1.3982
		a_3	-0.4245
		R^2	0.462
		p -value	0.045

Based on the relationship between growth trait and its increment, the yielded curves for hybrid aspen coppice stands with any given density can be predicted. As the input data, the initial stand density (N , trees ha^{-1}), the initial stand basal area and the average height measured after 5-years since the stand establishment [19] were used to model the further development for subsequent years by using Equations (3) and (4). The quadratic mean stem diameter at breast height (D) was estimated for each year according to Equation (7):

$$D = \sqrt{\frac{40000 \cdot G}{\pi \cdot N}}. \quad (7)$$

Thinning decreases N , and as a consequence, G changes as well. In the case of thinning, the following equation was used:

$$G_2 = \frac{N_2}{N_1} \cdot (G_1 + Z_G), \quad (8)$$

where G_2 is the stand basal area in the post-thinning year ($\text{m}^2 \text{ ha}^{-1}$), N_2 is the number of trees in the post-thinning year (trees ha^{-1}), N_1 is the number of trees in the given year prior to thinning (trees ha^{-1}), G_1 is the stand basal area in the given year prior to thinning ($\text{m}^2 \text{ ha}^{-1}$), and Z_G is the increment of the stand basal area ($\text{m}^2 \text{ ha}^{-1} \text{ year}^{-1}$).

To calculate the stand stem volume, the officially acknowledged equations from the Forest Management Guidelines [35] were applied. The distribution of stem volume into wood assortments was estimated based on the following steps:

1. Trees were assigned stem diameter classes [36];
2. Height was estimated for each diameter class [36];
3. Based on the obtained diameters, heights and tree numbers, the volumes of different assortments were estimated using the Ozolinš' stem taper curve [37,38]. The algorithm (Equations (9) and (10)) for calculating assortments based on the Ozolinš' stem taper curve was published by Padari [39];
4. As the stem taper equation considers stem diameters over bark, necessary corrections were applied to obtain stem diameters and volumes under bark [36];
5. The wood assortments from all diameter classes were summed up to obtain their volumes at the stand level ($\text{m}^3 \text{ ha}^{-1}$).

Equations (9) and (10) were written as:

$$\gamma(x) = 1 + (x^2 - 0.01) \cdot (p \cdot (h - h_0) + q \cdot (d_{1,3} - d_0)), \quad (9)$$

$$d_l = d_{1,3} \cdot \frac{\gamma\left(\frac{l}{h}\right) \cdot \left(a_0 + a_1 \cdot \left(\frac{l}{h}\right) + a_2 \cdot \left(\frac{l}{h}\right)^2 + a_3 \cdot \left(\frac{l}{h}\right)^3 + a_4 \cdot \left(\frac{l}{h}\right)^4 + a_5 \cdot \left(\frac{l}{h}\right)^5 + a_6 \cdot \left(\frac{l}{h}\right)^6\right)}{\gamma\left(\frac{1.3}{h}\right) \cdot \left(a_0 + a_1 \cdot \left(\frac{1.3}{h}\right) + a_2 \cdot \left(\frac{1.3}{h}\right)^2 + a_3 \cdot \left(\frac{1.3}{h}\right)^3 + a_4 \cdot \left(\frac{1.3}{h}\right)^4 + a_5 \cdot \left(\frac{1.3}{h}\right)^5 + a_6 \cdot \left(\frac{1.3}{h}\right)^6\right)}, \quad (10)$$

where $\gamma(x)$ is the perturbation coefficient ($x = \frac{l}{h}$ or $\frac{1.3}{h}$); p (0.0074 for aspen), h_0 (18), q (0.0002) and d_0 (20) are parameters of the perturbation coefficient's equation (Equation (9)); d_l is the stem diameter (cm) at distance l from the root collar; $d_{1,3}$ is the stem diameter at the breast height (cm), l is the distance from the root collar (m), h is the tree height (m); the coefficients of the aspen stem taper curve (Equation (10)) are as following: $a_0 = 120.224$, $a_1 = -310.985$, $a_2 = 1450.125$, $a_3 = -4238.703$, $a_4 = 6644.01$, $a_5 = -5408.312$, and $a_6 = 1743.64$ [37,38].

2.3. Costs

Operating costs (Table 3) related to energy wood processing, precommercial and commercial thinning and clearcutting are based on the data from the Estonian State Forest Management Centre (personal communication) and correspond to the average prices in Estonia. The operator's working times (h ha^{-1}) of different early thinning treatments were based on real-time estimation (time expenditure was measured per 0.12 ha sample

plot for each thinning treatment) carried out during the establishment of the thinning treatments [19].

Table 3. Operating costs related to different management scenarios.

Treatments/Operations and Items	Cost
Energy wood coppicing with 5-year cycles (method 1)	
Energy wood harvest	15.70 EUR m ⁻³
Chopping	7.10 EUR m ⁻³
Transportation of chopped wood	8.40 EUR m ⁻³
Establishment of the early (precommercial) thinning treatments (methods 2–4)	
Operator's gross salary	12.10 EUR h ⁻¹
Holiday pay reserve	8.00 %
Employer's taxes	33.80 %
Establishment of the corridor treatment after the 2nd year (method 2)	
Working time	30.80 h ha ⁻¹
Total cost for the operator's employer	528.46 EUR ha ⁻¹
Fuel and depreciation of the equipment	70.00 EUR ha ⁻¹
Total cost	598.46 EUR ha ⁻¹
Establishment of the crosscorridor treatment after the 2nd year (method 3)	
Working time	45.80 h ha ⁻¹
Total cost for the operator's employer	785.83 EUR ha ⁻¹
Fuel and depreciation of the equipment	100.00 EUR ha ⁻¹
Total cost	885.83 EUR ha ⁻¹
Establishment of the single-tree treatment after the 2nd year (method 4)	
Working time	56.30 hours ha ⁻¹
Total cost for the operator's employer	965.98 EUR ha ⁻¹
Fuel and depreciation of the equipment	130.00 EUR ha ⁻¹
Total cost	1095.98 EUR ha ⁻¹
Commercial thinning and clearcutting at the age of 25-years (methods 2–4)	
Thinning	21.60 EUR m ⁻³
Clearcutting	12.00 EUR m ⁻³

2.4. Revenues

For calculating the revenues, the time series of monthly roadside prices (EXW) of aspen logs, aspen pulpwood and fuelwood from the State Forest Management Centre were used. In the case of harvest residues (tops and branches), the price from the warehouse (DAT) was used. All the prices were without the value-added tax.

Based on the historic monthly price data from January 2012 to December 2020 (Figure 2), we considered different price scenarios as input (Table 4). That is, five scenarios were created based on the assumption that future price reflects:

- The first quartile of the historic price;
- The second quartile (i.e., median) of the historic price;
- The third quartile of the historic price;
- The minimum historic price;
- The maximum historic price.

These scenarios were treated identically for the prices of assortments, e.g., in case of “a”, and the first quartile historic price for all four assortments was considered. The latter is a feasible option, as there is a high significant correlation between the assortment prices. The price scenarios “d” and “e” reflect extreme situations, while “a”, “b” and “c” are more likely to reflect actual future situations. When considering historic prices, then it is evident that the prices of different assortments followed a pattern subject to certain demand and supply contexts. Thus, when forecasting future revenues, it is not rational to use a constant growth rate, e.g., based on the consumer price index (CPI), which would lead to an unfounded expectation of sustained price growth. Because of the latter reason,

future costs were also not adjusted with the CPI, e.g., when wood prices were low because of dropped demand, there was no pressure for the increase of salaries in the specific sector. The latter scenarios led to the following prices of assortments in further analysis.

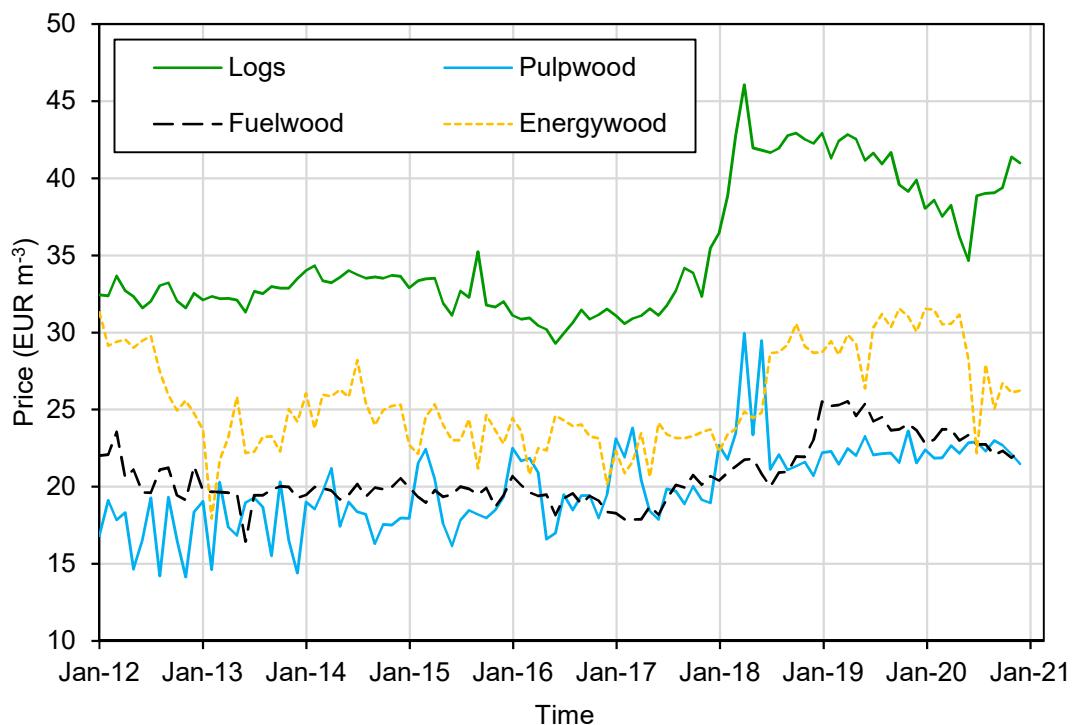


Figure 2. Price dynamics of aspen wood assortments in Estonia (from January 2012 to December 2020), which was used as an input for different price scenarios analysed in this study (Table 4).

Table 4. Prices of assortments for different price scenarios applied in this study (EUR m⁻³).

Assortment/Price	1st Quartile	2nd Quartile	3rd Quartile	Minimum	Maximum
Aspen logs	32.02	33.42	38.91	29.29	46.07
Aspen pulpwood	18.15	19.59	22.04	14.14	29.95
Fuelwood	19.46	20.00	21.97	16.44	25.54
Energy wood	23.27	24.84	28.67	17.94	31.56

2.5. LEV

We applied in this study a standard method to calculate the return of investment, namely the LEV (also phrased as a bare land value in the relevant literature [40]). This method calculates the net present value based on cash inflows and outflows over the expected 25-year management cycle for hybrid aspen in the region [11,12,16] as follows (Equation (11)):

$$LEV = \frac{\text{Cash inflow}_1 - \text{Cash outflow}_1}{(1 + \text{discount rate})^1} + \dots + \frac{\text{Cash inflow}_{25} - \text{Cash outflow}_{25}}{(1 + \text{discount rate})^{25}}. \quad (11)$$

We applied Equation (11) by combining forest thinning, price and discount ratio options, thus resulting in $4 \times 5 \times 4 = 80$ different scenarios. While the thinning and price scenarios were explained in Sections 2.1 and 2.4, in case of the discount rate, we applied four different options. That is, we provided results in case of 1%, 5%, 10% or 20% as the required rate of return by the investor. These discount rates provided a suitable range accounting for low (1%), average (5%) and high (10% and 20%) rates of return required.

3. Results

3.1. Production of Wood Assortments under Different Management Scenarios

The yield of energy wood coppicing scenario was 89.7 m^3 at the end of each 5-year cycle (Figure 3a), which corresponded to 249 m^3 of chopped wood. Based on the model predictions, the further management following early corridor (Figure 3b) and cross-corridor (Figure 3c) thinning will include two commercial thinning operations during the 25-year rotation period, whereas a slight precommercial thinning would be needed in the corridor thinning scenario. According to both scenarios, the first commercial thinning provided mainly energy wood, and the second one offered also more valuable assortments (logs and pulpwood). The first commercial thinning would be needed a few years earlier in the cross-corridor scenario than in the corridor scenario. At final felling, these two scenarios provided relatively similar volumes of assortments. The single-tree thinning scenario (Figure 3d) included only one commercial thinning and provided notably greater volumes of assortments from final felling.

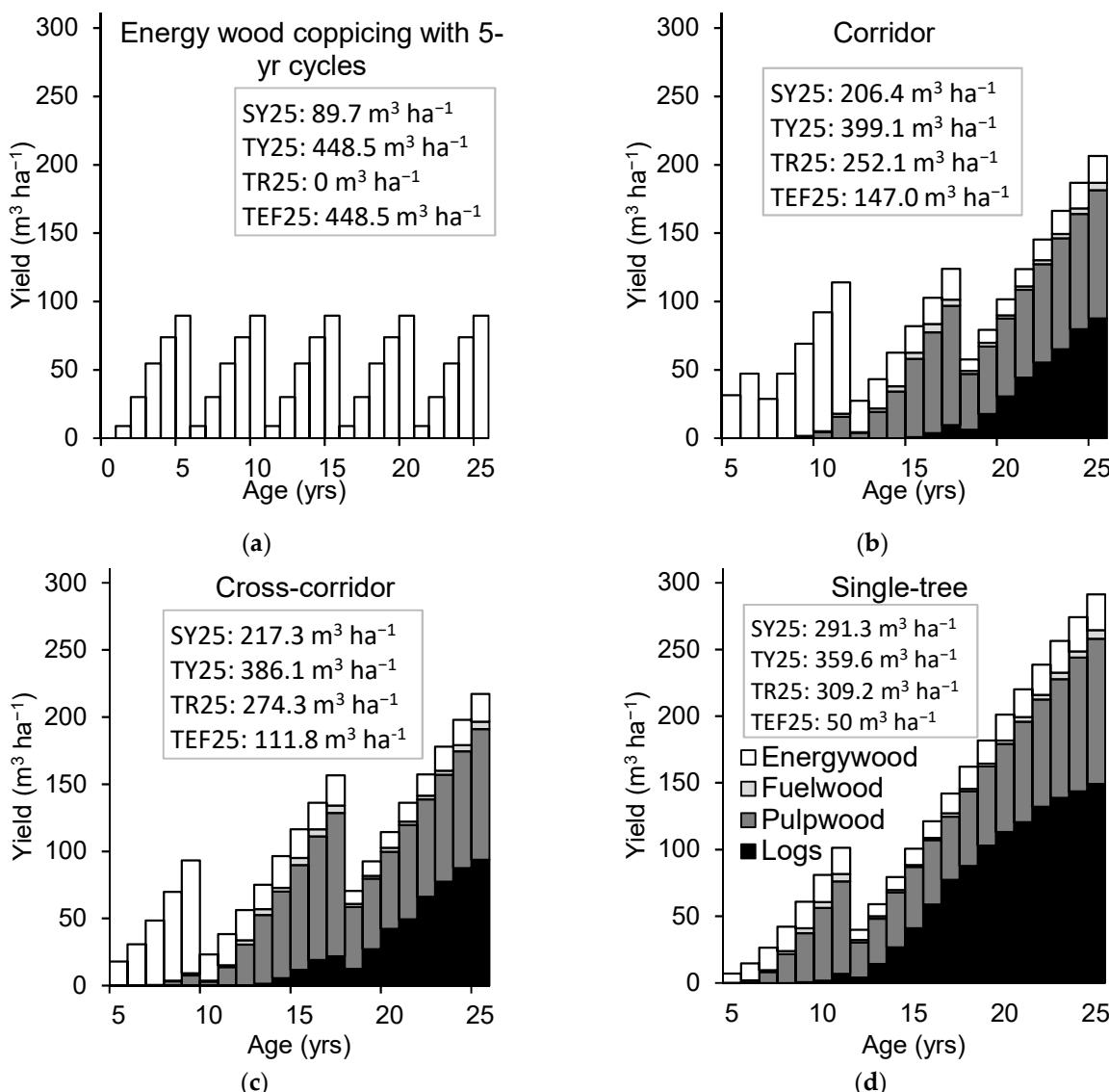


Figure 3. The predicted yields of merchantable wood assortments according to the four compared management scenarios: (a) energy-wood coppicing; (b) corridor thinning; (c) cross-corridor thinning; (d) single-tree thinning. The standing volumes (SY25) and the total yields (TY25) at the age of 25-years as well as the total yields of roundwood (TR25) and the total combined yields of energy and fuelwood (TEF25) during 25-years are shown in text boxes.

3.2. LEVs for Different Scenarios

Based on the results from the LEV scenarios subject to varying forest thinning, wood price and discount rate options, several generalisations can be made (Table 5). With the growth in the expected rate of return, the LEVs decrease, and with a (very) high expected rate of return (e.g., 20%), an investment in growing aspen is likely to be unprofitable. For instance, in the case of a 20% discount rate, only the “energy-wood coppicing” strategy is likely to create positive values for an investor. Up to the average discount rate, an investor is likely to yield positive gains from the project with all thinning strategies, unless the future price dynamics are very unfavourable.

Table 5. Land expectation values (EUR ha⁻¹) from scenarios (subject to different forest thinning, price and discount rate options).

1% discount rate					
Forest thinning/price	1st quartile	2nd quartile	3rd quartile	Minimum	Maximum
1. Energy wood coppicing	181	789	2270	-1880	3388
2. Corridor thinning	2192	2674	3872	807	5793
3. Cross-corridor thinning	2032	2490	3643	760	5605
4. Single-tree thinning	2425	2832	3947	1389	5937
5% discount rate					
Forest thinning/price	1st quartile	2nd quartile	3rd quartile	Minimum	Maximum
1. Energy wood coppicing	107	466	1341	-1111	2002
2. Corridor thinning	670	916	1516	-60	2413
3. Cross-corridor thinning	481	704	1257	-160	2150
4. Single-tree thinning	370	548	1019	-91	1884
10% discount rate					
Forest thinning/price	1st quartile	2nd quartile	3rd quartile	Minimum	Maximum
1. Energy wood coppicing	62	272	782	-647	1167
2. Corridor thinning	16	137	428	-357	820
3. Cross-corridor thinning	-164	-60	192	-474	566
4. Single-tree thinning	-415	-343	-163	-606	184
20% discount rate					
Forest thinning/price	1st quartile	2nd quartile	3rd quartile	Minimum	Maximum
1. Energy wood coppicing	28	122	350	-289	522
2. Corridor thinning	-238	-197	-100	-371	8
3. Cross-corridor thinning	-382	-351	-276	-483	-182
4. Single-tree thinning	-590	-572	-533	-638	-451

In the circumstances of very low expected rates of return, the “single-tree thinning” strategy is likely to create largest gains for investors, as very low rates of return do not significantly affect cash flows occurring in the further future. Still, it must be noted that the difference between the gains of the “single-tree thinning” strategy and those of “corridor thinning” and “cross-corridor thinning” strategies are not substantial at low rates of return levels.

With a growth in the expected rate of return, the “single-tree thinning” strategy is clearly outrun by “corridor thinning” and “cross-corridor thinning” strategies by means of

investor gains. The results indicated that an investor aiming at an average expected rate of return (5%) should choose either of those two. When comparing the latter two strategies, the “corridor thinning” should be considered better than the “cross-corridor thinning” strategy by means of investor gains, although the differences are not large.

With a high expected rate of return, the “energy-wood coppicing” strategy could be the best option for an investor. That is, the latter strategy is clearly the only one providing positive gains for an investor in case of non-extreme price developments (LEVs with a 20% discount rate in Table 5).

4. Discussion

We analysed the profitability of a novel forest management system (resprouted hybrid aspen coppice stands) and novel thinning treatments (two different types of systematic corridor harvests) in comparison with intensive coppicing cycles (5-years) and conventional single-tree thinning in Northern Europe [20,23] under various discount rates (1–20%) over the expected rotation cycle of 25-years. The early thinning can be considered as an alternative investment strategy for managing the future hybrid aspen stands. Although the early thinning (at year 2) does not provide immediate profit, it offers a substantial competition release for the remaining trees [21]. The cost of systematical thinning (e.g., the corridor method) could be almost twice less than with the single-tree method at year 2. The management strategy of repeated 5-year coppice cycles does not involve any intermediate costs but provides only energy wood as the final product.

We found that second-generation (resprouted) hybrid aspen stands can be a profitable investment under various management strategies, similarly to the planted first-generation stands of hybrid aspen [16] and other *Populus* spp. plantations [41]. The results indicated that when investors consider their expected rate of return and likely price dynamics at the market, the forest thinning strategies suitable for them can substantially vary. While the expected rate of return as an endogenous factor affecting the LEV is known for an investor, although it can vary in time (especially over such a lengthy period of 25-years), then the exogenous factor of price dynamics cannot be altered by an investor. Still, as Table 5 indicates, the prices fluctuate in a very large range (especially when considering the difference between the 1st and 3rd quartiles), and thus, it is, to a certain extent, possible to schedule cutting activities to consider more favourable price conditions at the market.

In the case of the low discount rate (1%), the single-tree thinning scenario should be favoured for aspen stand management, as it ensures very high LEVs even though it is the most expensive early thinning treatment. In the considered scenarios, single-tree thinning provided the highest share of aspen logs among the assortments at the end of the 25-year rotation. The results showed that risks are well mitigated with the single-tree method, similarly to the first-generation (planted) hybrid aspen plantations [16], because even at the period of low wood prices a high LEV is still obtained. With the 2nd quartile prices, the highest LEV is also provided by the single-tree method, although the difference of the LEVs from the corridor and cross-corridor methods is smaller. Compared to the single-tree method, the main difference in LEV is related to different proportions of logs and energy wood. When energy wood production is also aimed, then corridor methods should be chosen, whereas corridor method should be preferred over the cross-corridor method. In the case of the low discount rate, energy wood coppicing in repeated 5-year cycles turned out to be an undesirable investment. A similar tendency was observed with natural birch stands in Sweden, where unmanaged stands (large proportion of biofuel) provided lower LEVs than thinned stands with a discount rate of 1% [25]. Although with the highest possible prices, energy wood coppicing also offered high LEVs, the minimum prices resulted in negative LEVs and with the 2nd quartile prices the LEVs were notably lower compared to in other management scenarios. With the single-tree method, the main revenues will be obtained once at the end of the 25-year rotation. In the case of low wood prices, clearcutting can be postponed 1–2 years to ensure higher profit. With repeated 5-year energy wood coppices, delaying with harvest to wait for better market

situations would be more complicated. This also suggests that the aim to apply the energy wood-oriented management system is not a rational option in the case of the low discount rate (1%). However, potential subsidies for bioenergy production that are applicable in willow plantations (5-year cycles) in Estonia and other countries might reduce the risks [29], but at present, such subsidies are not applicable for hybrid aspen.

In the case of the discount rate of 5%, the corridor method should be preferred, as it creates the best outcomes with all price scenarios. The cross-corridor method offers close but always slightly inferior outcomes. Single-tree selection as well as energy wood coppicing is clearly inferior to the corridor methods. Energy wood production is profitable in resprouted birch stands in Finland with discount rates up to 5% [30], but we found that thinnings provide higher profitability with such discount rates (<5%). The success of the corridor and cross-corridor methods lies in a more balanced distribution of assortments. Compared to repeated 5-year energy wood coppices, the two corridor methods provide higher LEVs because of more valuable assortments (logs and pulpwood). Compared to the single-tree selection, the corridor methods involve one more commercial thinning and hence greater total wood production.

Contrary to the lower discount rates (1% and 5%), in the case of the 10% discount rate, the repeated 5-year energy wood coppicing becomes the most favourable management scenario. It provided the highest LEV with the 1st, 2nd and 3rd quartile of prices as well as with the maximum prices. Energy wood price can be very volatile [31], although the LEV is negative with the minimum prices. It must be noted that in the historic prices, such a period was very short-term in our case and already 3 months later the prices exceeded the 2nd quartile price level. The profitability of energy wood harvest is mainly controlled by harvest costs and biomass production [30,42,43]. For example, the technological developments for harvesting small-dimension trees (energy wood coppicing in our study) can improve the efficiency of harvest operations and therefore the final profit [44]. The breakeven point for short-rotation coppice is usually dry tons of >6 per ha [43,44], which was observed also in our study [19]. The second best LEV was provided by the corridor method, where commercial cuttings (three thinnings and final felling) were planned in 5–8-year intervals but the total yield during 25-years remained lower than that accumulated from repeated 5-year cycles. The single-tree selection method provided negative LEVs with all three price quartiles. The single-tree method involves only one intermediate cutting, and most of the revenues come from final felling, which in the case of high discount rates much of its net present value is lost and results in negative LEVs. A study in Sweden found that unmanaged forests become an economically viable strategy in comparison with thinned stands in natural birch forests with discount rates over 2% [25].

In the case of very high discount rates (20%), the only economically feasible option was the repeated 5-year energy wood coppicing. Hence, the higher the discount rate, the more advantageous energy wood coppicing becomes in very short rotations. All the other management scenarios (with longer rotations) provided negative LEVs, no matter which price scenario was considered. The price of energy wood can have a great impact on the final LEV value in unmanaged deciduous stands [25], but in our case, the price of energy wood remain consistent over the observed period.

The wood market in Estonia runs on the principles of open market economy. There are no restrictions for the import and export of roundwood, energy wood and wood products. Although we considered historic wood price fluctuations, this might not exactly reflect the reality in the future. For instance, the change of availability and public policies towards fossil and renewable energy sources can foster price increase or reduction. The operating costs were considered stable as no growth rate was applied for assortment prices as well, while the latter two can witness somewhat different growth rates. Products with low added values (e.g., energy wood) are more sensitive to operating costs. However, the expected increase in the prices of carbon emission and electricity will likely even out the potential impact of rising operating costs on energy wood production. Among the compared scenarios, the cross-corridor method involves the highest operating costs and is

therefore most sensitive to their change. While these limitations will probably not affect the ranking of choices for an investor, some cases with borderline profitability could turn marginally unprofitable or vice versa. It must be also noted that the current study relied on the modelled yield of wood assortments from the final harvest of the second 25-year rotation period, which needs to be checked by empirical estimations in the future.

The bioeconomy targets set by the European Union [1–4] aim to mitigate climate change through the substitution of fossil-based sources with renewables (incl. wood) such as carbon storage in products with a longer lifetime as well as a higher share of renewable energy. Therefore, the corridor method with the highest combined yield of energy wood and roundwood assortments (Figure 3a) would be the most suitable option to satisfy both of the mentioned goals. One may argue that the mechanised (less expensive) corridor method would result in even better economic outcome. For large landowners, mechanised strip felling can be relatively cost-effective [23], but for small land owners, manual thinning, which was applied in our study, is a more convenient option.

5. Conclusions

We presented the first economic evaluation of different management scenarios recommended for the second-rotation hybrid aspen coppice stands in Northern Europe. The results indicated that the choice of the most suitable management scenario depends on investors' expectations. Generally, the longer the rotation period is, the lower the economic expectation from managing a resprouted hybrid aspen stand must be. High economic profit can be expected only with a very short rotation period, which among the compared aspen stand management scenarios energy wood coppicing in 5-year rotations was repeated. When moderate or smaller profit is acceptable, then a longer rotation period of 25-years represents a relatively safe choice as a management strategy for resprouted hybrid aspen stands. The corridor method for early thinning is economically superior over the cross-corridor method with all of the price and discount rate scenarios. The corridor method is also less sensitive to possible future fluctuations in operating costs and encompasses the best options for climate change mitigation. The single-tree method is more profitable than the two corridor methods only in the case of very low discount rates. To summarise, second-generation (resprouted) hybrid aspen stand can be a profitable investment under various management strategies.

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