Chapter 8
Financial Performance

Anssi Ahtikoski, Peichen Gong, Per Kr Rørstad, Esa-Jussi Viitala, and Jaakko Repola

Abstract

- Financial comparisons between rotation forestry (RF) and continuous cover forestry (CCF) are based on simulations in which the growth and yield of trees is estimated using a growth simulator. These often include an optimisation tool to present the maximum value of the objective function (usually the present value of net income).
- Studies have shown that the profitability of CCF depends on the initial state of a stand, especially the diameter distribution of the trees. The effect of interest discount rate also depends on the initial state.
- As a rule, it is safe to say that the more the forest structure resembles the target diameter distribution of the trees in CCF (i.e., a forest with heterogeneous structures), the more profitable it is to shift from RF to CCF.
- The more heterogeneous the tree structure on mineral soil, the higher the applied interest rate, the higher the forest establishment costs (soil preparation and culti-

A. Ahtikoski (✉)
Natural Resources Institute Finland (Luke), Tampere, Finland
e-mail: anssi.ahtikoski@luke.fi

P. Gong
Department of Forest Economics, Swedish University of Agricultural Sciences (SLU), Umeå, Sweden
e-mail: peichen.gong@slu.se

P. K. Rørstad
Faculty of Environmental Sciences and Natural Resource Management, Norwegian University of Life Sciences (NMBU), Ås, Norway
e-mail: per.kristian.rorstad@nmbu.no

E.-J. Viitala
Natural Resources Institute Finland (Luke), Helsinki, Finland
e-mail: esa-jussi.viitala@luke.fi

J. Repola
Natural Resources Institute Finland (Luke), Rovaniemi, Finland
e-mail: jaakko.repola@luke.fi

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vation), and the poorer the growth conditions (site type and temperature sum), the more profitable CCF is. Few studies have been found that focus on peatland forests.

- Future financial studies should also consider risks associated with wind, harvesting, and insect and fungus damage as well as carbon payments and nontimber benefits

Keywords Stand-level optimisation · Rotation forestry · Continuous cover forestry · Profitability · Economic-ecological model

8.1 Recent Financial Studies

The profitability of continuous cover forestry (CCF) has been studied in Finland (e.g., Tahvonen 2009, 2011; Pukkala et al. 2010; Tahvonen et al. 2010; Rämö and Tahvonen 2014, 2015, 2017; Tahvonen and Rämö 2016; Juutinen et al. 2018a; Assmuth and Tahvonen 2018; Assmuth et al. 2018, 2021; Parkatti et al. 2019; Parkatti and Tahvonen 2021). These studies have focused on the stand level and compared the financial outcome of rotation forestry, RF (i.e., a management system based on clearcuttings and artificial regeneration) with those of CCF or have examined how an even-aged stand could optimally be converted into a CCF stand (Rämö and Tahvonen 2017). Recent studies have also examined the impact of carbon payments on optimal forest management (Tahvonen 2022). These studies share a significant multidisciplinary approach in which ecological models are combined with an economic calculation framework, thereby integrating algorithms of numerical optimisation into the economic-ecological model. Tahvonen's review (2022) is a modern synthesis of economic studies focusing on CCF. Common to all these studies (apart from Juutinen et al. 2018a) is that they are based on numerical optimisation, which enables a transparent and approved calculation method based on economic theory (e.g., Amacher et al. 2009; Tahvonen 2022). Another common factor is that forest growth is estimated by simulating the development of individual trees or tree size classes.

The simulation of tree growth introduces a need for caution. Historically, in Fennoscandia, tree growth modelling has been mainly based on field measurements representing RF (see, e.g., Bianchi et al. 2020). Consequently, growth models for RF have been based on considerably larger and longer field measurements than the corresponding models for CCF. A recent comprehensive study (Hynynen et al. 2019) suggests that RF and CCF stands respond differently to cutting treatments, and there are likely differences between RF and CCF stands with respect to the risk of abiotic and biotic damage (Nevalainen 2017). The effects of damage on stand growth have not been considered in detail in financial analyses.

8.2 Profitability Comparisons

The financial outcome of forest management is calculated by comparing revenues with expenses. Revenues mainly derive from the sale of trees (usually at stumpage), and expenses arise from investments, i.e., silvicultural measures. The time period between investments and return on investments can be very long in forestry—the period between stand establishment and clearcutting may be 50–100 years, in northernmost boreal biome even longer. Capital may also have other uses (opportunities), and borrowed capital also comes with a price, so the profitability of forestry is usually examined by incorporating commensurate revenues and expenses occurring at different times.

The profitability of forestry can be affected by length of rotation period, stand density and management intensity. Traditionally, no silvicultural expenses arise from CCF, since it relies on natural regeneration (i.e., trees are assumed to regenerate naturally), nor is there need for sapling stand management.

The most robust comparison method involving economic theory is based on calculating the net present value (NPV) of timber production (Haight 1985; Tahvonen and Viitala 2006; Tahvonen 2011). Calculating NPV considers all revenues deriving from forest management and all expenses arising from the present into the infinite future. Revenues and expenses generated at different times are discounted into present values, and the difference between them calculated to obtain the NPV. For RF starting from stand establishment at time zero, the NPV of the first and all future rotations can be calculated using a simple formula called the Faustmann model (Faustmann 1849):

$$V(T) = \left(1 - e^{-rT}\right)^{-1} \left[\sum_{t=1}^{T} R(t) e^{-rt} - c \right] \tag{8.1}$$

where $V(T)$ = present value of net incomes (EUR/ha), r = continuous time interest rate, T = rotation period (years), e^{-rt} = continuous discount factor, $R(t)$ = net revenue or silvicultural cost at time t (EUR/ha), and c = stand regeneration cost (EUR/ha). [Note that for each continuous time interest rate r there is a corresponding discrete time interest rate i, $i = e^{r} - 1$]. Revenues are calculated by multiplying timber assortment volumes by corresponding unit prices. Net revenues are obtained by deducting harvesting costs from timber revenues. In Eq. 8.1, the numerator represents the NPV during a rotation starting from bare land, and the denominator is used to repeat the NPV to infinity (Amacher et al. 2009). When $V \geq 0$ using the chosen interest rate, forest management is financially profitable. When an existing stand is managed according to an RF regime, the present value of the net revenues in current and all future time periods is

$$V_{RF}(s) = \sum_{t=0}^{T_r} R(s,t) e^{-rt} + V(T) e^{-rT_r} \tag{8.2}$$

where s = the initial state of the stand, T_r = the time when the existing stand is harvested and regenerated, $R(s, t)$ = net revenues at time t for the existing stand (EUR/ha), $V(T)$ = the bare land value determined according to Eq. 8.1. If the stand is to be managed according to a CCF regime (through selective harvesting), clearcutting will never be carried out in the stand, which means that $T_r = \infty$, and the NPV of the stand becomes

$$V_{CCF} = \sum_{t=0}^{\infty} R_s\left(s,t\right)e^{-rt} \tag{8.3}$$

where $R_s(s, t)$ = net revenues from the existing stand (EUR/ha) at time t. Assuming that timber prices are constant over time, and ignoring uncertainty in stand growth as well as risks of forest damage, optimal selective harvesting will lead to a cyclical steady state of the stand and a constant periodic net revenue (Rämö and Tahvonen 2017; Parkatti and Tahvonen 2020). Let T_c denote the time when the stand reaches a steady state, $\overline{R}$ the steady state periodic net revenue, and T_h the length of the cutting cycle. Eq. 8.3 can be rewritten as

$$V_{CCF} = \sum_{t=0}^{T_c} R_s\left(s,t\right)e^{-rt} + \overline{R}e^{-rT_c}\left(e^{rT_h} - 1\right)^{-1} \tag{8.4}$$

By comparing the NPVs associated with RF (Eqs. 8.1 and 8.2) and CCF (Eqs. 8.3 or 8.4), we can determine which method is financially more advantageous in each situation.

8.3 Optimisation Method

Forest management is primarily a goal-driven activity, requiring the best possible solution within the given limits. In economics, the best solution can be achieved by seeking an optimal solution in which the objective function is at its maximum (Intriligator 2002). Finding an optimal solution in RF requires the identification of thinning timings and intensities and the length of a rotation period. These are based on growth and yield models (in short, growth models) that produce estimates for tree growth. Because growth models are usually included in simulators consisting of several subprograms (e.g., diameter growth model, survival model, and height model), the financial assessment becomes especially complex, and it is practically impossible to solve them analytically (Pukkala 2009). In CCF, the problems are similar in principle, while the rotation period does not need to be defined separately, unless the technical calculation framework has not been built to enable solutions for both RF and CCF (Tahvonen 2015a, b; Tahvonen and Rämö 2016; Parkatti et al. 2019). Due to the complexity of the calculation framework, financial analyses at stand level are often based on numerical optimisation, in which the maximum value of the objective function (usually the NPV) is determined numerically using mathematical calculation algorithms that have been integrated with tree growth models (Niinimäki et al. 2012).

The optimisation methods on which calculation algorithms are based can be roughly divided into two groups: gradient-based and derivative-free methods (Cao 2010; Pyy 2021). Which optimisation method is most suitable depends on the convexity of the target function, the dimensions of the variables, and how growth models have been technically implemented in the simulator (Valsta 1992; Cao 2010). In turn, growth models can be based on stand-level models, process-based models, size distribution transition matrix models, size class matrix models, or growth models representing individual tree growth dynamics (Parkatti 2021).

Research based on the stand-level financial optimisation of CCF can be considered to have started systematically in the 1970s (Adams and Ek 1974), continued in the 1980s (e.g., Haight 1985; Haight and Getz 1987), and increased significantly in the 2010s, especially in Finland (e.g. Tahvonen et al. 2010; Pukkala et al. 2010; Tahvonen 2015a, b; Rämö and Tahvonen 2017; Parkatti et al. 2019). At the same time, financial studies on CCF have undergone a methodological shift, from static to dynamic models, so that recent studies have even been able to simultaneously examine the respective profitability of RF and CCF using the same initial stands. Methods applied to optimisation have also developed, so that recent financial studies (e.g., Parkatti et al. 2019; Parkatti and Tahvonen 2021) have used hierarchical multilevel optimisation, in which the rotation period usually represents the highest-level problem, and the thinning intensity the lowest level. Conceptually, this is a mixed-integer non-linear optimisation problem, in which some variables are integers and some are continuous real numbers. Technically, solving such an optimisation task requires a separate calculation algorithm, which is linked to growth models in the simulator software. In practice, solving a single optimisation task numerically may take several hours, even with the most powerful computers, while the calculation can be accelerated using machine learning. As a result, models can also include randomness related to tree growth, as well as natural damage (Malo et al. 2021). Recently, reinforcement learning (RL) algorithms have been applied in stand-level optimisation to capture stochasticity related to stand growth and prices (Tahvonen et al. 2022).

8.4 Profitability Comparisons in Different Situations

The table below presents the situations (site type, tree species, geographical location, and initial state) in which CCF on mineral soils is a financially better option than RF. In the literature, initial stands have often been divided into (1) bare land, (2) young, and (3) mature stands (ready for clearcutting). The structural features of stands have been described to make it easier to interpret the results. According to recent studies, it seems that when starting the financial analysis from bare land, spruce forests and spruce-dominated mixed forests (<40% deciduous trees) are more profitable when using CCF than RF, at least in southern and central Finland

and when applying an interest rate of at least 3%. The situation is less straightforward in pure pine forests. If stand establishment costs can be kept below EUR 1000/ha, RF could be a better option financially than CCF in dryish sites in central Finland, for example. For young even-aged spruce forests, it is probable that CCF would become more profitable than RF, at least in mesic forests in southern Finland. For mature stands, CCF is categorically more profitable than RF, at least in spruce forests, provided that the site type is not too fertile. The financial outcome depends on the initial stand structure (diameter distribution and stand age): the more the structural features resemble the target stand structure, i.e., uneven-aged forest, the more profitable CCF is compared to RF with clearcutting and artificial regeneration. Profitability of CCF also seems to improve in spruce forests further north compared with RF (e.g., Tahvonen 2011).

The Table 8.1 below presents the key results of financial studies divided according to the initial state of a stand, tree species, site type and location. The profitability of CCF is compared with RF. Results apply for mineral soils only.

Only a few studies have compared NPV of CCF and RF in Sweden. In contrast to the results from the Finnish studies, Swedish studies showed that, in most cases, CCF is less profitable than RF and that the difference in NPV between the two regimes is greater when the interest rate is higher (Granath and Söderström 2022; Nordström et al. 2013; Sonesson 2017; Wikström 2000, 2008).

There are several possible reasons behind the Swedish conclusion that selection cutting would result in a lower NPV than RF. First, a majority of the cases examined are old multi-storeyed stands with a large growing stock of timber, and the harvest intensity in the selective harvesting regime is strictly constrained (Granath and Söderström 2022; Sonesson 2017; Wikström 2008). In such cases, the stands should be harvested and regenerated immediately or in the near future under a RF regime, whereas a selective harvesting regime (CCF) implies that harvest of much of the growing stock of timber should be postponed, which means the retained timber capital would incur a high opportunity cost. This also explains why selective harvesting (CCF) becomes even less profitable than RF when the interest rate is high. Relaxing the constraints on harvest intensity would increase the NPV associated with selective harvesting (Sonesson 2017; Wikström 2008), but the Swedish studies did not consider the high harvesting intensities allowed in Finnish studies that showed CCF to be more profitable.

Secondly, in two of the studies, simulated timber growth was significantly lower under selective harvesting compared with the RF alternative (Sonesson 2017; Wikström 2000). The growth simulators used in these studies are not necessarily suitable for predicting the growth of the stand and future timber yield under selective harvesting management. Thirdly, in most of the studies, selective harvesting plans (cutting cycle and harvest intensity) were determined based on some simple rules, whereas the management programme under RF was optimised to maximise the NPV. This may have led to underestimation of the NPV associated with the CCF regime. Although Wikström (2000) determined the maximum NPV under both management regimes by optimising harvest plans, the growth simulator used in the

Table 8.1 Background information, key results and limitations related to financial studies on CCF-RF comparison

Initial state	Tree species	Location/Site type	Key results	Specifications and limitations
Bare land	Spruce	Central Finland/ Mesic forest (H_{100} 24 m)	If forest regeneration costs are at least EUR 1000/ha, and the interest rate is at least 3%, CCF is more profitable[a]	The initial state comprised a 20-year-old seedling stand, in which the tree density is 1750 or 2250 seedlings/ha, but the results can be generalised for bare land
	Spruce	Southern Finland/Mesic forest	With an interest rate of 3%, RF is more profitable[b] than CCF. The cutting cycle ranged from 10 to 30 years, and the basal area after cutting was 4–16 m^2/ha	The study was not based on optimisation, as it identified alternative cutting cycles and intensities and compared results with RF
	Spruce, birch, pine (mixed forest)	Central Finland/ Mesic forest	With an interest rate of 3% and a deciduous tree coverage of 40%, CCF is more profitable than RF in mixed forests[c]	The initial state comprised a 20-year-old seedling stand with 1750 spruce seedlings/ha and 250 natural seedlings of other tree species (deciduous trees), but the results can be generalised for bare land
	Spruce, pine	Central Finland/ relatively sub-xeric (+) forest	For spruce, CCF is more profitable[d] if the interest rate is 3%, and forest regeneration costs are more than EUR 0/ha. For pine, RF is more profitable when the Bollandsås model is applied, regeneration costs are no more than EUR 1000/ha, and the calculated interest rate is 3%. When the Pukkala model is applied, CCF is more profitable[d] when the interest rate is 3%, and regeneration costs range from EUR 0 to 2000/ha	The results were calculated according to two different ecological models (Bollandsås and Pukkala) using two calculated interest rates (1% and 3%) and different regeneration costs: EUR 0, 500, 1000, 1500 and 2000/ha

(continued)

Table 8.1 (continued)

Initial state	Tree species	Location/Site type	Key results	Specifications and limitations
Young forest	Spruce	Southern and Central Finland/ fresh herb-rich forest heath	CCF is categorically more profitable[e] than RF when the interest rate is 1–5%	The financial examination involved three different initial states, one of which represented an optimal steady-state tree structure, one a young even-aged forest, and the third a mature stand
	Spruce	Southern Finland (Juupajoki) / Mesic forest	RF is more profitable than CCF[f] when using the interest rate of 3%. The cutting cycle ranged from 10–30 years, and the basal area after felling was 4–16 m^2/ha	The study was not based on optimisation, as it identified alternative cutting cycles and intensities, and compared results with RF
Mature stand	Spruce	Southern Finland/Mesic forest	CCF is more profitable[g], provided that the cutting cycle ranges from 10 to 20 years, and the cutting intensity is 4–16 m^3/ha (area after cutting), when using the calculated interest rate of 3%	Stand-level optimisation was not applied
	Spruce	Southern and Central Finland/ fresh herb-rich forest heath	When the interest rate is 3% or higher, CCF is more profitable than clearcutting and artificial regeneration, i.e., RF[h]	The financial examination involved three different initial states, one of which represents an optimal steady-state tree structure, one a young even-aged forest, and the third an even-aged mature stand

The initial state categorized to bare land, young forest and mature stand
[a] Tahvonen and Rämö (2016), Tables 5 and 6
[b] Juutinen et al. (2018a), Fig. 3a (note: forest-level optimisation not used in the study)
[c] Parkatti and Tahvonen (2020), Figs. 4c, 4 g, 4i and Table 5
[d] Parkatti et al. (2019), Table 4
[e] Tahvonen et al. (2010), Fig. 7
[f] Juutinen et al. (2018a), Fig. 3b
[g] Juutinen et al. (2018a), Fig. 4
[h] Tahvonen et al. (2010), Fig. 8

optimisation underestimated the growth of the stands when they were managed through selective harvesting.

Research on the economics of CCF is also limited in Norway. In a series of field trials on 12 mature fields in southeast Norway it was found that selection harvest increased both timber price and harvesting cost slightly compared to RF. The difference in gross margin ranged from −2% to 9% (Glommen Skogeierforening and Mjøsen Skogeierforening 2005). The reported increase in harvesting costs was about one-third of the figure reported from Sweden by Jonsson (2015). Økseter and Myrbakken (2005) calculated the NPV of CCF and RF for the same trials. Their main result is that profitability on average is roughly the same for both regimes and is independent of the interest rate (2.5–4%). There is a large spread between the individual trials. At a 2.5% discount rate, CCF yielded a NVP from 90 to 120% of that for RF, varying according to the field characteristics and assumptions about growth response to selective harvest.

Granhus et al. (2022) studied 19 Norway spruce fields, comparing CCF with RF. The stands cover a large range of different forest conditions and CCF harvest types, ranging from shelterwood cutting to multi-layer CCF. Thinning quotient ranged from 0.77 to 1.69. The results from the economic analysis revealed that, for about half of the stands, CCF resulted in a higher NPV than RF. Since the stands were not selected systematically, it is hard to generalise the results.

A matrix model for economic evaluation of forestry including CCF under Norwegian conditions—the T model (Gobakken et al. 2008)—was developed more than a decade ago. The underlying growth model (Bollandsås et al. 2008) has been used in Finland by, e.g., Tahvonen and Rämö (2016), but is hardly used in Norwegian studies. Gobakken et al. (2008) estimated the optimal choice of management system (CCF vs. RF) in terms of NPV for a set of regenerated spruce stands. These had the same basal area (20 m^2/ha), but different diameter distributions. CCF yielded the largest NPV for the stands with a clear inverse J-shaped tree diameter distribution. For uniformly and normally distributed stands, RF with natural regeneration was most profitable.

8.5 Conclusions and Further Measures

Based on recent studies, CCF is more profitable than RF in spruce forests and spruce-dominated mixed forests on mineral soils when the interest rate is at least 3%, and the site type is not too fertile (e.g., Parkatti et al. 2019; Parkatti and Tahvonen 2020; Tahvonen 2022). The initial state (bare land, young forest, or forest mature for regeneration felling) is a less significant factor than the stand structure in the initial situation (size class distribution). However, estimates of financial profitability involve various uncertainties (Juutinen et al. 2020), and existing growth models need to be constantly improved to better describe tree growth dynamics (Kuuluvainen et al. 2012). Processes needing better models include natural regeneration (e.g., Hokkanen 2001; Eerikäinen et al. 2014; Saksa and Nerg 2008), the growth of large trees, higher than 1.3 m (e.g., Lundqvist 2017; Hynynen et al. 2019; Bianchi et al. 2020), harvesting costs (e.g. Granhus and Fjeld 2001; Surakka and Sirén 2007; Laitila and Repola 2023), and damage risks (e.g., Piri and Valkonen 2013; Hanewinkel et al. 2014; Pukkala et al. 2016; Nevalainen 2017; Nevalainen and Piri 2020). To date, these processes have not been taken into account in detail in financial analyses. This also applies to how stumpage prices develop, including the prices of different assortments relative to one another.

Financial studies of CCF have focused on mineral soils and only one study has considered Finnish peatland forests (Juutinen et al. 2021). The financial performance of CCF should also be studied further from the perspective of climate change mitigation. New studies will also be required to identify the financially reasonable growing stock in CCF on peatlands, while taking into account the ability of trees to maintain a favourable water level for growth through evaporation without the need for remedial ditching (Juutinen et al. 2021; Shanin et al. 2021).

Carbon sequestration should also be considered with regard to CCF. According to preliminary research results, if landowners were paid for the carbon sequestered in trees, CCF would be even more profitable than RF, but this depends on the carbon price applied (Parkatti et al. 2023). A higher carbon-emission trading price seems to extend the cutting cycle in CCF and increase the average tree capital (Assmuth et al. 2018, 2021; Parkatti and Tahvonen 2021). This also seems to apply to RF. In pine forests where RF is applied, a carbon price of EUR 20–60/tCO_2 extends the cycle by 10–40 years and increases carbon stocks per hectare by 27–80% (Niinimäki et al. 2013; Pihlainen et al. 2014).

Some studies (e.g., Assmuth et al. 2018; Rørstad 2022) suggest that the impact of carbon payments is more significant at higher interest rates. When low interest rates are used, the tree capital is usually higher, the cutting cycle longer, and carbon sequestration higher compared to when high interest rates are applied. A high interest rate favours early revenues, considering the carbon payments relative to cutting revenues. However, the results partly depend on what proportion of a forest's carbon stocks is included in calculations, and what carbon sequestration payment scheme is assumed (Juutinen et al. 2018b).

In the light of recent studies, CCF is an optimal solution in northern Lapland when the interest rate is 3% or higher (Parkatti and Tahvonen 2021). If the price of carbon is between €EUR 60-€EUR 100 tCO_2^{-1}, harvesting any old pine forests in the region could never be profitable. If an old-growth forest is, however, managed according to RF the carbon choke price would be €EUR 29 (interest rate 1%) or €EUR 14 tCO_2^{-1} (interest rate 3%), when the benefits of multiple uses (reindeer husbandry) are considered.

In conclusion, the reliability of estimates of tree development has a significant impact on the results of profitability comparisons between CCF and RF. The development dynamics of even-aged forests are fairly well known, and their growth and regeneration models are based on extensive long-term empirical studies on mineral soils and peatlands. However, the impact of CCF on growth and profitability is not yet well known, and reliable tree growth and regeneration models are currently unavailable. Regeneration, initial tree development and the revival of suppressed trees are key to assessing the long-term growth and yield impact and cutting possibilities of CCF, but little research data is yet available about harvesting costs and damage. No harvesting cost models based on empirical data have been published, and the costs presented are often based on models derived from even-aged forests.

Take Home Messages
When deciding whether to apply CCF or RF the structure and volume of the initial stand define the elements for success. As a rule of a thumb: on mineral soils low interest rates (<3%) favour RF, while CCF outperforms RF when high interest rates are applied. Then including carbon sequestration might change the financial ranking between RF and CCF, but the outcome depends greatly on the carbon price applied and how carbon is included in the models. Also benefits of multiple uses (e.g., reindeer husbandry) need to be taken into account which might alter results, too. To date, few results are available for peatlands—more studies are needed to enable financial comparison between CCF and RF.

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