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Comparison of the economic return of conventional and novel silver birch management strategies

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ABSTRACT
Forests provide many essential ecosystem services. In Sweden, roundwood assortments and residual biomass are vital feedstock sources. Swedish forestry is slowly replacing conifer monocultures with mixed conifer-broadleaf forests to enhance climate resilience. This study evaluates the economic returns of managing mixed forest stands comprising 0.25 ha patches of individual species compared to larger Norway spruce and silver birch monocultures. Specifically, we investigate (1) harvesting silver birch as energy biomass in the first thinning and timber in the final felling and (2) determining thinning timing based on stand basal area versus species-specific criteria. We used the Heureka forest growth and development modelling software to simulate various stand types and management strategies based on experimental forest data. Group-mixed stands were simulated by integrating separate species' monoculture data. Results indicate that incorporating energy thinning into birch-spruce mixed stands can generate positive net revenues, supporting the economic viability of biomass harvesting. Strengthening birch biomass and timber markets, optimising thinning logistics, and refining harvesting methods will promote sustainable birch management. Expanding these strategies could significantly enhance the economic and ecological resilience of mixed and broadleaf-dominated forests in Sweden.

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Silver birch timber; mixed stand management; bioenergy; biomass; Norway spruce

Introduction

Increasing the use of broadleaf and broadleaf-mixed forests in Sweden is frequently discussed as a means to enhance biodiversity, climate resilience, pest resistance, and recreational value (Felton et al. 2010, 2016, 2021; Gao et al. 2014; Lindbladh et al. 2014; Holmström et al. 2021; Huuskonen et al. 2021). Silver birch (*Betula pendula* Roth) and downy birch (*Betula pubescens* Ehrh.) are Sweden's most common broadleaf species by volume (Skogsdata 2023) and they often grow naturally in mixtures with conifers (Lundqvist et al. 2014; Holmström et al. 2016; Lidman et al. 2021). These frequently occur in what are known as "group mixtures" (Holmström et al. 2021), where broadleaf patches at least 25 m wide can provide suitable habitat for bird species and promote a rich understory (French et al. 1986; Hedwall et al. 2019; Felton et al. 2021, 2022). This patch-based spatial arrangement may thus be an effective strategy to increase broadleaf canopy cover, thereby achieving associated ecological benefits. Admixture with birch can increase spruce survival against storms and bark beetle attacks (Griess et al. 2012).

Silver birch and Norway spruce (*Picea abies* (L.) Karst.) share similar site requirements but differ markedly in their light requirements and growth patterns (Hynynen et al. 2010). Silver birch, a fast-growing and shade-intolerant pioneer species, reaches its peak height growth within 10–20 years of planting (Hein et al. 2009; Hynynen et al. 2010; Dubois et al. 2020; Huuskonen et al. 2023). In contrast, Norway spruce, a late-successional and shade-tolerant species, grows slowly during its early stages, up to around 20 years of age (Huuskonen et al. 2023). These attributes make silver birch (hereafter referred to as "birch") and Norway spruce (hereafter "spruce") compatible in a mixed forest. However, achieving the full benefits of such mixtures requires active management, particularly pre-commercial and commercial thinnings, to maintain stand structure and produce high-quality wood products (Hynynen et al. 2010; Fahlvik et al. 2011; Fahlvik et al. 2015; Lidman et al. 2021; Ara et al. 2022; Huuskonen et al. 2023).

Although naturally regenerated birch is common (Götmark et al. 2005; Holmström et al. 2016), using improved birch planting material can increase growth

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and yield without compromising wood quality (Dunham et al. 1999; Luostarinen and Verkasalo 2000; Liziniewicz et al. 2022). With appropriate management, such birch stands can produce high-quality timber in as little as 30–50 years (Hynynen et al. 2010; Dubois et al. 2020; Liziniewicz et al. 2022). This timber can be processed into high-value products, including wood veneer and non-wood products such as sap, bark extracts, and lignin-derived biochemicals (Verkasalo et al. 2017; Dubois et al. 2020). As a result, group mixtures of spruce and fast-growing birch patches could sustainably help meet the demand for wood, non-wood products, and lignocellulosic biomass for renewable energy and materials. Despite these diverse opportunities, timber production remains a central objective of well-managed forests. However, Sweden's birch timber market is currently small. To fully understand the potential of birch timber as a primary product in birch-mixed or birch-dominated stands, it is essential to carefully evaluate its economic outcomes.

Realizing this potential requires precision in the timing and type of thinning operations. Species within mixed stands respond differently to thinning. Birch, for example, is highly sensitive to early thinning, which influences its growth trajectory and timber quality (Hynynen et al. 2010). Precision thinning, where species-specific guidelines are applied to different patches (e.g. thinning by basal area for spruce and by stem density for birch), could help optimise the growth of both species (Hägglund 1972; Hynynen et al. 2010; Persson et al. 2022). Birch grows faster than spruce in the early stages, often overtopping spruce even when both are planted at the same time. This can happen before spruce reaches the height and basal area needed for thinning. As a result, optimal management requires thinning birch earlier, ideally before it exceeds 15 meters in height (Hynynen et al. 2010). In this study, we introduced a time-sensitive precision approach by managing group-mixed stands through species-specific thinning within their respective patches, based on individual species' needs over time. We refer to this approach as "time-sensitive patch thinning".

In parallel, the demand for forest-based biomass as a renewable energy source is expected to continue rising (Börjesson et al. 2017; Swedish Energy Agency 2023). Although logging residues, such as branches and tops, are already a common source of bioenergy whose use may expand further, their supply potential alone is insufficient to meet future needs (Börjesson et al. 2017; IRENA 2019; Camia et al. 2021). Early thinnings, which typically yield stems too small for pulpwood or timber, could offer an additional biomass source (Fernandez-Lacruz et al. 2015; Eggers et al. 2020). In Fennoscandia, pulpwood procurement from the first thinning is often unprofitable due to small stem sizes, low harvested volumes per hectare, and high handling costs (Hakkila 2005; Heikkilä et al. 2009). Consequently, thinning-to-waste is often the default option, despite young forests in Sweden having the potential to supply about 21 TWh of bioenergy annually (Fernandez-Lacruz et al. 2015). Under such conditions, directing these small-diameter stems to energy biomass production can be economically viable if the biomass-to-pulpwood price and volume ratios are favourable (Heikkilä et al. 2007; Di Fulvio et al. 2011). In young birch stands, for example, the volume available as energy biomass can be up to 3.5 times greater than that of pulpwood (Di Fulvio et al. 2011). Ensuring this energy biomass production meets sustainability standards, such as sourcing from well-managed forests and not diverting roundwood-quality material, is essential (IPCC 2000, 2012, 2021; EEB 2022). If properly integrated, early thinnings could enhance revenue streams while contributing to national and international bioenergy targets (Heikkilä et al. 2007; Heikkilä et al. 2009; Di Fulvio et al. 2011). Studies of novel forest management systems are required to increase the supply of sustainable energy biomass beyond logging residues and move toward net zero greenhouse gas emissions by 2050 (EC 2021).

In this study, we aimed to explore how patch thinning with a precision at a temporal scale (time-sensitive patch thinning) and the integration of energy biomass (hereafter "biomass") harvesting from early thinnings can be optimised in different forest types to maximize economic returns and to determine whether birch timber production can justify the costs of active management. We have re-evaluated contemporary, adapted, and novel forest management strategies, as well as the introduction of biomass and birch timber into the value chain. To achieve the aim, we addressed three research questions:

i Can biomass harvesting from first thinnings be integrated into the Swedish forest value chain without compromising revenue?
ii Is the time-sensitive patch thinning method economically feasible for practical implementation in forest management?
iii Can the production of birch timber from group-mixed forests economically justify the active management costs of these forests?

Materials and methods

We used a simulation tool to model forest stand development, costs, and revenues over time for eight sites across Sweden. Various management scenarios were created in order to study the objectives and to compare with current practices, and their costs and land expectation values (LEVs) were evaluated based on the modelled data.

Data description

Modelling data

The study area comprised eight sites across five municipalities in northern (>60° N) and southern (<60° N) Sweden (Figure 1 and Table 1). Although most sites are forest lands, Spöland and Bullstofta are former agricultural lands converted to forests. All sites have mixed mesic soils. These sites were chosen to represent Sweden's geographic diversity.

Plot data

We used inventory data from 45 experimental forest plots across the selected sites (Figure 1). Birch dominated 23 plots, and spruce dominated 22. All were established as monocultures in planting trials conducted in 1964–1968 (Siljansfors) and 1992–1995 (all other sites). Plot sizes ranged from 0.1 to 0.15 ha, and the diameter at breast height (DBH, cm) and height (dm) of all trees were measured before the first thinning, with no prior silvicultural intervention.

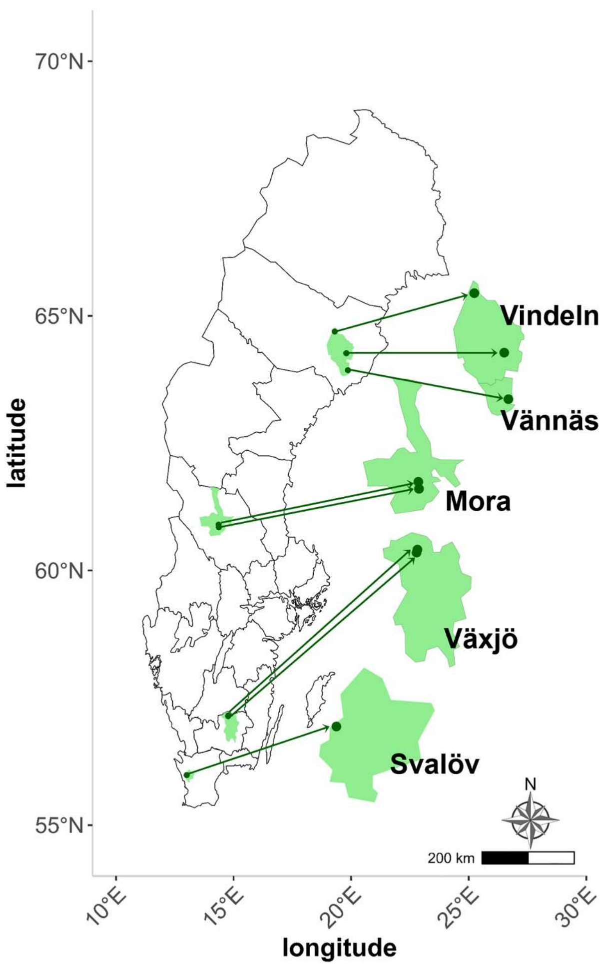

Figure 1. Map of Sweden, showing the locations of the eight study sites in their respective municipalities. The three southern sites are located in Svalöv (1) and Växjö (2), the two middle sites in Mora, and the three northern sites in Vännäs (1) and Vindeln (2).

Modelling

Stand structure modelling

We applied a theoretical approach and systematically designed three different stand structures, each of one hectare, for this study (Figure 2, Table 2):

(a) spruce monoculture,
(b) birch monoculture, and
(c) spruce-birch group-mixed stand, with a checkerboard pattern of spruce and birch patches.

In the group-mixed stands, we adopted a simple checkerboard layout to facilitate interpretation and future field reproducibility. Each 0.25-hectare birch or spruce patch was assumed to retain the characteristics of its respective monoculture, producing a patchy mixture within the stand.

We used Heureka-Planwise version 2.21.2.0 (hereafter "Heureka") to simulate the stand types and various management strategies. Heureka is an advanced decision-support system developed with data from the Swedish National Forest Inventory (Wikström et al., 2011; Lämås et al. 2023). It integrates a growth simulator that predicts stand development and an optimisation module that aligns forest management with user-defined objectives. The growth simulator applies empirical models to predict tree height and diameter growth, mortality, and ingrowth for common Swedish forest species, including birch and spruce (Elfving and Nyström 2010; Fahlvik et al. 2014). These predictions incorporate factors such as site index and climatic conditions.

Data from the experimental forest plots were imported into Heureka to simulate future stand development and management programmes. In the input data, experimental plots were assigned to their original sites, with site names used as stand names for theoretical stand simulations. Input parameters included stand size, plot size, inventory year, geographic coordinates (latitude, longitude, altitude), site index, stand age, DBH, height, species, and plot type (sapling: mean height < 7 m and DBH < 4 cm; tree: DBH ≥ 4 cm). Simulations were carried out for one-hectare stands. Monocultures of birch and spruce were simulated using species-specific data, while group-mixed stands were modelled by combining monoculture data from the experimental plots.

Table 1. Site conditions at the eight study locations.

Municipality	Site	Latitude (°N)	Longitude (°E)	Altitude (m)	Average annual temperature (°C) *	Average precipitation (mm/year) **
Svalöv	Bullstofta	55.98	13.01	85	8	900
Växjö	Asa – 1	57.13	14.78	200	7	900
	Asa – 2	57.25	17.77	200	7	900
Mora	Siljansfors – 1	60.90	14.37	240	4	800
	Siljansfors – 2	60.91	14.38	360	4	800
Vännäs	Spöland	64.26	19.80	300	3	600
Vindeln	Renberget	63.93	19.86	80	3	600
	Manjaur	64.69	19.29	315	2	600

*(SMHI 2023a), **(SMHI 2023b).

Scenarios

To address our research questions, we developed six management scenarios with incremental, progressive changes rather than sharp distinctions (see also Table 3).

(1) **spruceMono**: spruce monoculture under business-as-usual (BAU) management (Skogsstyrelsen 1984), with timber and pulpwood as the harvested assortments;
(2) birchMonoBAU: birch monoculture managed under recommended thinning regimes (Hynynen et al. 2010), with pulpwood as the only harvested assortment;
(3) birchMonoNew: birch monoculture managed under recommended thinning regimes (Hynynen et al. 2010), but with the first thinning's harvest directed to energy biomass and later thinnings' harvests to pulpwood-only. At the final felling, birch timber was introduced as an additional assortment along with birch pulpwood;
(4) **mixedPatchBAU**: mixed forest composed of 0.25 hectares of spruce and birch patches arranged in a checkerboard pattern, managed under BAU management practices (Skogsstyrelsen 1984), with spruce timber and pulpwood, and birch pulpwood as the only harvested assortments;
(5) **mixedPatchNew**: same stand structure and management regime as mixedPatchBAU, but with the first thinning's harvest directed to energy biomass and later thinnings' harvests directed to timber and pulpwood for spruce, and to pulpwood-only for birch. At the final felling, birch timber was introduced as an additional assortment besides birch pulpwood and spruce timber and pulpwood; and
(6) **mixedPatchTiming**: same stand structure and harvested assortments as mixedPatchNew, but with a time-sensitive patch thinning applied.

The spruceMono, birchMonoBAU, and mixedPatch-BAU scenarios served as economic benchmarks, reflecting typical Swedish forest conditions against which the other scenarios were compared. The birch scenarios and all mixed-stand scenarios addressed research questions i and iii, with all mixed-stand scenarios also addressing research question ii. The spruce monoculture served solely as an economic benchmark, reflecting

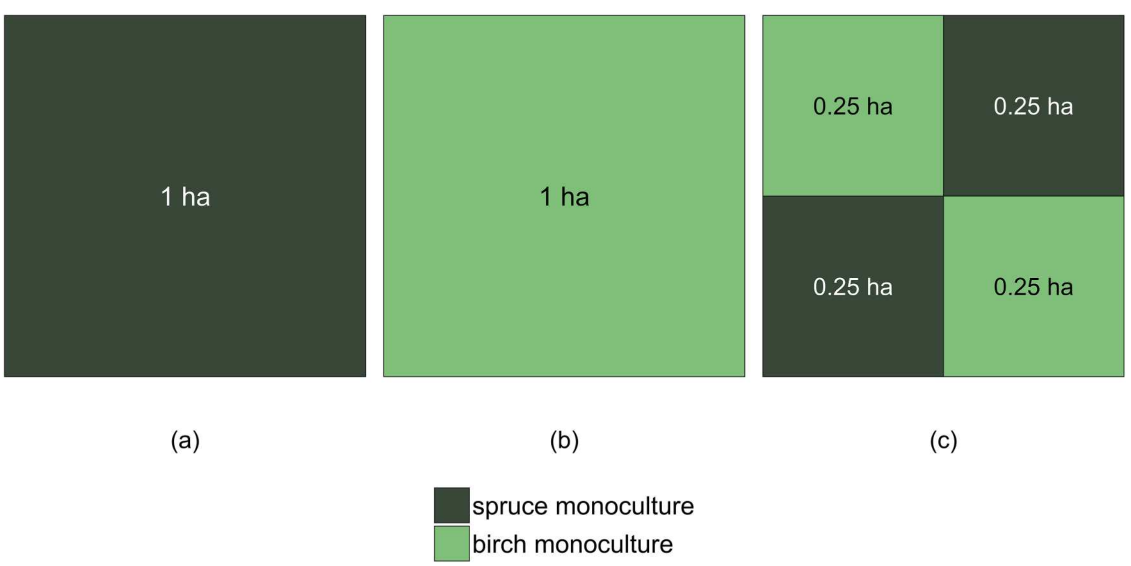

Figure 2. Systematically designed theoretical stand types (1 ha) modelled and analysed: (a) spruce monoculture, (b) birch monoculture, (c) mixed stand with spruce and birch group mixture.

Table 2. Initial conditions in each stand type (birch monoculture, spruce monoculture, spruce-birch group mixtures) at each site at the simulation start year. Stems per hectare values are taken from Heureka. Simulation was done for the data per plot; however, the site properties below are shown as the site average.

			Site							
			Svalöv	Växjö		Mora		Vännäs	Vindeln	
Stand type	Conditions	Unit	Bullstofta	Asa – 1	Asa – 2	Siljansfors – 1	Siljansfors – 2	Spöland	Renberget	Manjaur
Spruce monoculture	Stand density	stems ha^{-1}	2288	2194	2101	2395	2154	1833	2479	2058
	Basal area	m^2 ha^{-1}	42	14	29	21	24	4	18	2.25
	Average DBH	cm	17	10	15	12	13	6	10	5.4
	Average height	m	14	9	15	12	13	4	9	3
	Stand age	year	22	26	31	49	40	19	29	28
	Site index	m	43	29	36	25	28	28	29	20
Birch monoculture	Stand density	stems ha^{-1}	1581	2144	2017	2164	1919	1246	2171	1930
	Basal area	m^2 ha^{-1}	13	18	21	16	19	12	24	10
	Average DBH	cm	11	12	13	11	13	12	13	10
	Average height	m	12	13	15	13	14	10	15	10
	Stand age	year	15	24	23	24	23	18	29	27
	Site index	m	28	23	25	23	24	25	22	19
Spruce-birch group mixture	Stand density	stems ha^{-1}	1935	2169	2059	2280	2037	1540	2325	1994
	Basal area	m^2 ha^{-1}	31	16	25	18	22	8	21	6
	Average DBH	cm	16	11	14	11	13	11	12	9
	Average height	m	13	12	15	13	13	9	12	9
	Stand age	year	19	25	27	33	32	19	29	28
	Site index	m	37	26	31	23	26	26	26	20

typical Swedish forest conditions against which the other scenarios were compared.

To keep the design tractable and causal attribution clear, we limited the analysis to six scenarios that spanned the key management dimensions involving the stand composition, harvested assortments, and thinning timing, while holding other factors constant. A full factorial analysis would generate an unbounded set of variants and blurred effects. This scope necessarily omitted some spatial configurations, management prescriptions, and market conditions, such as price volatility. Therefore, our findings are most robust for the specified settings and should not be interpreted as universally optimal.

Management alternatives

Optimal management schedules for each scenario were generated using Heureka (Table 3). The treatment schedules and rotation ages were determined by maximising net present values at a 3.5% discount rate. The only exception is mixedPatchTiming, which was optimized under a fixed-rotation constraint. The rotation length was set to the mixedPatchBAU value, and thinning schedules followed the corresponding monocultures. In all cases, stands were clear-felled at the end of the rotation. All stands were clear-felled at the end of rotation. The group-mixed scenarios (mixedPatchBAU, mixedPatchNew, mixedPatchTiming) shared the same initial stand structure but differed in thinning schedules and harvested outputs. mixedPatchBAU versus mixedPatchNew varies only in assortments, whereas mixedPatchTiming differs from mixedPatchBAU in both assortments and the timing of species-specific thinning.

All thinning was selective, from below. The thinning plan of spruceMono, mixedPatchBAU, mixedPatchNew and the spruce patches of mixedPatchTiming (Table 3) followed the guidelines by (Skogsstyrelsen 1984). The thinning plan of birchMonoBAU, birchMonoNew and the birch patches of mixedPatchTiming (Table 3) followed guidelines by Hynynen et al. (2010). Thinning intensity was fixed according to the silvicultural guidelines and did not vary across scenarios (Table 3). The guidelines prescribe species-specific removal ranges, so the mandated percentages were different for the two species. This difference reflects standard management requirements, not a modelled variable. First thinning products from birchMonoNew, mixedPatchNew, and mixedPatchTiming were allocated to energy biomass.

Group-mixed stands comprised 50% birch and 50% spruce in a checkerboard design, with species in 0.25 ha patches (Figure 2). In the group-mixed scenarios, stand input data were created by combining original plot-level data from the monoculture plots without averaging, thereby retaining the spatial structure of the checkerboard configuration. In both mixedPatchBAU and mixedPatchNew, thinning operations were applied at the same time across all species patches, with thinning intensities adjusted individually at the plot level based on BA. In contrast, the mixedPatchTiming scenario

Table 3. Descriptions and thinning plans for the simulated scenarios. BA, Eb, P and T stand for basal area, energy biomass, pulpwood and timber, respectively.

					Harvested assortments					
					birch			spruce		
Scenario	Description	Thinning guideline	Thinning range	Thinning intensity*	1st Thinning	Later Thinning	Final Felling	1st Thinning	Later Thinning	Final Felling
spruceMono	spruce monoculture (Figure 2a)	stand mean BA	entire stand	20–40%	–	–	–	P + T	P + T	P + T
birchMonoBAU	birch monoculture (Figure 2b)	stem density	entire stand	30–40%	P	P	P	–	–	–
birchMonoNew	birch monoculture (Figure 2b)	stem density	entire stand	30–40%	Eb	P	P + T	–	–	–
mixedPatchBAU	spruce-birch group mixture (Figure 2c)	stand mean BA	entire stand	20–40%	P	P	P	P + T	P + T	P + T
mixedPatchNew	spruce-birch group mixture (Figure 2c)	stand mean BA	entire stand	20–40%	Eb	P	P + T	Eb	P + T	P + T
mixedPatchTiming	spruce-birch group mixture (Figure 2c)	**spruce group:** mean BA	spruce group	20–40%	–	–	–	Eb	P + T	P + T
		birch group: stem density	birch group	30–40%	Eb	P	P + T	–	–	–

*Thinning intensity = the minimum and maximum percentage of stand BA/ stem density allowed to remove at each thinning operation; fixed according to the thinning guidelines; not varied across scenarios.

introduced species-specific management phases: birch and spruce patches were thinned independently, allowing for temporally optimised thinning schedules for each species while maintaining the overall group-mixed layout. However, for clarity and brevity, Table 2 reports stand-level averages of key parameters.

The maximum height was 16 m for the first thinning in spruceMono, mixedPatchBAU, mixedPatchNew, and the spruce patches of mixedPatchTiming. In birchMonoNew and in the birch patches of mixedPatchTiming, the maximum height was 15 m for the first thinning. Data on harvested products (Table 3), except birch at final felling, were extracted from Heureka. Economic analyses were conducted separately for each scenario.

Economic evaluation

As Heureka's default settings estimate birch volume using only Brandel's volume function and form factors (Brandel 1990), and do not include a birch taper function, birch timber volumes from final felling were excluded from its outputs. Instead, data on birch pulpwood and timber from final felling were optimised separately using DBH (cm) and height (dm) values exported from Heureka and processed in R version 4.3.2 (R Core Team 2023). Machine productivity and costs were recalculated using the models by Eriksson and Lindroos (2014) and Ackerman et al. (2014), respectively, by combining and harmonising the two approaches (equation 5). All remaining data were sourced from Heureka simulations.

We estimated planting and soil scarification costs (€ ha^{-1}), net revenue from harvested stems (€ ha^{-1}), and machine costs both per hectare (€ ha^{-1}) and per cubic meter (€ m^{-3}) for each treatment. Harvest revenues were based on prices at landing (forest roadside). These values were then used to calculate discounted net cash flow in perpetuity, i.e. the land expectation value (LEV), for all stands and scenarios. Additionally, we assessed differences in first thinning and energy thinning costs across scenarios, as well as the contribution of biomass and birch timber to LEV. All economic calculations used 2023 as the base year, with inputs adjusted for inflation (SCB 2023) and an exchange rate of 1 € = 11.48 SEK (Exchange-Rates.org 2023).

Birch timber and pulpwood assortment estimations

We used Heureka-simulated DBH (cm) and height (dm) of individual birch trees to calculate timber and pulpwood volumes, maximizing revenue for each assortment. Total volumes and revenues for pulpwood and timber were then summed for each site and scenario to estimate birch volume and revenue per hectare. Minimum top diameter thresholds were set at 14 cm under bark for timber and 5 cm under bark for pulpwood.

As we did not have inventory data for the diameter at 20% of tree height, we based calculations on DBH (cm) using the taper function by Laasasenaho (1982), recalibrated by Kangas et al. (2023). The adapted model required DBH (cm), tree height (m, converted from dm), and taper height (m) as inputs, as described by equation 1 - 3.

$$d_l = d_{20} \times b_1 l + b_2 l^2 + b_3 l^3 + b_4 l^5 + b_5 l^8 + b_6 l^{13} + b_7 l^{21} + b_8 l^{34} \quad (1)$$

$$d_{20} = \frac{dbh}{C_{dbh}} \quad (2)$$

$$C_{dbh} = b_1 l_{dbh} + b_2 l_{dbh}^2 + b_3 l_{dbh}^3 + b_4 l_{dbh}^5 + b_5 l_{dbh}^8 + b_6 l_{dbh}^{13} + b_7 l_{dbh}^{21} + b_8 l_{dbh}^{34} \quad (3)$$

where d_l (cm) is the diameter at the taper height, d_{20} is the diameter at 20% of the total tree height, l is the relative distance of the taper height to the tree top, dbh is the diameter at breast height (1.3 m above ground), C_{dbh} is the taper function for dbh, based on d_{20}, l_{dbh} is the relative distance of the dbh height to the top, and $b_1 - b_8$ are empirically determined parameters (Kangas et al. 2023).

Machine productivity

Harvester and forwarder productivity (m^3 solid under bark per productive machine hour, referred to as m^3 PMH^{-1} hereafter) for each management intervention was estimated using the models by Eriksson and Lindroos (2014). For both thinning and final felling, mean tree volume (m^3 stem^{-1}) was the primary input, derived from scenario – and site-specific simulated data. Forwarder loading capacities and forwarding distances (Table 4) were also used to calculate forwarder productivity; these were fixed across all scenarios. In the absence of reliable data on how species-specific thinning schedules affect forwarding distance, we kept the forwarding distance the same across all scenarios.

Table 4. Assumptions in forwarder productivity (m^3 PMH^{-1}) calculations, based on Eriksson and Lindroos (2014).

Property	Unit	Value
Thinning forwarder load capacity	m^3	10
Final-felling forwarder load capacity	m^3	15
Forwarding distance	m (one way)	150

Machine cost per hectare

Harvester and forwarder costs per hectare (€ ha^{-1}) were used to estimate total machine cost per hectare (€ ha^{-1}; equation 4 and 5). Table 5 summarises the values applied in the machine cost estimation for thinning and final felling operations.

The machine utilisation rate was equal across all scenarios. Certain variables were assumed (Table 5) and plugged into the cost model. The remaining parameters in the business model by Ackerman et al. (2014) were unchanged, except for inflation adjustments (SCB 2023), where necessary.

$$C_{ha} = C_m \times V_{ha} \quad (4)$$

$$C_m = \frac{C_{PMH_{harvester}}}{P_{harvester}} + \frac{C_{PMH_{forwarder}}}{P_{forwarder}} \quad (5)$$

where C_{ha} is the machine cost per hectare (€ ha^{-1}), C_m is the machine cost per cubic meter (€ m^{-3}), and V_{ha} is the total harvested volume per hectare (m^3 ha^{-1}) simulated for each treatment. $C_{PMHharvester}$ and $C_{PMHforwarder}$ are the harvester and forwarder costs per productive machine hour (€ PMH^{-1}), while $P_{harvester}$ and $P_{forwarder}$ are their respective productivities (m^3 PMH^{-1}).

Due to the structure of the available data, the machine cost per cubic meter was calculated based solely on forest operations, i.e. cutting and forwarding logs and biomass to the forest roadside. Costs such as machine relocation between harvesting sites and other overhead expenses were not included.

Land expectation value

The land expectation value (LEV) was calculated from net harvesting revenues, machine costs, and planting and soil scarification costs (Table 6), with the latter assigned to year 0. Revenues included timber, pulpwood, and energy biomass.

Spruce and birch timber were assumed to be distributed among two quality classes: 86% in class 1 and 14% in class 2, each priced according to the respective timber price lists. Spruce timber prices were based on the 2023 Swedish average (Skogsstyrelsen 2023b). As Sweden does not have a well-established birch-timber market, we used Finnish data to assess the price difference relative to spruce timber, setting birch timber prices approximately 9% lower (Luonnonvarakeskus 2024). For birch at final felling, Heureka's simulated roundwood and revenue outputs were replaced by our own calculations for birch timber and pulpwood. Swedish average pulpwood prices for spruce and birch were applied to estimate the pulpwood revenue (Skogsstyrelsen 2023b). In birchMonoNew, mixedPatchTiming, and

Table 5. Assumptions used to calculate costs (€ m^{-3}) using the cost model by Ackerman et al. (2014).

Variables		Unit	Value
Assumptions	Working days a year	days $year^{-1}$	210
	Scheduled machine hours (SMH)	hours $year^{-1}$	3360
	Productive machine hours (PMH; 85% of SMH)	hours $year^{-1}$	2856
	Expected economic life	year	5
	Machine insurance	‰	6
	Salvage value	% of base machine purchase	10
	Machine maintenance cost	% base machine of base machine purchase	80
	Machine utilisation rate	%	85
	Contractor's profit margin	%	5
	Diesel price	€ l^{-1}	2
	Operator wage	€ SMH^{-1}	16
	Thinning harvester purchase price	k€	444
	Final felling harvester purchase price	k€	479
	Thinning forwarder purchase price	k€	366
	Final felling forwarder purchase price	k€	392
Machine costs (estimated)	Thinning harvester cost	€ PMH^{-1}	209
	Final felling harvester cost	€ PMH^{-1}	225
	Thinning forwarder cost	€ PMH^{-1}	172
	Final felling forwarder cost	€ PMH^{-1}	184

mixedPatchNew, all first thinning harvest was considered biomass (hereafter *biomass thinning*). Biomass revenues in these scenarios were calculated using the assumed biomass price (Table 6).

Net revenue for each treatment year was calculated by subtracting total costs from total revenues, then discounting to year 0 using a 3.5% discount rate. LEV was then calculated according to Equation 6:

$$LEV = \frac{\sum_{y=0}^{r}\{(R_y - C_y)*(1+i)^y\} - C_i}{\{(1+i)^y - 1\}} \quad (6)$$

where r is the rotation length in years, y is the year in which a treatment took place, R_y is the revenue at year y (€ ha^{-1}), C_y is the cost (€ ha^{-1}) at year y, C_i is planting and soil scarification cost (€ ha^{-1}) at year 0, and i is the discount rate.

Sensitivity analysis

To address uncertainties in key assumptions, such as price levels, we performed a one-at-a-time sensitivity analysis on biomass price, diesel price, discount rate, and birch timber price. A linear model (Equation 7) was used to assess the significance of differences between each variable change, followed by an ANOVA test.

$$y = \mu + ax_{bio} + bx_{diesel} + cx_{disc} + dx_{b.timber} + \varepsilon \quad (7)$$

where μ is the overall mean, x_{bio}, x_{diesel}, x_{disc} and $x_{b.timber}$ represent biomass price, diesel price, discount rate and birch timber price, respectively. LEV sensitivity was analysed for a ± 30% variation in all variables except for the discount rate, which was tested across a 1-5% range. All linear model fitting and ANOVA tests were performed using R version 4.3.2 (R Core Team 2023).

Results

Stem size, growth, and rotation age

The average stem size at first thinning ranged from 0.06 to 0.11 m^3 per stem (Table 7), influencing harvest cost per cubic meter. For instance, in the birch scenarios, the average harvested stem size was 60% of that in spruceMono, resulting in higher costs per cubic meter. However, the total harvest cost per hectare was more strongly influenced by harvested volume than by stem

Table 6. Assumptions for planting and soil scarification costs, and product revenues (base year 2023).

Variables	Unit	Value	Reference
Seedling purchase price, birch	€ $seedling^{-1}$	0.61	Svenska Skogsplantor (2023)
Seedling purchase price, spruce	€ $seedling^{-1}$	0.35	Svenska Skogsplantor (2023)
Planting density	stems ha^{-1}	2000	Collected data
Number of seedlings in a mixed stand, spruce	stems ha^{-1}	1000	Collected data
Number of seedlings in a mixed stand, birch	stems ha^{-1}	1000	Collected data
Spruce monoculture planting cost	€ ha^{-1}	700	No. of seedlings × seedling purchase price
Birch monoculture planting cost	€ ha^{-1}	1220	No. of seedlings × seedling purchase price
Mixed stand planting cost	€ ha^{-1}	960	No. of seedlings × seedling purchase price
Soil scarification cost	€ ha^{-1}	280	Skogsstyrelsen (2023a)
Average timber price, spruce	€ m^{-3}	62	Skogsstyrelsen (2023b)
Average pulpwood price, birch	€ m^{-3}	43	Skogsstyrelsen (2023b)
Average pulpwood price, spruce	€ m^{-3}	41	Skogsstyrelsen (2023b)
Average biomass price	€ m^{-3}	32	Average of the prices from Mellanskog (2023) and Norraskog (2023)

Table 7. Average rotation age, mean annual increment, harvested stem volume, and total harvested feedstock in the scenarios (standard deviation in the parentheses).

		Scenario					
Parameter	Treatment	spruceMono	birchMonoBAU	birchMonoNew	mixedPatchBAU	mixedPatchNew	mixedPatchTiming
Rotation time (years)	–	72 (14)	53 (1)	53 (1)	60 (10)	60 (10)	60 (10)
Mean annual increment (MAI) (m^3 ha^{-1} $year^{-1}$)	–	5.5 (3.0)	1.6 (0.3)	1.6 (0.3)	5.3 (2.4)	4.9 (1.7)	4.1 (1.7)
Average harvested stem volume (m^3 $stem^{-1}$)	1st Thinning	0.10 (0.02)	0.06 (0.02)	0.06 (0.02)	0.11 (0.05)	0.11 (0.05)	0.08 (0.02)
	Later Thinning	0.10 (0.13)	0.06 (0.06)	0.06 (0.06)	0.07 (0.11)	0.07 (0.11)	0.06 (0.07)
	Final Felling	0.47 (0.37)	0.32 (0.12)	0.32 (0.12)	0.32 (0.20)	0.32 (0.20)	0.32 (0.15)
Biomass (m^3 ha^{-1})	1st Thinning	–	–	28 (12)	–	46 (17)	38 (15)
	Later Thinning	–	–	–	–	–	–
	Final Felling	–	–	–	–	–	–
Pulpwood (m^3 ha^{-1})	1st Thinning	38 (15)	28 (12)	–	36 (9)	–	3 (8)
	Later Thinning	21 (25)	37 (12)	37 (12)	13 (19)	13 (19)	22 (12)
	Final Felling	102 (20)	167 (26)	76 (21)	168 (37)	128 (21)	88 (9)
Timber (m^3 ha^{-1})	1st Thinning	13 (9)	–	–	10 (9)	–	–
	Later Thinning	33 (43)	–	–	15 (29)	15 (29)	10 (21)
	Final Felling	298 (172)	–	91 (24)	123 (90)	185 (92)	185 (89)

size. Thus, while smaller stems raise the costs per cubic meter, stand-level volume is the primary cost driver within this size range.

Mean annual increment (MAI) varied as expected with site index (SI). In birch scenarios, MAI remained consistent between northern and southern sites, whereas spruceMono showed an 8.0 m^3 ha^{-1} $year^{-1}$ difference between the northernmost (2.4 m^3 ha^{-1} $year^{-1}$) and southernmost (10.8 m^3 ha^{-1} $year^{-1}$) locations. mixedPatchTiming had a lower MAI among the mixed scenarios due to more frequent thinnings and higher volume removal.

Rotation time followed the expected pattern of longest rotation at the least fertile northern site (Manjaur), and shortest at the most fertile southern site (Bullstofta). SpruceMono had the highest average rotation age, while birch scenarios had the lowest (Table 7).

Harvested volumes of feedstock

The birchMonoNew scenario yielded a lower average biomass volume at first thinning compared to mixedPatchTiming and mixedPatchNew. Nevertheless, in some mixedPatchNew sites, there was insufficient stand basal area growth for a thinning, making birchMonoNew and mixedPatchTiming consistently reliable for biomass production.

At final felling, birchMonoNew produced on average 42% and 31% more birch timber than mixedPatchTiming and mixedPatchNew, respectively. However, at the northernmost sites (Manjaur and Renberget), mixedPatchNew outperformed birchMonoNew in both timber and total harvested volume. These differences can be explained by the longer rotation time at these locations, and by the additional thinnings in the birch patches under mixedPatchTiming, potentially reducing its average pulpwood volume at final felling.

Overall, harvested feedstock volumes (biomass, pulpwood, timber) depended on site index, rotation age, and management strategy. birchMonoNew stood out regarding total birch timber on average, but site-specific conditions sometimes favoured mixed stands.

Costs and revenues from first thinning and biomass thinning

The costs and revenues from first thinning (spruceMono, birchMonoBAU, mixedPatchBAU) and biomass thinning (birchMonoNew, mixedPatchTiming, mixedPatchNew) are presented per hectare in Figure 3 and per cubic meter in Figure 4. Although spruceMono, birchMonoBAU and mixedPatchBAU are included in the Figure 4, they do not generate biomass revenue from the first thinning (Table 3). Therefore, the line for the biomass revenue (€ m^{-3}) in Figure 4 does not apply to these scenarios. However, their thinning costs (€ m^{-3}) are included to allow for comparison.

All scenarios, except birchMonoNew, achieved net profit from the initial thinning (Figure 3). BirchMono's negative net revenue primarily stemmed from its relatively low harvested volume. MixedPatchNew also experienced reduced revenue from the first thinning because both spruce and birch harvests were sold as biomass rather than higher-value pulpwood or timber, particularly for spruce. Although mixedPatchTiming

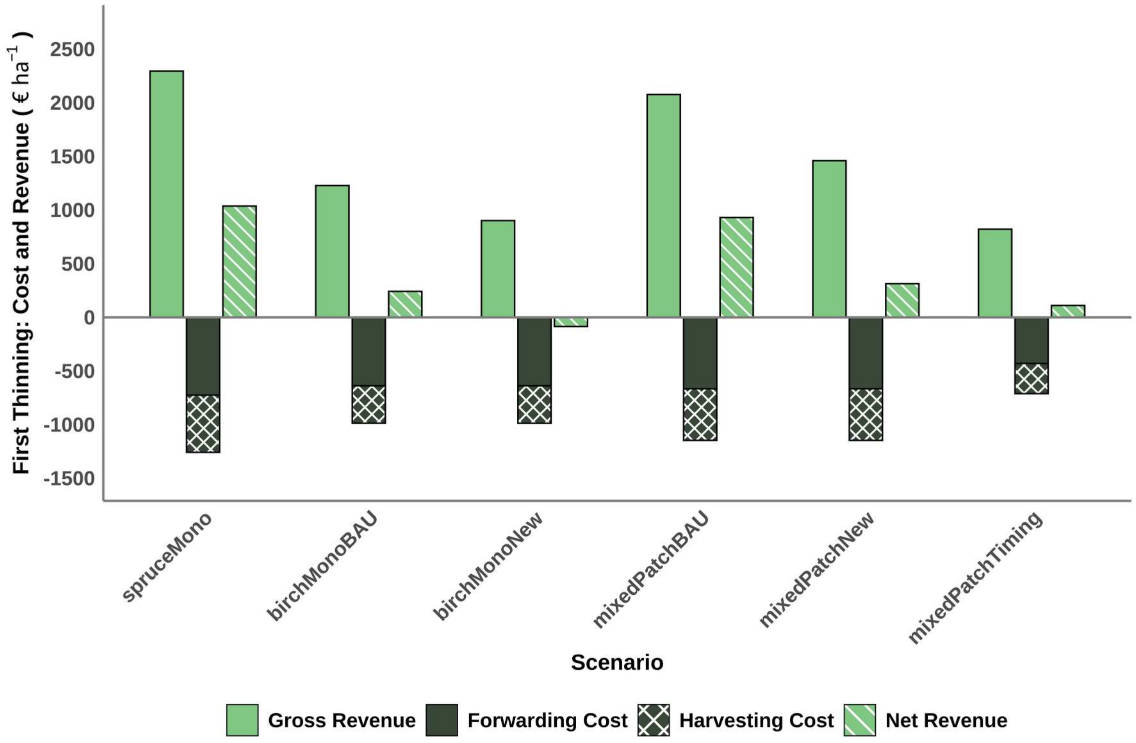

Figure 3. First thinning (mixedPatchBAU, spruceMono, birchMonoBAU) and biomass thinning (birchMonoNew, mixedPatchTiming, mixedPatchNew) costs, gross revenues and net revenues per hectare of forest stands.

incurred higher harvesting costs due to two separate thinning operations, the additional spruce volume at thinning still resulted in a net profit.

As shown in Figure 4, biomass thinning costs per cubic meter in birchMonoNew and mixedPatchTiming exceeded Swedish average thinning costs by

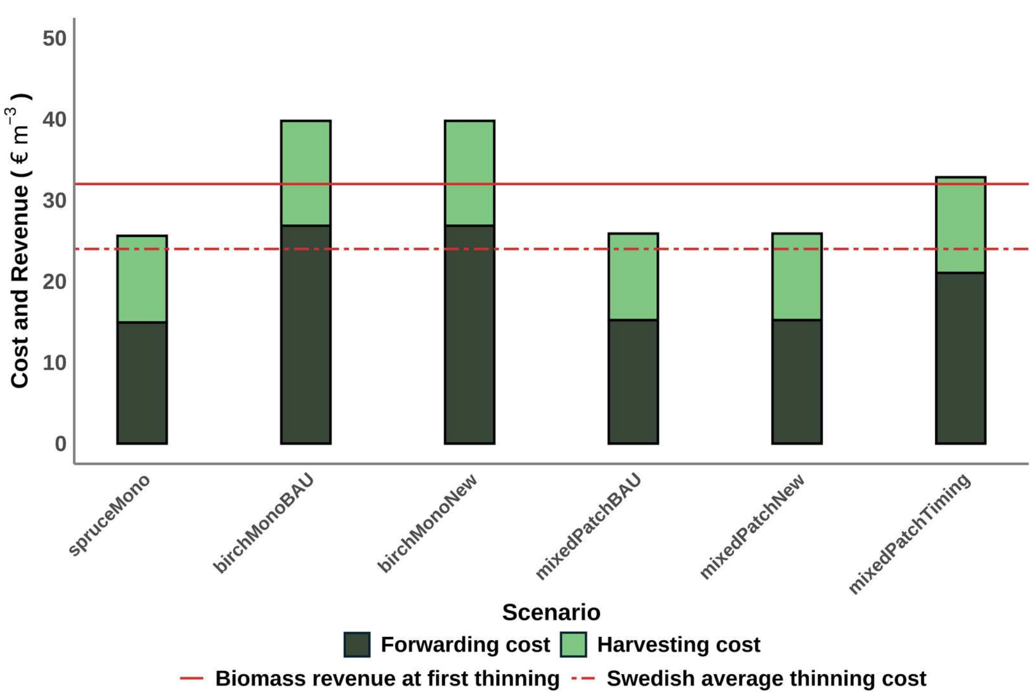

Figure 4. First thinning (in mixedPatchBAU, spruceMono, birchMonoBAU) and biomass thinning (birchMonoNew, mixedPatchTiming, mixedPatchNew) costs per cubic meter. The solid red line represents the assumed biomass price per cubic meter (Table 6), and the dashed red line represents Sweden's average cost for all types of thinnings in 2023 (Skogsstyrelsen 2023b).

approximately 50% and 38%, respectively. This is mainly due to smaller average harvested stems. Meanwhile, the costs of the other mixed scenarios and spruceMono exceeded the Swedish average by only 7%. This smaller deviation likely reflects their more standard species composition and management, aligning better with typical thinning conditions in Sweden. Additionally, the Swedish average thinning cost represents all thinning operations, while in first thinning, the costs tend to be higher than later thinnings due to dense stands and small average stem sizes.

Land expectation value

Figure 5 shows that site variability had a higher impact on LEV than the scenario variability, as the site index influenced basal area growth, thinning decision and product revenue. While birchMonoNew was profitable in 50% of the stands, it performed poorly in others. At Manjaur, this could be due to climatic and site conditions, while Spöland, despite being a fertile site, had a low initial number of birch stems due to storm damage. Conversely, Asa-1 and Siljansfors-1 had lower site indexes than the corresponding Asa-2 and Siljansfors-2 sites, resulting in lower initial basal area, average stem volume, and harvested volume.

On average, adding birch timber in the final felling increased stand LEVs. Despite a net gain at the first thinning in birchMonoBAU and an average net loss in birchMonoNew, birchMonoNew ultimately outperforms birchMonoBAU across all sites due to the addition of timber in the harvest assortments. Similarly, mixedPatchNew achieved 9% higher LEV than mixedPatchBAU, while mixedPatchTiming was only 4% below mixedPatchBAU, despite more frequent, costlier thinnings. At Bullstofta, however, mixedPatchNew and mixedPatchTiming underperformed compared to mixedPatchBAU, likely because large-sized stems were sold as biomass at initial thinning – an unprofitable approach on this highly fertile site. When excluding Bullstofta, mixedPatchNew and mixedPatchTiming thus exhibited even larger LEV gains over mixedPatchBAU (36% and 25% higher, respectively).

Overall, the frequent thinnings in mixedPatchTiming raised harvesting costs, resulting in lower LEV, but at certain sites they enabled timely stand interventions that increased revenues.

Sensitivity analysis

In the sensitivity analysis (Figure 6), the discount rate was the only variable that significantly affected the

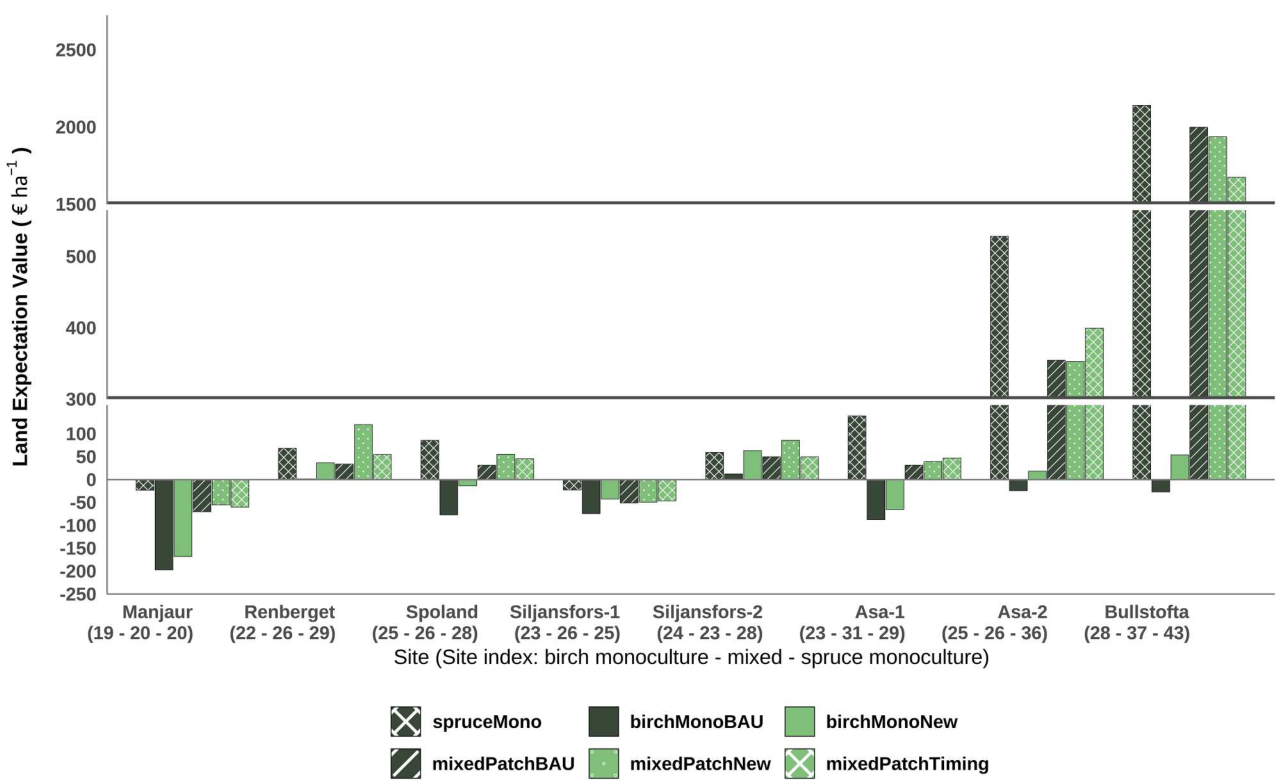

Figure 5. Land expectation value (LEV) for all sites and scenarios.

Note the break in scale on the y-axis (2021). The x-axis represents the sites, with site indices for different scenarios shown in parentheses. The indices are arranged in the order of birch stands – group-mixed stands – spruce stands.

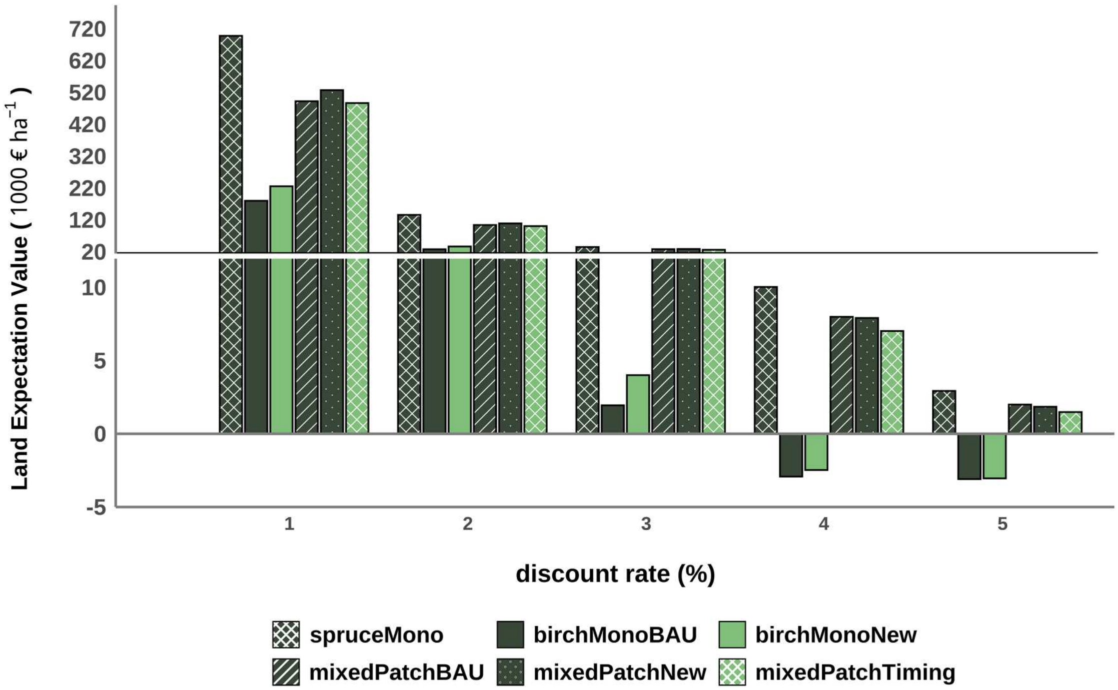

Figure 6. Sensitivity analysis of impact of discount rate on LEV.
Note the break in scale on the y-axis (2021).

LEV, while changes in biomass price, diesel price, and birch timber price had negligible impact on overall profitability (data not shown). At higher discount rates, mixedPatchBAU, with earlier thinnings and shorter rotations, became more attractive. Both the birch scenarios remained unprofitable at discount rates over 3%, largely due to higher operational costs. However, as discussed above, at the discount rate of 3.5% used in our study, LEV outcomes depended primarily on the site conditions. Therefore, birch scenarios made a positive LEV in some sites and did not in others.

Overall, those results underscore that discount rate is crucial for long-term profitability, and that it outweighs moderate changes in biomass or birch timber prices, as well as in diesel price. This indicates that many of the tested management strategies can remain economically viable unless interest rates climb significantly.

Discussion

Thinning costs

Among the scenarios, spruceMono exhibited the lowest thinning costs, followed by mixedPatchBAU and mixedPatchNew. This aligns with expectations; the spruceMono scenario benefited from economy of scale due to a larger harvested volume per hectare (Table 7), despite having an average stem volume similar to the mixed scenarios. This finding indicates that if the total harvested volume per hectare could be increased in the mixed scenarios, e.g. by using improved birch varieties, the harvesting cost could be lower than shown in this study.

The relatively small average stem sizes in the birch scenarios led to a limited harvested volume per hectare, increasing the cost per unit harvested. According to Kärhä et al. (2005), mechanized harvesting becomes unprofitable when the average stem size is below 0.03 m^3 and the total harvest volume is below 30 m^3 ha^{-1}. Although the average thinned stem volume in the birch scenarios did exceed 0.03 m^3, the total volume harvested per stand remained below 30 m^3 (Table 7), likely contributing to higher harvesting costs. This emphasizes the importance of timing in thinning to ensure sufficient stem diameters, while still keeping the stand within the recommended first thinning height range. Timing issues emerge as a main challenge to cost-effective biomass harvesting of birch in both monocultures and group-mixed forests. Additionally, the initial planting density in the birch scenarios (around 2000 stems ha^{-1}) exceeded the 1600 stems ha^{-1} recommended by Hynynen et al. (2010). Higher early-stage competition can reduce diameter growth and average stem volume, further complicating efforts to maintain favourable harvesting conditions.

In mixedPatchTiming, having two separate first thinnings (one for each species patch) contributed to higher costs. However, without real-time machine work data or patch-thinning productivity models, we relied on mean stem volume to estimate costs. The productivity would likely fluctuate with machine driving time and biomass distribution in the stand. We expect that an integrated harvesting system (Jylhä and Jylhä 2007; Heikkilä et al. 2009; Kärhä 2011; Kärhä et al. 2011) could increase average harvested volume per hectare, thus lowering unit costs. As we did not include detailed cost metrics, such as machine loading-unloading time or biomass density, our results may not fully capture potential efficiency improvements. Additionally, variation in the spatial arrangement of birch patches within mixed stands would likely affect costs, which we did not account for in this study.

Overall, on average, in the mixedPatchTiming scenario, the first thinning of spruce occurred 10–15 years after the first thinning of the birch, and the rest followed accordingly. The northernmost site, Manjaur, had the highest first thinning cost, while the southernmost site, Bullstofta, had the lowest. Costs also appeared to vary with site fertility as the site fertility was represented through mean stem size and total harvested volume.

Biomass thinning revenue

Both mixedPatchTiming and mixedPatchNew generated positive net revenue from first thinning at the applied biomass price (32 € m^{-3}). However, the practicality of these results for mixedPatchTiming remains uncertain. We assumed a 150 m forwarding distance, but, particularly in time-sensitive patch-thinned stands, forwarding distances and costs could be higher, rendering biomass revenues insufficient to ensure profitability. For instance, Eliasson et al. (2021) found that patch-cutting in final felling can increase forwarding distance by 29%, leading to an 18% increase in total harvesting costs. Their average stem size was also about 6-11% higher than in our mixedPatchTiming scenario, suggesting that our cost estimate for biomass thinning could be conservative. Further research into optimising forwarding distances, strip road layouts, and machine-route planning is necessary before recommending this approach.

Although mixedPatchNew attained the highest biomass revenue at the applied price, there are sustainability concerns under current regulations (EEB 2022) as many stems would qualify as pulpwood or timber rather than energy biomass. Without integrated harvesting systems or adjusted cutting strategies, mixedPatchNew may not meet sustainable biomass sourcing requirements. By contrast, birchMonoNew, despite lower profitability at present, features a consistent thinning regime that can reliably produce biomass under existing rules.

Site selection also proved crucial. At Manjaur, the least fertile site, first thinning costs were roughly double those at other sites. Thus, biomass thinning at medium to high-fertility sites appears more cost-effective. However, high site index stands are typically more profitable when focusing on higher-priced products (pulpwood or timber) rather than biomass. Moreover, the selective thinning method applied in this study contributed to higher costs by yielding a lower total volume per PMH in stands with low site index or sites with a high number of small-diameter trees. A systematic thinning method could potentially increase the harvested biomass volumes and reduce costs (Bergström et al. 2010; Bergström et al. 2022).

These thinning cost and revenue patterns strongly influence overall stand profitability, as reflected in the LEV.

Effects on land expectation value

We initially expected that introducing birch timber (mixedPatchNew) would generate a significantly higher LEV than that of mixedPatchBAU. While the results revealed an overall insignificant difference, mixedPatchNew still achieved a 9% higher LEV, even with 42% lower first thinning revenue. On most sites, mixedPatchNew improved LEV, but at Bullstofta, Asa-2, and Siljansfors-1, mixedPatchBAU performed better. Notably, Bullstofta's high site index (Table 2) meant that trees qualifying as pulp or timber were sold as biomass, thus forfeiting potential pulpwood or timber revenue. Unless biomass prices increase significantly or integrated harvesting is practised, utilizing roundwood-size stems as biomass is not optimal, especially as this might conflict with the sustainable energy directive (EEB 2022), as discussed above. Therefore, the potential of pre-commercial biomass thinning in high-fertility sites should be explored.

Conversely, at Asa-2 and Siljansfors-1, the pulpwood-only management for birch in mixedPatchBAU yielded higher returns than splitting into pulpwood and timber, as in mixedPatchNew. This suggests that if top diameters are too small to fetch good timber prices, pulpwood-only approaches may be preferable. Future changes in birch timber markets could, however, alter this outcome.

Although mixedPatchTiming had a lower LEV on average than mixedPatchNew and mixedPatchBAU, it outperformed both at specific sites (Siljansfors-1, Asa-1, Asa-2; Figure 5). Since thinning in mixedPatchNew and mixedPatchBAU was based on BA targets, areas with insufficient BA growth were not thinned. For example, in Asa-2, spruce had good basal area development, but birch did not. As a result, areas occupied by birch were left unthinned, generating no birch pulpwood revenue. However, mixedPatchTiming allowed thinning in birch patches based on stem density, enabling pulpwood revenue from birch and leading to a higher LEV than mixedPatchBAU and mixedPatchNew in Asa-2. This suggests that mixedPatchTiming could be a viable alternative for group-mixed stands, allowing birch to be thinned when stem density, rather than basal area, meets the criteria. This approach may enable timely thinning in both birch and spruce patches. Further studies are needed to evaluate the logistics, economic feasibility, and ecological impacts of timed patched thinning, particularly regarding repeated machine interventions.

The birchMonoNew scenario demonstrated higher LEVs than previously reported birch-spruce mixtures (Lidman et al. 2021), although direct comparisons are complicated by differences in stand structure and management. With consistent thinning based on stem density, birchMonoNew may reliably produce biomass, pulpwood, and timber. birchMonoNew outperforms birchMonoBAU, indicating a more economically attractive broadleaf management option in Swedish forestry, provided the development of a substantial market for birch timber.

We also found potential to obtain, on average, 8 oven-dried tonnes per hectare (OD t ha^{-1}) of birch bark during thinning and 13 OD t ha^{-1} during final felling (data not shown). This additional yield could offset costs, although its viability depends on future market demand and the establishment of relevant industries and logistics.

Our analysis further indicates that harvesting biomass at the first thinning while excluding birch timber and relying only on biomass and pulpwood yields an LEV approximately 171% lower than that of birchMonoNew. While a roundwood-only strategy could theoretically surpass birchMonoNew, the growing demand for renewable and sustainable energy underscores the need to explore alternative assortments from forest woody biomass.

Although variability in site characteristics can hinder direct comparisons, it also validates the robustness of these observed trends across diverse contexts. Another notable point is that birch often regenerates naturally on moist or wet sites, eliminating planting costs and potentially raising LEVs for the birchMonoNew, mixedPatchTiming, and mixedPatchNew scenarios.

Finally, since biomass costs were estimated at the landing, actual costs at the power plant gate may be higher, depending on transportation distances and volumes. Addressing logistical challenges, improving site selection, and fostering robust markets for birch timber and biomass products will be essential to fully realize the economic potential of these strategies.

In summary, the choice between these scenarios may hinge on site fertility, regulatory constraints, and whether a market for birch timber develops. Under the right conditions, group-mixed approaches can outperform pure stands, but cost uncertainties and potential operational complexities remain. However, this study did not account for the ecological and economic resilience benefits that mixed forest management can offer. Incorporating these aspects in future research would be essential for developing a more comprehensive understanding of the system.

Sensitivity analysis revisited

The sensitivity analysis indicated that only the discount rate significantly influenced LEV (Figure 6). According to our results, mixedPatchBAU became the most favourable option at higher discount rates, likely because it had earlier thinning and final felling than spruceMono. MixedPatchNew might be the best choice at high discount rates if pulpwood and timber were the primary harvest products from first thinning. Although mixedPatchTiming involves higher operational costs, it remained economically viable up to a 5% discount rate, which can be explained by the birch timber at final felling. By contrast, the operational costs of birch scenarios were too high for profitability at discount rates above 3%. However, we did not re-optimize each scenario for different discount rates; instead, we only adjusted the discount rate during the final LEV calculation. Since higher discount rates typically lead to earlier thinnings and final fellings when optimization is applied, our sensitivity analysis reflects changes in LEV only under the assumption that treatment schedules remain unchanged.

It was unexpected that LEV showed no major sensitivity to biomass, diesel or birch timber price changes, even though these factors affect machine costs and revenues. While diesel price strongly affected forwarding costs per cubic meter (data not shown), careful planning and optimisation (e.g. stand-based strip road design) can mitigate this cost effect. This finding is presumably more relevant to machine work contractors than forest owners or managers.

Finally, our ±30% variations in biomass and birch timber prices did not noticeably shift LEV, but extreme price fluctuations could yield different outcomes, necessitating further investigation.

Conclusion

This study has explored whether time-sensitive patch thinning and the integration of energy biomass harvesting from early thinnings can be economically viable in different forest types, and whether birch timber production can justify the costs of active management. Our findings show that incorporating energy thinning in birch-spruce group-mixed stands can yield positive net revenues, provided site conditions (e.g. fertility) are favourable. Under these circumstances, biomass harvesting can be integrated into Swedish forest value chains without substantially compromising economic returns.

By contrast, birch monocultures face revenue losses if early-thinning harvests are sold solely as energy biomass at current prices. Including birch timber as a harvested product offsets these thinning costs, as is evident from the improved LEVs of the mixedPatchNew scenario compared to mixedPatchBAU. Developing markets and management practices for birch timber is imperative to encourage forest owners to actively manage both birch monocultures and birch patches in mixed forests.

Finally, although the mixedPatchTiming scenario showed promise, particularly where basal area growth was too low for conventional mixed-stand thinning, further studies on logistical aspects (e.g. machine-route planning) are necessary before it can be recommended for practical implementation in Swedish forestry. Future efforts should focus on optimising the forest value chain to capture both biomass and roundwood assortments from birch, while also adhering to sustainability guidelines. A better understanding of birch timber markets and improvements in thinning operations and logistics will be vital to ensuring economically and ecologically sustainable management strategies for birch in Swedish forestry.

Disclosure statement

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Declaration of generative AI and AI-assisted technologies in the writing process

During the preparation of this manuscript, the authors used the ChatGPT-4o tool to receive suggestions aimed at improving the readability and language of parts of the text. After using the tool, the authors thoroughly reviewed and edited the content as necessary and take full responsibility for the final content of the article.

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