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Private Land, Public Goods: Aligning Forest Management with Climate Goals in Sweden

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Abstract

To comply with EU climate targets, Sweden urgently needs short-term policies to enhance carbon sequestration. This study examines how the introduction of carbon subsidies affects harvest decisions, profitability and carbon storage in mature forests in northern Sweden. Using an empirically calibrated optimal rotation model that distinguishes between pulpwood and sawlogs to reflect changing timber composition with age, we show that a carbon subsidy of 400 SEK/tCO_2 ($40) postpones harvest by 14 to 19 years and increases per-hectare profitability for private forest owners by 7 to 18 percent. Higher carbon subsidies yield longer postponements but at a diminishing rate. At the regional level, the harvest deferrals could increase carbon storage by up to 7 million tCO_2 annually from 2026–2029. Even modest carbon subsidies (115–213 SEK/tCO_2) can drive significant deferrals given fixed-length contracts. Economically, these results demonstrate that targeted carbon payments can align private incentives with societal climate objectives, offering both immediate financial benefits to forest owners and significant public benefits through increased carbon sequestration.

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1 Introduction

Climate change poses a fundamental threat to life on earth and requires urgent political action. To avoid severe consequences, carbon dioxide levels must be rapidly reduced through both emission cuts and enhanced carbon sequestration. While carbon capture technology remains largely experimental, increasing attention has been directed toward nature's capacity for carbon storage to mitigate climate change.

The EU legislative framework on Land Use, Land-Use Change, and Forestry (LULUCF) (2018/841, revised in 2023) aims to ensure that carbon removals from forests, agricultural land, and wetlands contribute to the EU's climate targets by requiring member states to balance emissions from this sector with removals. A key aspect of the regulation for the period 2026-2030 is the new net carbon removal targets, which Member States must integrate into their National Energy and Climate Plans (NECPs). If the Member States fail to comply with the regulation, they may face financial penalties (European Commission 2025). As Sweden holds a substantial share of the forested land in the EU, the nation plays a pivotal role in achieving these objectives. Consequently, proposals for economic incentives, such as carbon sequestration payments to forest owners for delaying harvests, have gained attention to enhance carbon storage in forests. By postponing harvests, forests continue to accumulate carbon, thereby contributing to climate mitigation efforts. These policy measures highlights the broader environmental and economic significance of Sweden's forestry sector in addressing climate change.

In August 2022, the Swedish parliamentary committee Miljömålsberedningen (hereafter referred to as the Committee on Environmental Objectives) was tasked with assessing the national measures required to meet Sweden's LULUCF commitments of increased carbon sequestration. Specifically, these commitments include increasing total carbon sequestration by 3,5 million tonnes per year and at least 14 million tonnes in total between 2026 and 2029, compared to a baseline period of 2016-2018. One of the suggestions is for the Swedish Forest Authority to establish carbon sequestration agreements, granting private forest owners financial compensation for refraining from harvesting their trees for a period of 5 or 20 years. The participating forest owners are proposed to receive a payment of 400 SEK per tonne of CO_2 sequestered during the given period. At the end of the contract, the forest stand must have reached an average age greater than the final recommended harvest age (SOU 2025:21).

Because most forests will eventually be harvested, causing large parts of the sequestrated carbon to be returned to the atmosphere, the rationale for the proposal is primarily intended as a short-term measure to achieve the LULUCF target for the 2026–2029 period. The proposal aligns with numerous past initiatives in both policy and academia that advocate for using economic instruments to incentivize harvest postponement (Assmuth et al. 2024; Gren and Aklilu 2016).

There is a lack of empirical research assessing the potential of carbon sequestration incentives in Sweden. Our study addresses this gap by analyzing how varying levels of financial compensation for carbon sequestration influence forest owners' decisions regarding rotation length (defined as the time between the planting and final harvest of a stand) and the corresponding effect on forest owner profitability as well as the carbon sink. Using an extended version of the well-established Faustmann model calibrated with data from northern Sweden, we estimate optimal rotation lengths under varying carbon subsidies, assuming profit-maximizing forest owners and infinitely lived households. The results offer policy-relevant insights on how carbon subsidies can better align private landowner incentives with climate objectives.

Our study adds to the existing literature both theoretically and empirically. First, we extend the Faustmann model with carbon payments to consider mature stands as well as the changing ratio of forest products. This extension illustrates how rotation length influences timber quality, and better adjusts the model for short-term policy analyses. Empirically, we provide numerical estimates on optimal harvest deferral, forestry profitability, and the carbon sink based on data from northern Sweden.

We address the following research questions:

- How do different levels of carbon subsidies influence the optimal rotation age in privately owned Swedish forests?
- What are the effects on the profitability of private forest owners under such subsidy schemes?
- How do these subsidies impact total carbon storage in Sweden?

Our results indicate that carbon benefits can substantially delay harvest for mature stands with positive short-term effects on both the carbon sink and forest owner profitability. Under a carbon subsidy of 400 SEK/tCO_2, all private forest owners will postpone harvest for at least four years. Assuming that all mature stands would otherwise be harvested, this could yield an additional 29.42 million tons of CO_2 sequestered in northern Sweden by 2029. It would also increase the net present value per hectare of forest land by between 7 to 18 percent. Our results further suggest that for

the time period 2026-2029, a four year deferral can likely be obtained already at a benefit level of 115-213 SEK/tCO_2 given fixed length contracts, depending on ecological conditions.

While our model offers estimates of carbon impacts and private profitability, it does not assess the total fiscal cost of the program or the opportunity cost of public spending. These outcomes depend on broader political priorities and are therefore beyond the scope of this study. Nevertheless, our results offer a clear starting point for informing those discussions. Policymakers can estimate the subsidy's total cost by multiplying the per-ton rate by the projected volume of CO_2 sequestered (before adding administration and transaction expenses). Likewise, dividing total outlays by total tonnes stored yields a cost-per-tonne metric that can be benchmarked against alternative carbon-sink investments.

The remainder of the paper is organized as follows. Section 2 provides background on the Swedish forest sector and the economic principles underlying carbon subsidies. Section 3 provides a review of the previous literature on forest carbon sequestration dynamics and optimal rotation length models. Section 4 presents the model specification, while Section 5 reports on the results from the different empirical specifications. Section 6 synthesizes the empirical findings and discusses the results. Section 7 contains the conclusions.

2 Background

2.1 The Swedish Forest and Ownership Structures

Forests cover approximately 70 percent of Sweden's land area, amounting to over 28 million hectares, of which 23.2 million hectares are classified as productive forest land. The Swedish forests primarily consist of Norway spruce (42 %) , Scots pine (39 %), and birch (12%) (Swedish Forest Agency 2014). Forest land is generally distinguished based on the site productivity, which is determined by the average yield and can be measured through the site index (SI). Although the Swedish forest land exhibits relatively low site productivity on a global scale, notable internal variation exist. Typically, SI values increase towards southern regions and coastal areas in the east (Petersson et al. 2024).

Sweden's forests are of considerable importance to the national economy. The forestry sector represents around 2.5 percent of Sweden's GDP and employs approximately 40,000 people directly, with considerably higher indirect employment figures. Furthermore, the forestry sector is one of Sweden's largest export industries, with forest-related exports accounting for approximately 10 percent of the total exports. The industry involves several stages of production. In the first step, harvested material is sorted into sawlogs and pulpwood. These are then processed into key products such as sawn timber, paper, and bioenergy. A distinctive feature of Sweden's forestry sector is that much of the value chain, from harvesting to processing and export, is carried out domestically, fostering strong integration within the national industry (Swedish Forest Industries 2022).

There are about 311,000 individual forest owners in Sweden. Collectively, they own around half of the total forest area, and the average holding is 34 hectares. As is implied by this modest number, most forest owners do not earn their primary income from the forest; only 8 percent of those surveyed in The Forest Barometer 2023 derive the majority of their income from forestry. Most individual Swedish forest owners have acquired their land through family inheritance, and there is a general trend of property transfer within families rather than through sales on the open market (Olsson et al. 2023).

Private forestry in Sweden typically yields low or even negative profits, although absolute numbers depend on market dynamics and weather conditions. This pattern is especially evident in low site index regions such as northern Sweden, where estimated net present values from a bare land perspective often are negative (as shown in Table 6). Harvesting and regeneration costs become high

relative to the anticipated future revenues from timber sales, which reduces the overall profitability.

The Swedish forests have in recent years been subject to two opposing trends with major impacts on timber volumes and the carbon sink. On the one hand, the total standing timber volume has almost doubled during the last century and is estimated at 3.6 billion cubic meters. The development of timber stocks is primarily driven by forest management practices aimed at enhancing production and growth. In general terms, this involves harvesting older, sparse, and low-productive stands and replanting them with improved seedlings, resulting in new, rapidly growing forests. Replanting of forests after felling is further mandated by Swedish law (Petersson et al. 2024).

On the other hand, annual forest growth has decreased substantially in the past seven years, marking a departure from the generally increasing growth trend observed since the 1950s. This downturn is likely attributable to changing temperature and precipitation conditions (Rummukainen 2024). The slowdown in growth, combined with historically high harvesting levels, averaging 95,4 million m^3 per year during the 2018/2019-2022/2023 season, has caused a significant decline in net growth. Harvesting levels have increased partly as a result of shorter rotation ages. More stands are harvested closer to the lowest legal harvest age than 20 years ago. As a result, Sweden's aggregate net forest growth is currently at its lowest level since the 1970s (Petersson et al. 2024).

In this paper we focus on northern Sweden, both in terms of data and modeling. In forest economics literature, Sweden is typically divided into a northern and southern region due to significant differences in both geographic conditions and market characteristics. We follow the classification used by the Swedish Forest Agency in its official guidance documents, where northern Sweden comprises all of Norrland, the region of Dalarna, and the municipality of Torsby in Värmland. This area accounts for approximately 56 percent of Sweden's total productive forest land (Swedish Forest Agency 2023a). Due to slower forest growth in northern Sweden, only 34 percent of the total national harvest originated from the region during the 2018/2019 to 2022/2023 period. This limited output reflects the northern region's lower average soil productivity: 3.35 m^3sk per hectare, as compared to 8.9 m^3sk per hectare in Götaland. This represents site index values of approximately 18 and 28, respectively (Petersson et al. 2024).

2.2 Externalities and Pigouvian taxes

Markets align private and social costs and benefits when they function efficiently. When this alignment fails and private costs differ from social costs, externalities arise. A common response is to implement price-based instruments known as *Pigouvian taxes*. The underlying idea is that when an

economic activity imposes unpriced costs on others, a corrective tax can be used to bring private incentives in line with the social optimum (Baumol 1972). However, as Coase (1960) famously argued in *The Problem of Social Cost*, government intervention is not necessary to resolve externalities provided two conditions are met: (i) property rights are well-defined, and (ii) transaction costs are negligible.

In the case of carbon dioxide emissions and corresponding carbon sequestration, such conditions are not met. When private forest owners plant and nurture trees, they provide a carbon sequestration service for which they are not compensated, resulting in an underprovision. The absence of enforceable property rights to atmospheric carbon and the high transaction costs of coordinating with thousands of small forest owners makes a strong case for the application of a Pigouvian taxation scheme. But who is to be taxed or subsidized? In his seminal work, Baumol (1972) theoretically proved that when externalities involve public goods, Pigouvian taxes or subsidies applied to the generator of the externality are sufficient to achieve optimal resource allocation.

Solving the underprovision of carbon sequestration in the forestry sector is far from easy, since goal conflicts are common. Increasing carbon storage typically reduces timber harvests and may have negative short-term effects on biodiversity when more intense harvest practices are used (SOU 2025:21). Designing a comprehensive Pigouvian system requires accounting for all these values, which is practically and politically difficult.

One of the main challenges with Pigouvian instruments is determining the correct level of taxation or subsidy. Ideally, this level should reflect the marginal cost or benefits of the activity. Due to administrative costs and political constraints, policymakers sometimes prefer bans or regulations over price mechanisms, since direct controls make outcomes more predictable. Baumol (1972) raises this concern, but concludes that even when imperfect, market-based instruments, such as approximate taxes or subsidies, have the potential to improve efficiency.

In Swedish forestry, the alignment of private and social interests has traditionally been pursued through regulation, examples including mandatory replanting and minimum legal felling ages (SOU 2025:21). In this paper, we explore the potential of Pigouvian-inspired carbon subsidies, which would reward the production of carbon sequestration. Theoretically, this is an extension of the arguments by Baumol (1972), suggesting that an optimal allocation is rendered through a tax/subsidy on the generator of an externality. In our case, forest owners who defer harvest provide an additional carbon sink and should therefore be rewarded. In contrast, emissions from harvested wood products are generally not attributable to private forest owners but to industry actors or

consumers. Taxation of harvest is hence not justifiable from a theoretical standpoint.

Because it is very difficult to quantify the marginal social benefit of all forest ecosystem services, we do not attempt to identify the optimal subsidy from a societal point of view. Instead, we evaluate the effects of a range of carbon payment levels, with the goal of extending rotation periods to support Sweden's LULUCF targets.

3 Literature Review

3.1 Forestry and Carbon Sequestration Dynamics

A substantial body of research examines the role of carbon sequestration in forests and its impact on mitigating climate change. Estimates indicate that global forests have absorbed 107 petagrams (Pg) of carbon since 1990, equivalent to nearly half of the world's fossil fuel emissions over the same period. This sequestration potential is however increasingly threatened by deforestation and declining forest growth rates, which undermines the long-term capacity of forests to act as carbon sinks (Pan et al. 2024; Rummukainen 2024).

The impact of forestry practices on the carbon sequestration potential of forests is the subject of academic debate. Proponents of the forest industry generally argue that maintaining high harvest and replanting rates is essential, as young, rapidly growing trees sequester more carbon annually than older ones. From this perspective, intensive forest management could improve the long-term carbon sink capacity of forests (Holmgren 2021).

In the short term, adopting more cautious forest management strategies, such as extending rotation periods, can lead to an immediate increase in carbon sequestration, as forests are given more time to grow and absorb carbon (Swedish Forest Agency 2022). After clear-cutting, studies on boreal forests suggest that it takes 8 to 13 years before the affected area returns to being a net carbon sink (Grelle et al. 2023; Peichl et al. 2023). Short-term increases in carbon uptake are not only important in the moment, but also influence long-term climate outcomes. Surpassing of certain thresholds for global warming is predicted to yield irreversible climate risks that cannot be reversed by stronger action later. In this context, rapid reductions in emissions and accelerated increases in carbon sinks are essential to improve the odds of avoiding such tipping points (Rummukainen 2024).

Moreover, a significant share of the forest carbon sink is stored in the soil. Due to scientific uncertainty, this component is not included in our analysis. It should however be noted that soil carbon stocks can be severely depleted due to harvesting practices (Nave et al. 2009) which further strengthens the case for extended rotation periods as a means to enhance short-term carbon storage.

Additionally, the assumption that older trees sequester significantly less carbon has been challenged. Some studies indicate that mature forests can continue to sequester carbon for centuries,

often at a higher rate than previously assumed (Luyssaert et al. 2008; Rummukainen 2024). These findings suggest that the preservation of older forests may play a more salient role in climate mitigation than traditionally believed.

In a 2023 review, the Swedish Forest Agency analyzed various measures to expand Sweden's carbon sink. The report highlights that delayed harvesting, reduced harvest volumes, and minimized wildlife damage all can contribute to increased carbon sequestration, even in the long term. They found that a 10 percent reduction in harvest volumes has the potential to increase carbon dioxide uptake by 9.6 $MtCO_2$ per year until 2100. Similarly, extending harvest cycles was found to be able to enhance carbon sequestration by 7.5 $MtCO_2$ per year (Swedish Forest Agency 2023b).

Evaluating forest carbon dynamics is further complicated by the role of harvested wood products. Timber products can function as carbon storage pools beyond the point of harvest as long as they remain in use. Some products remain carbon pools for decades, but the general longevity of this type of storage varies significantly depending on the type of product. For example, short-lived paper products, such as disposable cups, release stored carbon back into the atmosphere quickly after production (Bhattacharyya et al. 2013). In Sweden today, the majority of harvested timber is processed into short-lived products, which limits the long-term carbon storage potential (Rummukainen 2024).

To account for this perspective, the LULUCF framework incorporates harvested wood products (HWPs) into carbon accounting, but with weighting factors that reflect their expected lifespan and decomposition rates. While long-lived products such as construction materials can serve as extended carbon sinks, short-lived products contribute to carbon sequestration to a lesser extent due to their rapid turnover (IPCC 2003). An assessment of a carbon benefit program must include the contribution of HWPs to the overall carbon sink.

3.2 Overview of models determining Optimal Rotation Age

Net present value (NPV) calculations have long been used to determine the optimal rotation length in forestry. The foundation of modern forest economics was laid by the German economist Martin Faustmann, who in (1849) developed the *Faustmann formula*: the discounted sum of timber revenues from an infinite sequence of identical rotations. Max Pressler refined the mathematical representation in (1860), and Bertil Ohlin later provided the formal proof, showing that the NPV of forest land is maximized when its derivative with respect to harvest time is zero (1921). These

contributions established the intertemporal optimization approach that is still widely used today.

3.2.1 Incorporating Externalities and Carbon Pricing

Over time, the model has been expanded by numerous researchers to account for additional factors influencing forest management. Hartman (1976) extended the Faustmann formula by incorporating non-market benefits, such as the value of recreation. By allowing forest owners to derive value from standing forests beyond just timber, he demonstrates that this can incentivize delayed harvesting and lead to more efficient outcomes.

Building on this, Van Kooten et al. (1995) adapted the model to include carbon taxes and subsidies to account for the positive externality of carbon sequestration. In this commonly applied long-term scheme, based on Pigouvian principles, landowners receive a subsidy for carbon uptake, and pay an equally sized tax when carbon is released at harvest. Their findings, based on Canadian empirical data, suggest that introducing a carbon price of $50 could extend the optimal rotation period of boreal forest by 8 to 56 years under a 5 percent discount rate, with variation depending on the timber price and the proportion of harvested wood allocated to long-term storage.

More recent extensions study alternative setups for the carbon benefit schemes. J. Sartori et al. (2024) develop a model in which landowners receive a fixed, annual carbon subsidy only during the first rotation, in exchange for deferring harvest. All subsequent rotations then follow the standard Faustmann formula for net present value. Their goal is to identify the socially optimal deferral by equating landowners' marginal costs with society's marginal benefits of sequestration. To better reflect current policy debates, they omit any carbon release tax at harvest. Calibrating the model with U.S. data and a 2 percent discount rate, they show that on low-productivity soils a subsidy of about $90 per tCO_2 induces a harvest delay of roughly 14 years, whereas on high-productivity soils the optimal rotation age remains unchanged from the no-subsidy benchmark.

The carbon payment structure proposed by J. Sartori et al. (ibid.) can be further contrasted with papers such as West et al. (2019) who apply an ex-post payment structure and applies it in all future periods, and the policy proposal by the Committee on Environmental Objectives (SOU 2025:21) who suggests ex-post payments through "carbon agreements". We adopt Sartori's conceptual logic of annual carbon benefit streams without a carbon release tax during the harvest deferral period, but determine the subsidy level based on forest growth, following the approach of Van Kooten et al. (1995). Unlike ex-post payments, this setup initiates the subsidy stream immediately, resulting in

lower discounting of benefits. To ensure predictability and administrative feasibility, forest owners could still enter formal contracts with the payment authority responsible for payments.

Table 1: Comparison of Optimal Rotation Models in previous studies. The original equations have been edited to facilitate comparison.

Model	Main Feature	NPV Equation
Faustmann (1849)	Maximizes *net present value (NPV)* by determining the optimal harvest age T* from bare land.	$\max_T \frac{\pi v(T) e^{-rT} - C_R}{1 - e^{-rT}}$
Hartman (1976)	Incorporates *non-market benefits, $\gamma(t)$* (e.g., recreation, biodiversity) to the Faustmann model.	$\max_T \frac{\pi v(T) - C_R e^{-rT} + \int_0^T \left[\gamma(t) e^{-rt} dt\right]}{1 - e^{-rT}}$
Van Kooten et al. (1995)	Incorporates *Carbon Taxes and Subsidies* and determine the optimal harvest age T* from bare land.	$\max_T \frac{P_C \alpha \left[v(T) e^{-rT} + r \int_0^T v(t) e^{-rt} dt\right]}{1 - e^{-rT}} + \frac{(P_T - P_C \alpha(1-\beta)) v(T) e^{-rT}}{1 - e^{-rT}}$
Sartori et al. (2024)	Incorporates carbon subsidies, *S*, for landowners in exchange for a rotation deferral of *N* years only in the first period, starting from bare land.	$\max_N \pi v(T+N) e^{-r(T+N)} + \int_T^{T+N} S e^{-rt} dt - C_R + \frac{\pi v(T) e^{-rT} - C_R}{1 - e^{-rT}} e^{-r(T+N)}$

Note: π is the stumpage price (timber price - felling cost), C_R is the regeneration cost, r is the market interest rate, α is the biomass expansion factor, P_c is the carbon price, and P_T is the timber price.

3.2.2 Empirical Rotation Studies in Sweden

Some studies have assessed the impact of carbon benefits using Swedish empirical data. Backéus et al. (2005) applies a Faustmann-style optimization to Västerbotten county and finds that a carbon price of 680 SEK/tCO_2, the Swedish carbon tax at the time, would effectively halt all harvesting, generating an additional 2.09 million tonnes of CO_2 sequestration each year. Already at a price level of approximately 100 SEK/tCO_2 they find a significant optimal harvest deferral. The model includes both a subsidy for carbon sequestration and a tax on carbon losses from harvest. Similarly, Guo and Gong (2017) employ a forest sector optimization model and empirical parameters that capture 85 percent of Swedish productive forestland and estimate that a carbon price of 680 SEK/tCO_2 could yield a net increase in the carbon sink of approximately 150 million tonnes over 2015-2050 compared to the counterfactual case.

3.2.3 Timber Price Dynamics

The treatment of timber prices varies widely across the existing literature. While Van Kooten et al. (1995) assumes an exogenous and fixed price, Ekholm (2019) adopts a timber price function that increases as the forest matures. J. Sartori et al. (2024) accounts for this value progression by

differentiating between pulpwood and sawlogs, while Guo and Gong (2017) employ an endogenous timber-price mechanism within a dynamic forest sector optimization model. Under carbon pricing, Guo and Gong (ibid.) find that reduced harvest volumes and the inelastic demand for timber drive up market prices which makes harvesting more profitable.

Given our focus on the behavior of the individual forest owner and the substantial price difference between sawlogs and pulpwood, we adopt the approach of J. Sartori et al. (2024) using exogenously given prices for each product type. The proportion of sawlogs relative to pulpwood evolves over time, with the share of sawlogs increasing as the forest matures. Given that sawlogs typically generate higher revenue compared to pulpwood, this provides forest owners with additional economic incentive to extend their rotation periods. Additionally, sawlogs are more often used in long-lived wood products, which contributes to a larger carbon sink.

All of the cited optimal rotation models assume that forest management begins on bare land, even though a substantial share of forest land is already mid-rotation at any given time. In contrast, we adapt the Faustmann-style model used in J. Sartori et al. (ibid.), which includes carbon subsidies only in the first rotation period, but modify it to start from mature forest. To our knowledge, this is the first study to extend the Faustmann formula to a mature stand case. The approach aligns with our focus on the 2029 to 2029 period, as meaningful deferral can only occur in stands that would otherwise have been harvested. This has important implications for optimal deferral, as regeneration costs are avoided in the first period and carbon payments can be received immediately which reduces the impact of discounting.

4 Methodology

This paper extends the optimal rotation model with carbon sequestration payments to apply specifically to mature stands. Building on the work of Van Kooten et al. (1995), we consider homogeneous, even-aged forest stands harvested through clear-cutting at the end of each optimal harvesting cycle and employ a dynamic intertemporal optimization model where carbon benefits are linked to biomass increases. To increase Swedish policy relevance, we adjust our model to incorporate the concept of *additionality*, compensating forest owners only for carbon gains from delayed harvests that exceed the minimum legal harvest age. This is economically efficient, as forest owners otherwise would be compensated for a service they are legally required to provide due to Sweden's mandatory minimum rotation ages. Future rotations revert to the traditional Faustmann model, in line with Swedish policy proposals and long-term uncertainty. We also distinguish between pulpwood and sawlog growth to reflect changing timber composition with age.

The model assumes infinitely lived forest owners which reflects the inter-generational nature of forest ownership in Sweden, where land often is passed down within families. The model therefore maximizes the net present value over an infinite time horizon. The focus on private forest owners follows the policy proposals from the Committee on Environmental Objectives (SOU 2025:21). Their harvest decisions are particularly responsive to financial incentives such as short-term deferral programs because their land use is more flexible than industrial actors tied into supply chains and long-term contracts.

The following sections outline the model in detail. We specify the structure of the optimization problem, and compare it to that of a bare land case. Next, we derive the first-order conditions, and explain the forest growth functions. Lastly, we quantify the effects of carbon payments on both net present value and carbon sequestration—first at the stand level, and then in aggregate for northern Sweden.

4.1 The Optimization Problem

Our theoretical foundation is simple. Forest owners respond to prices when deciding when to harvest and carbon subsidies change the relative payoff of harvesting now versus postponing. Therefore, a well-calibrated subsidy can shift behavior toward longer rotations.

The forest owner optimizes the net present value of their stand, in SEK/ha, by determining the optimal harvest period deferral N in the first period and the optimal rotation length in all following periods T. The equation thus follows a nested optimization structure. For forest owners with mature stands at the time of the policy intervention, the equation becomes:

$$\max_{T,N} \underbrace{\big(\pi_s v_s(T_1{+}N) + \pi_w v_w(T_1{+}N)\big)e^{-rN}}_{\text{(i) timber revenue}} + \underbrace{P_c\alpha \int_0^N \big[v_{\text{tot}}(T_1{+}t) - v_{\text{tot}}(T_1{+}t-1)\big]e^{-rt}\,dt}_{\text{(ii) carbon benefits}} + \underbrace{\frac{\big[\pi_s v_s(T) + \pi_w v_w(T)\big]e^{-rT} - C_R}{1-e^{-rT}}\, e^{-rN}}_{\text{(iii) value of future rotations}} \tag{1}$$

To enable comparison and highlight the contribution of our model, we also perform calculations on a more traditional version of the model from a bare land perspective:

$$\max_{T,N} \underbrace{\left(\pi_s v_s(T_1+N) + \pi_w v_w(T_1+N)\right) e^{-r(T_1+N)}}_{\text{(i) timber revenue}} + \underbrace{P_c\alpha \int_{T_1}^{T_1+N} \left[v_{\text{tot}}(t) - v_{\text{tot}}(t-1)\right] e^{-rt}dt - C_R}_{\text{(ii) carbon benefits with regeneration cost subtracted}} + \underbrace{\frac{\left[\left(\pi_s v_s(T) + \pi_w v_w(T)\right) e^{-rT} - C_R\right]}{1-e^{-rT}} e^{-r(T_1+N)}}_{\text{(iii) value of future rotations}} \tag{2}$$

where:

- π = timber profit for sawlogs (s) and pulpwood (w), calculated as the timber price minus the harvesting cost in SEK/m^{3}fub, where m^{3}f ub is the timber volume without bark.
- r = market interest rate.
- C_R = discounted regeneration cost starting from bare land in SEK/ha.
- P_c = carbon subsidies per tonne of additional CO_2 stored by extending rotation length.
- α = biomass expansion and conversion factor (BECF). Following previous research, a value of 1 is used in this paper (Guo and Gong 2017).
- T_1 = the lowest legal harvest age, which is determined by soil productivity and stipulated in Swedish law.
- v = forest growth function for sawlogs (s), pulpwood (w) and the total biomass (tot).

Timber prices and harvest costs are determined exogenously by historical data from the Swedish

Forest Agency (2025a). The optimal net present value is calculated using a sawlog price of 553.5 SEK/m^3f ub, a pulpwood price of 378.8 SEK/m^3f ub, and a felling cost of 143 SEK/m^3f ub. The regeneration costs are based on standards provided by the Swedish Forest Agency (2009) and include expenses for site preparation, planting, and pre-commercial thinning. They are set to 14500 SEK/ha and 11400 SEK/ha for high- and low-productivity sites, and assumed to increase linearly with site index. Our model excludes thinning revenues and costs, as early thinnings in northern Sweden often yield minimal returns. A thorough presentation of prices and costs can be found in Appendix A.

Eq (1) and (2) illustrate our key theoretical contributions, namely the distinction between sawlog and pulpwood as well as the adaption of the model from bare land to mature stand conditions. Notably, all revenue (both from timber and carbon subsidies) is heavily discounted in the bare land case since it lies at least 65 years into the future. Carbon benefits on mature stands are however payed out directly, which is why the integral starts at year 0.

We evaluate net present value and optimal harvest deferral across different carbon subsidy levels. In addition to the 400 SEK/tCO_2 proposed by the Committee on Environmental Objectives, we apply 800 SEK/tCO_2, reflecting the current EU ETS price, and 1200 SEK/tCO_2, based on the social cost of carbon from the DICE-model (Barrage and Nordhaus 2023). Unlike approaches such as J. Sartori et al. (2024), carbon benefits are treated as exogenous rather than derived from a social optimization framework. The model is implemented in the statistical program `R` and solved using nested optimization, where the long-term rotation age T must be at least as large as T_1. The nested methodology, optimizing over both N and T, constitutes an additional contribution of this study. If one sets $P_c = 0$, the model simplifies to a standard Faustmann optimization framework, differentiated for the main forest products.

4.2 First Order Condition

We differentiate Eq. (1) with respect to the optimal harvest deferral period N to obtain the first order condition of the forest owner's optimization problem. In principle, the maximization in (1) is defined over both the initial delay period N and the subsequent rotation length T. However, in all numerical cases considered (given legal minimum ages, growth curves, and reasonable parameter values), the interior solution for T coincides with the legal lower bound such that $T = T_1$. Accordingly, we impose this constraint and reduce the problem to a single-variable maximization with respect to N. Rearranging yields the following expression:

$$\underbrace{\pi_s\, v_s'\big(T_1+N\big)+\pi_w\, v_w'\big(T_1+N\big)+P_c\,\alpha\big[v_{\text{tot}}(T_1+N)-v_{\text{tot}}(T_1+N-1)\big]}_{\text{(i) marginal timber benefit + marginal carbon benefit}}$$

$$=\underbrace{r\Big[\pi_s\, v_s(T_1+N)+\pi_w\, v_w(T_1+N)\Big]}_{\text{(ii) opportunity cost of delaying one year}}+\underbrace{r\,\frac{\big[\pi_s\, v_s(T_1)+\pi_w\, v_w(T_1)\big]e^{-rT_1}-C_R}{1-e^{-rT_1}}}_{\text{(iii) opportunity cost of all future rotations}} \tag{3}$$

This condition ensures that, at the optimum, the sum of the marginal timber and carbon benefits must equal the opportunity cost of delaying harvest revenues one more year, along with the opportunity cost of all future rotations, all multiplied by the discount rate.

Rearranging Eq. (3), we can isolate the carbon subsidy and thus get an expression for the marginal break-even carbon subsidy evaluated at the optimal harvest deferral:

$$P_c^* \;=\; \frac{r(\pi_s v_s+\pi_w v_w)+r\,\dfrac{(\pi_s v_s(T_1)+\pi_w v_w(T_1))e^{-rT_1}-C_R}{1-e^{-rT_1}}-(\pi_s v_s'(T_1+N)+\pi_w v_w'(T_1+N))}{\alpha\big(v_{\text{tot}}(T_1+N)-v_{\text{tot}}(T_1+N-1)\big)} \tag{4}$$

P_c^* is the subsidy that exactly balances the incremental benefit and opportunity cost of extending the harvest decision from year N to year $N{+}1$. When the subsidy equals P_c^*, the forest owner's first-order condition is satisfied, making N the privately optimal postponement. Thus, $N = 4$ can be plugged into Eq. (4) to find the P_c^* that results in a four-year deferral being the optimal choice for the forest owner.

Importantly, the optimal choice on the margin does not necessarily mean the most cost-efficient subsidy level. How carbon subsidies influence the optimal rotation age depends on the setup of the carbon program. The Committee on Environmental Objectives has proposed fixed-length carbon contracts, where forest owners commit to a pre-decided period of postponement. We therefore complement our analysis of the three subsidy levels presented in Section 4.1 with a calculation of the "average participation subsidy", defined by the condition $\Delta\,\text{NPV}(N, P_c) = 0$. Under the given assumptions, this subsidy would make the owner indifferent between harvesting immediately and committing to an N-year postponement. The contractual setup delivers the desired postponement at a lower fiscal cost than P_c^*. If opting in and out of the scheme instead was possible each year, the marginal break-even subsidy in Eq. (4) would be required to secure the same outcome.

The objective function is verified to be strictly concave in N, as negative second finite differences across scenarios ensure a unique global optimum is returned by the numerical maximizer. A full derivation of the first and second order conditions is provided in Appendix B. The formulation of

the model assuming a rotation starting from bare land is derived in J. Sartori et al. (2024).

4.3 Modeling Forest Growth

Forest growth and timber yield volumes are calculated using the functions from *The Stand Method for Forest Valuation* (*Beståndsmetoden för skogsvärdering*), a methodology developed in 1988 by Swedish authorities Lantmäteriverket and Lantbruksstyrelsen. All growth functions are estimated specifically for northern Sweden.

Optimal harvest ages varies between Sweden's two dominant tree species: Norway Spruce and Scots Pine. While previous studies on optimal rotation lengths have emphasized the importance of the type of tree (Ekholm 2019; West et al. 2019), the role of tree species in boreal forests is relatively small compared to that of site quality. Additionally, timber supply functions for specific Swedish tree types are not available (Guo and Gong 2017). To account for the differences that exists between different site qualities, calculations will be performed for all site indexes found in northern Sweden. Numerical examples focus on one case of low productivity soil (SI=16) and one case of high productivity soil (SI=28). These also differ in legal minimum harvest age, with full details provided in Table 2.

The growing stock of timber, expressed in m^3sk/ha (forest cubic meter per hectare), is given by the function

$$v_{tot}(t) = MP \cdot FT \cdot 1.6416 \cdot \left(1 - 6.3582^{-t/FT}\right)^{2.8967} \tag{5}$$

where MP is the maximum mean annual increment and FT is the stand age at peak mean annual average increment.

The sawlog yield is given by the expression

$$v_S(t) = Vub(t) \cdot TUB(t) \tag{6}$$

The pulpwood yield is given by the function

$$v_W(t) = Vub(t) \cdot \big(G3M(t) - TUB(t)\big) \tag{7}$$

where $v_S(t)$ and $v_W(t)$ are total harvested volume of sawlog and pulpwood under bark, $Vub(t)$ is the harvested timber volume under bark, $TUB(t)$ is share of sawlog in the harvested volume under bark, and $G3M(t)$ is the share of merchantable timber. Please see Appendix C for further development of these parameters.

4.4 Quantifying the Effect on the Carbon Sink

4.4.1 Carbon sink per hectare

The carbon sink before harvest is modeled solely based on the total forest growth function $v_{tot}(t)$, multiplied by the BECF. The carbon sink after harvest consists of two components: (1) the carbon sequestration of the newly planted forest, and (2) the carbon stored in harvested wood products (HWP). Based on LULUCF guidelines (IPCC 2003), we assume a half-life of 30 years for sawlogs and 2 years for pulpwood, modeled using an exponential function defined by the decay parameter λ. The half-life for sawlogs is based on the average of saw wood and panels, while the pulpwood estimate is based on the lifespan of paper products. We further assume that all of the pulpwood yield is made into end-use products, whereas the processing of sawlogs results in a 50 % biomass loss (International Renewable Energy Agency 2019). Carbon released from the decomposition of forest by-products is excluded, as we assume that all biomass not used for pulpwood and sawlogs is burned. Since a substantial share of the by-products are removed for use as biofuel, this assumption is expected to reflect real-world practices (Swedish Forest Agency 2025b).

$$CS_1(t) = \begin{cases} v_{\text{tot}}(t) & \text{for } t < T_M \\ v_W(T_M) \cdot e^{-\lambda_W (t-T_M)} + 0.5 \cdot v_S(T_M) \cdot e^{-\lambda_S (t-T_M)} + v_{\text{tot}}(t-T_M) & \text{for } t \geq T_M \end{cases} \tag{8}$$

$$CS_2(t) = \begin{cases} v_{\text{tot}}(t) & \text{for } t < T_M + N \\ v_W(T_M+N) \cdot e^{-\lambda_W (t-T_M-N)} & \\ \quad + 0.5 \cdot v_S(T_M+N) \cdot e^{-\lambda_S (t-T_M-N)} & \text{for } t \geq T_M + N \\ \quad + v_{\text{tot}}(t-T_M-N) & \end{cases} \tag{9}$$

CS_1 represents the case without carbon benefits where the trees are assumed to be harvested when they are mature at T_M. CS_2 represents the case with carbon benefits where harvest is delayed until

$T_M + N$. To estimate the annual and cumulative changes in carbon sink under different management scenarios, we simulate the carbon stock per hectare for each year $t \in \{2026, 2027, 2028, 2029\}$ as that is the period during which the LULUCF sector is expected to increase its carbon uptake by 14 billion tonnes. The annual change in carbon sink is computed as $\Delta CS_2(t) = CS_2(t) - CS_2(t-1)$ and $\Delta CS_1(t) = CS_1(t) - CS_1(t-1)$, and their difference is $\Delta CS(t) = \Delta CS_2(t) - \Delta CS_1(t)$.

In 2026, the immediate effect of harvest is captured by comparing the carbon stock at the start and end of the year, assuming harvest occurs mid-year. This results in: $\Delta CS_2(2026) = CS_2(\text{end of } 2026) - CS_2(\text{start of } 2026)$ and $\Delta CS_1(2026) = CS_1(\text{end of } 2026) - CS_1(\text{start of } 2026)$. The cumulative difference over the period is calculated as the sum of annual differences.

We model the net change with a counterfactual harvest year since it isolates the incentive effect and thus better visualizes the effects of this specific policy. The "no-benefit" scenario emulates the Forest Reference Levels concept from the LULUCF guidelines (IPCC 2003), but at the stand scale. However, for compliance with EU regulation the baseline is exogenous (2016-2018 average sink). This makes our results not directly comparable to previous policy proposals (SOU 2025:21).

4.4.2 Aggregate net carbon sink

To generalize our results, we proceed by calculating the aggregate net carbon sink for mature stands in northern Sweden by identifying every stand that is currently classified as mature in 2026 and is owned by private forest owners. We then examine the evolution of the carbon sink under both the harvest and delay scenarios. Similar to the per-hectare case, the annual change in carbon sink is calculated for each site index as $\Delta CS_2^{\text{SI}} = CS_2^{\text{SI}}(t) - CS_2^{\text{SI}}(t-1)$ and $\Delta CS_1^{\text{SI}} = CS_1^{\text{SI}}(t) - CS_1^{\text{SI}}(t-1)$.

The difference between the two scenarios is given by $\Delta CS^{\text{SI}} = \Delta CS_2^{\text{SI}}(t) - \Delta CS_1^{\text{SI}}(t)$. These values are multiplied by the area of mature forest (in hectares) corresponding to each specific site index in northern Sweden. Finally, the results from all site index categories are aggregated to determine the expected total carbon sink under each scenario. The difference between these two outcomes represents the overall net carbon sink attributed to private forest holdings in northern Sweden.

Data on privately owned forest areas were collected for Northern Norrland and Southern Norrland, private forest owners, and all available site productivity measures. Average standing-volume data (m^3sk / ha) were obtained for each of six age classes (A, B1, B2+B3, C, D1, D2) with D1 and D2 being the mature age classes. All data were obtained from SLU Riksskogstaxeringen (Petersson et al. 2024). We further elaborate on the data collection and assumptions used in Appendix D.

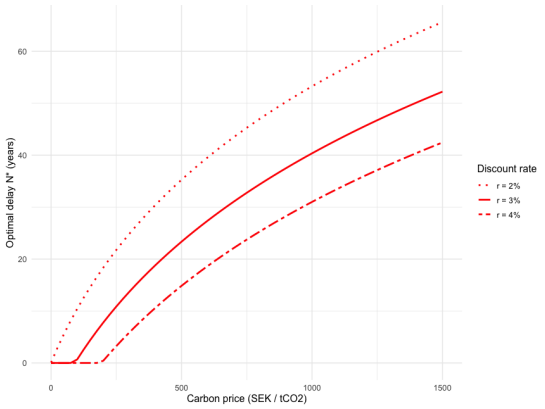
5 Results

We begin by presenting our results on how carbon benefits affect optimal harvest deferral, followed by a sensitivity analysis with respect to discount rates and timber prices. Next, we analyze the impact of carbon benefits on forest owner profitability and identify the carbon subsidy required to incentivize a four-year harvest deferral across site indexes. Finally, we present the resulting carbon sink development under carbon benefits, both at the per-hectare level and in aggregate.

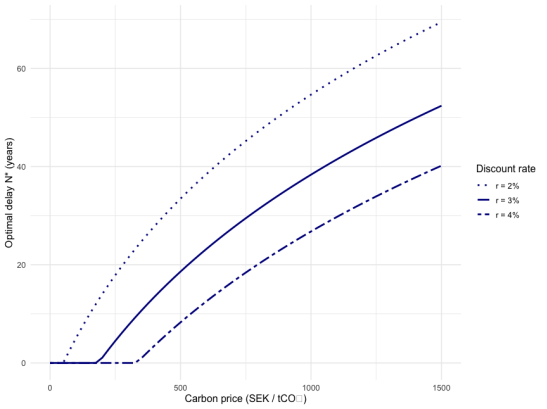
5.1 Optimal harvest deferral

The nested optimization yields a relationship between carbon subsidy and optimal deferral period, shown in Figure 1 for site indices 28 and 16, both for mature stands and bare land. To align with prior literature on boreal forests (Ekholm 2019; Guo and Gong 2017) we apply the standard market discount rate of 3 %. The appropriate discount rate for Swedish forest land does however remain uncertain, with Lantmäteriet (2024) recently suggesting a sliding model ranging from 2.55 to 2.70 %. To account for this uncertainty, panels (a) to (d) include a sensitivity analysis using discount rates of 2 % and 4 %. The 2 % rate reflects the value commonly adopted in the environmental economics literature when the decision-maker is modeled as a benevolent planner rather than a private owner, while Nordhaus's canonical 4 % rate remains prevalent in integrated assessment modeling (Drupp et al. 2018; Nordhaus 2007). For the mature stands case, a sensitivity analysis with timber prices is also conducted. The analysis is based on the average, lowest and highest real sawlog and pulpwood prices (SEK/m^3fub) for 2019-2024, in 2023's price level.

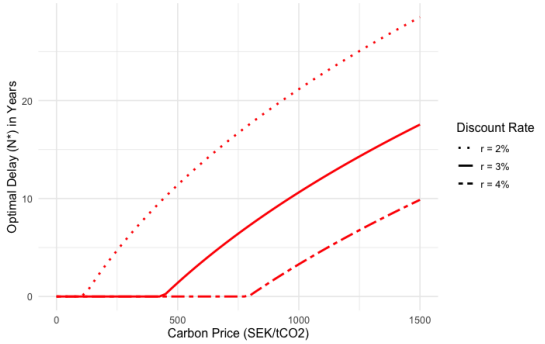
Figure 1: Optimal N^* under carbon benefits for different scenarios and site indices



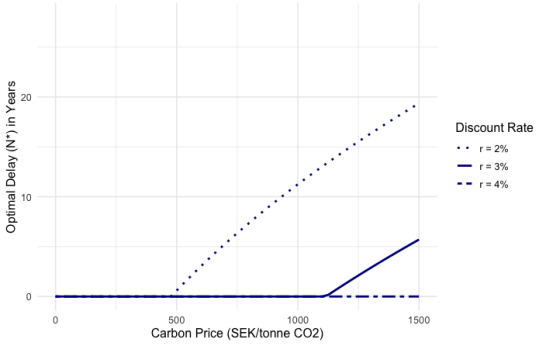
(a) Analysis on mature stands under varying discount rates (SI=28)



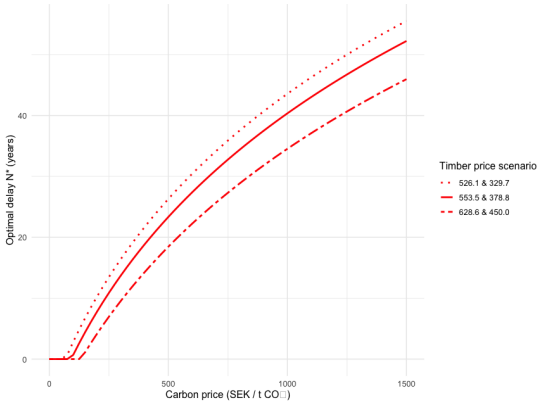
(b) Analysis on mature stands under varying discount rates (SI=16)



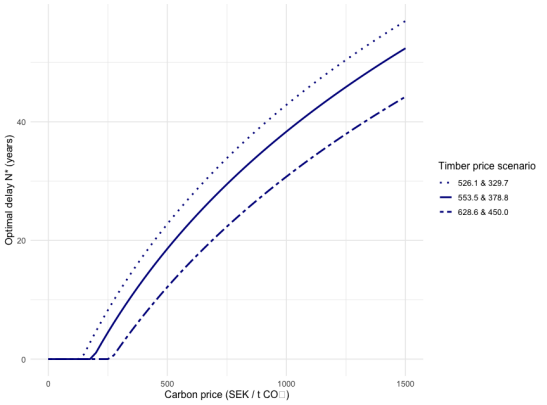
(c) Analysis on bare land under varying discount rates (SI=28)



(d) Analysis on bare land under varying discount rates (SI=16)



(e) Analysis on mature stands under varying timber prices (SI=28)



(f) Analysis on mature stands under varying timber prices (SI=16)

The graphs illustrate three key effects: (i) even modest carbon subsidies substantially increase the optimal deferral period for mature stands, while bare-land scenarios require much higher subsidies to incentivize a delay, (ii) higher carbon subsidies extend N^*, but at a diminishing rate, reflecting declining marginal returns as discounted biomass growth slows with stand age, and (iii) both higher

discount rates and timber prices reduce the optimal deferral period, as they raise the relative value of immediate harvest.

For example, at a carbon subsidy of 400 SEK/tCO_2, harvest on mature high-productivity stands (SI = 28) is optimally postponed by 30 years under a 2 % discount rate, but only 11 years under a 4 % rate. This illustrates the strong influence of time preference and capital cost on harvest decisions. In comparison, timber prices have a smaller effect within the observed range: the optimal delay for SI = 28 falls from approximately 22 years under low prices to 14 years under high prices. However, if carbon subsidies lead to tighter timber supply, future prices could exceed recent highs (2019–2024), potentially exerting a stronger influence on harvest timing.

The graphs suggest that a lower site index shifts the optimal deferral curve outward, meaning the optimal harvest deferral is shorter on low productivity soil. Table 2 shows that under $P_c = 400$ this pattern holds for most site indices, with SI = 12 as the sole outlier, likely because its low standing biomass yields comparatively small timber revenues and thus dampens the incentive effect.

Table 2: Optimal harvest deferral for mature stands N^* by site index at $P_c = 400$ SEK/tCO_2 and $r = 3\%$

SI	**Optimal deferral (N^*)** (years)	**Legal harvest age** (years)	**Regen. cost** (SEK/ha)
12	16	100	10 368
14	14	95	10 884
16	14	90	11 400
18	14	85	11 916
20	15	80	12 432
22	17	75	12 948
24	19	70	13 464
26	19	67	13 980
28	19	65	14 500

As Table 2 illustrates, optimal deferral time N^* varies between 14 and 19. The reason for the small differences across SIs, despite the substantial effect that SI has on forest growth, are the counteracting effects of the site index on the optimal deferral period. A higher site index can increase the optimal harvest deferral period by (i) accelerating forest growth, which increases annual carbon sequestration and thus the total carbon benefits, (ii) raising regeneration costs (see Appendix A), which incentivizes postponing costly replanting, and (iii) lowering the legal minimum harvest age, thereby allowing earlier deferral. On the other hand, a higher site index can shorten the deferral period by (i) increasing forest growth, which raises the opportunity cost of delaying harvest due to greater forgone timber revenue, and (ii) amplifying the relative value of timber revenues, since timber value scales with volume while carbon subsidy subsidies increase linearly with growth.

5.2 Profitability for Private Forest Owners

Forest owners with mature stands meet an increased profitability when carbon subsidy programs are introduced, but the absolute net present value varies greatly with site index.

Table 3: Net present value for mature stands by site index with and without carbon benefits ($r = 3\%$)

SI	**N***	**NPV (SEK/ha)** ($P_c = 400$)	**NPV (SEK/ha)** ($P_c = 0,\ N = 0$)	**ΔNPV** (SEK/ha)
12	16	23 789	21 431	2 358
14	14	36 286	33 663	2 623
16	14	50 008	46 632	3 376
18	14	64 819	60 123	4 696
20	15	80 639	73 882	6 757
22	17	88 978	79 163	9 815
24	19	96 984	83 159	13 825
26	19	105 852	89 894	15 958
28	19	115 070	98 290	16 780

Note: ΔNPV is the incremental value of the land under carbon benefits and optimal delay relative to immediate harvest with no carbon subsidy.

With carbon benefits at 400 SEK/tCO_2, the net present value increases with between 2,358 to 16,780 SEK per hectare, with figures increasing consistently with site index. For the average Swedish forest owner holding 34 hectares, our results translate into an NPV increase of 80,172 to 570,520 SEK, assuming the entire stand is even-aged and mature.

Under the alternative assumption that forest owners enter into fixed-length postponement contracts, the minimum payment that makes participation in the carbon program profitable is any subsidy that yields a ΔNPV marginally higher than zero when comparing a N-year deferral to the no-subsidy case. The rule is true for any length of the harvest deferral period. Accordingly, we solve our optimization function for the carbon subsidy that makes the four year deferral economically neutral for a forest owner, at $\Delta\text{NPV}_{N=4}(P_c) = 0$.

Table 4: Minimum carbon subsidy required for a contractual four-year delay on mature stands

	SI12	**SI14**	**SI16**	**SI18**	**SI20**	**SI22**	**SI24**	**SI26**	**SI28**
SEK/tCO_2	169	205	213	206	190	158	125	115	117

Table 4 shows that a four-year harvest delay can be secured with subsidies well below the 400 SEK/tCO_2 proposed by the Committee on Environmental Objectives. As in the fixed-subsidy analysis of optimal rotation length, owners of high-productivity sites generally show greater willingness to delay harvest, although that pattern is less pronounced here than in Table 2. Very low productivity sites (SI 12–14) diverge from this pattern, requiring lower subsidies than those at SI

16 and SI 18.

The impact of carbon benefits on the optimal harvest deferral and the resulting net present value is further strongly influenced by timber prices. Table 5 compares the NPV outcomes when including the average versus the highest timber prices observed during the 2019-2024 period.

Table 5: Optimal harvest deferral N^* and NPV under carbon subsidies and two different timber-price scenarios for mature stands (SI 28 and 16)

SI	**(SEK/tCO$_2$)**	**Average Prices**		**High Prices**	
		Optimal N^*	NPV (SEK/ha)	Optimal N^*	NPV (SEK/ha)
28	No carbon subsidy	0	98 290	0	122 438
	$P_c = 400$	19	115 070	14	133 923
	$P_c = 800$	34	158 937	29	172 909
	$P_c = 1\,200$	46	211 289	40	222 217
16	No carbon subsidy	0	46 632	0	59 436
	$P_c = 400$	14	50 008	7	60 678
	$P_c = 800$	31	65 589	24	73 041
	$P_c = 1\,200$	45	85 880	37	91 430

As shown in the rightmost column, higher timber prices reduce the optimal deferral period while increasing NPV across all scenarios at SI=28. In the SI=16 case, the pattern is similar, but the absolute values are considerably lower. The table shows how scenarios with high timber prices may result in quite short harvest deferrals under carbon subsidies at 400 SEK/tCO$_2$, especially on low productivity soil. Results under all SI and P_c (0, 400, 800, 1200) are presented in Appendix E.

While the mature land scenarios has positive NPV values both with and without carbon benefits, this is not the case on bare land.

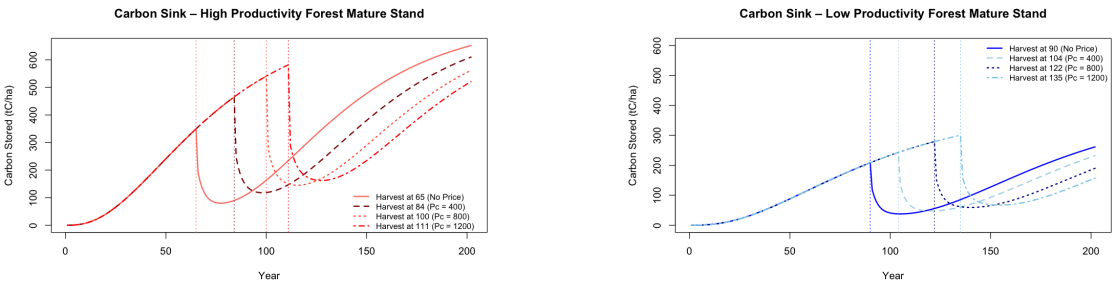
Table 6: Optimal rotation deferral N^* and NPV on bare land at selected carbon subsidies for two site-index classes

SEK/tCO$_2$	**SI = 28**			**SI = 16**		
	T^*	N^*	NPV (SEK/ha)	T^*	N^*	NPV (SEK/ha)
No carbon subsidy	65	0	1245.90	90	0	-7587.63
400	65	0	1245.90	90	0	-7587.63
800	65	7	1654.73	90	0	-7587.63
1200	65	14	2737.80	90	1	-7584.90

Table 6 illustrates how much higher carbon subsidies are needed to incentivize harvest delays from a bare land perspective. Forestry on such land in northern Sweden is often unprofitable, especially on low-productivity sites where NPV remains negative across all rotation ages, even in the presence of large carbon subsidies. Slow growth, high regeneration costs, and a high lowest legal harvest age substantially reduce profitability. Consequently, carbon subsidies need to increase to levels of 1200 SEK/tCO$_2$ to offset the opportunity cost of delay. These findings suggests that values beyond timber revenues may motivate forest management on such land.

5.3 Carbon sequestration dynamics

The postponed harvest impacts the carbon sink in both the short and the long run. Higher carbon subsidies lead to longer rotation periods, which in turn increase the size of the carbon sink. Calculations are only conducted for mature stands, showcasing what is relevant for the 2026-2029 LULUCF commitments.



(a) SI = 28 **(b)** SI = 16

Figure 2: Carbon sink dynamics under different carbon subsidy scenarios, in tCO_2/ha

Figure 2 illustrates how carbon storage dynamics evolve under different carbon subsidies, compared to the counterfactual case. The vertical lines indicate the optimal harvest year for each carbon subsidy, while the curves show the total carbon stored per hectare in the standing biomass and harvested wood products. Higher carbon subsidies encourage forest management strategies that delay harvest which allows the forest to sequester for a longer time and thereby expand the total carbon sink. The eventual decline in carbon sequestration due to harvest becomes smaller relative to the carbon benefits, partly because the share of sawlogs, which has a longer half life, increases with stand age. As shown in the figure, there is however a point where the forest that could have been replanted earlier in the no-price scenario becomes a larger carbon sink than the forest harvested after a delay. This underscores the importance of the chosen time horizon when evaluating the climate benefits of delayed harvest.

To further evaluate these dynamics, we consider the relative change in the carbon stored per hectare for different periods. For the 2026-2029 period, the optimal harvest delay will exceed four years for every site index and carbon subsidy analyzed in the mature stands case. For a more detailed analysis we therefore examine the effect on the carbon sink for each year within the period for site index 16 and 28.

Table 7: Annual change in carbon sink from 2026 to 2029 with and without carbon benefits (SI = 28 and SI = 16), in tCO_2/ha

Year	SI = 28			SI = 16		
	Δ Benefits	Δ No benefits	Difference	Δ Benefits	Δ No benefits	Difference
2026 Pre/Post harvest	2.87	-189.34	192.21	2.63	-112.77	115.4
2026–2027	2.85	-23.38	26.23	2.60	-16.42	19.03
2027–2028	2.81	-14.43	17.24	2.58	-11.84	14.42
2028–2029	2.77	-9.08	11.85	2.55	-8.57	11.12
Cumulative 2026–2029	**11.30**	**-236.23**	**247.53**	**10.36**	**-149.60**	**160.05**

Table 7 shows that with carbon subsidies, the carbon sink increases each year with a slightly declining rate due to the convex shape of the growth function. In contrast, the scenario without carbon subsidies, where the forest is harvested directly in 2026, exhibits a decline in the carbon sink throughout the period. The decline is attributed to the decaying sink in the harvested products. The sharpest drop occurs directly after harvest, as a large share of the carbon sink is lost through waste, which is why we kept the direct effect of harvest on the carbon sink in a separate row.

5.4 The maximum aggregate net change in the carbon sink

Table 8: Annual change in carbon sink from 2026 to 2029 with and without carbon benefits ($MtCO_2$, total for Northern Sweden)

Year	Benefits	No Benefits	Difference
2026 Pre/Post harvest	7.46	-259.75	267.00
2026–2027	7.39	-36.20	42.99
2027–2028	7.32	-26.18	33.00
2028–2029	7.24	-18.60	25.88
Cumulative 2026–2029	**29.42**	**-340.73**	**370.15**

If all privately owned mature stands in northern Sweden are harvested in 2026, the carbon sink in 2029 would exhibit a sharp cumulative decline by 340.73 million tCO_2 compared to the level immediately prior to harvest. In contrast, allowing these stands to continue to grow, as would occur under a carbon benefit scheme according to our findings, would result in an additional 29.42 million tCO_2 sequestered by 2029, or around 7 million tCO_2 annually. Although this estimate is based on a different reference period than the official LULUCF baseline, it suggests that a scheme could make a substantial contribution toward the target as the annual sequestration would more

than double the 3.5 million tonnes required by the legislation.

It is important to note that this analysis does not capture *entire* change in carbon sink in northern Sweden, as it excludes sequestration by immature stands. These younger stands are assumed to continue to grow regardless of carbon subsidies.

6 Discussion

6.1 Discussion of the main results

A central finding of this paper is that carbon subsidies can significantly delay harvests for mature stands across all site indices. At 400 SEK/tCO_2, profit-maximizing forest owners defer harvests by 14–19 years, with delays extending to around 30–40 years at 800–1200 SEK/tCO_2. Although the results are sensitive to discount rates and timber prices, the delay remains robust over the four-year LULUCF period. Notably, a four-year deferral could likely be achieved at much lower carbon subsidies (115-213 SEK/tCO_2) given fixed-length contracts.

Our findings differ from Backéus et al. (2005), who find that a 680 SEK/tCO_2 carbon price eliminates harvesting entirely when optimization begins from bare land. Their model is therefore more comparable to our bare-land simulations, where we estimate that a carbon subsidy of approximately 400 SEK/tCO_2 is needed to delay harvest on high-productivity sites (SI=28), and over 1000 SEK/tCO_2 on low-productivity sites (SI=16). The difference in outcomes is largely attributed to differences in policy design, particularly the inclusion of a harvest tax in Backéus et al. (ibid.) which sharply reduces timber profitability. In our model, which only includes a carbon subsidy, harvesting will always be economically attractive at some point in time, since biomass growth slows down and carbon revenues decline.

Furthermore, profitability increases with the introduction of carbon subsidies. At a carbon subsidy of 400 SEK/tCO_2, the net present value (NPV) of mature stands increases by roughly 7 to 18 percent. The effect size is modest compared to previous studies, but meaningful comparisons are once again limited since few have modeled carbon incentives in the context of mature stands. Considering the results from the bare land scenario, profitability in northern Sweden is generally low, but rises by up to 30 percent on high productivity land at a carbon subsidy of 800 SEK/tCO_2. We found no significant change in NPV on low-productivity land under the modeled conditions. These results are broadly consistent with previous research, though earlier estimates vary widely in magnitude. For example, West et al. (2019) find NPV increases of up to 40 percent at a carbon price of \$30/tCO_2 on bare land, though their analysis relies on different empirical assumptions, such as faster tree growth rates.

An important consideration is that forest owners' optimal harvest timing and profitability remain highly sensitive to future timber prices and climate policy. Since carbon subsidies are externally

introduced and applied only to mature stands, timber revenues remain the dominant driver of forest management decisions. As fossil-based materials are phased out, demand for forest products—such as sawlogs, pulpwood, and bioenergy—is expected to increase, potentially altering price levels and market structures, even without carbon subsidies. In particular, medium-term changes in average price levels could substantially shift harvest incentives, reducing the relative attractiveness of fixed carbon subsidies over time unless indexed to timber market trends. This implies that policymakers opting for the lowest possible carbon subsidy may face challenges later, as static subsidies risk becoming ineffective under rising timber prices. However, for the 2026–2029 period, we expect these market forces to play only a minor role.

To our knowledge, few papers emphasize the impact of a carbon benefit program on landowner profitability. Our results show that carbon subsidies can improve the economic viability of forestry and align private incentives with societal goals, particularly in northern Sweden, where costs often exceed revenues when discounted to a bare land perspective (as shown in Table 6). Promoting sound market dynamics among forest owners could be a policy goal in its own right, helping sustain local ownership and competitive market dynamics by providing income stability and buffering against low timber prices. Over time, predictable carbon subsidies could also attract new social groups to forest ownership, broadening ownership diversity and enhancing both economic resilience and support for long-term climate and forest policies.

Our model further suggests that harvest deferrals in northern Sweden could lead to an additional 7 million tonnes of CO_2 sequestered annually by 2029, as compared to the current (2025) levels. Although we have not calculated our results from the formal LULUCF reference levels, such figures imply a meaningful contribution to the Swedish LULUCF commitments. Contrasting our findings, Guo and Gong (2017) estimate a net increase of 150 million tonnes over 2015-2050 at the same price. Compared to our estimate of 29.42 million tonnes over just four years and a smaller geographical area, their figure appear disproportionally low. This discrepancy can likely be attributed to their model's endogenous timber price adjustments, which together with the longer time span amplify market feedback effects.

The net aggregate carbon sink figures should be viewed as upper-bound estimates. Our model assumes fully informed, profit-maximizing forest owners and excludes factors like industry influence, non-monetary owner preferences, and natural disturbances. Many stands in Sweden already exceed the legal minimum harvest age (Petersson et al. 2024) and Table 6 indicates that forestry continues even when NPV is negative which further challenges the profit-maximizing assumption. As a result,

the estimated 370.15 $MtCO_2$ difference risks violating the principle of additionality by rewarding forest owners for actions they may have taken regardless. This concern could be addressed by adopting a more realistic counterfactual that accounts for the fact that in reality, not all mature stands are harvested immediately when reaching the lowest legal harvest age.

Yet over the past 20 years, the average harvest age has steadily approached the legally mandated minimum, suggesting that forest owners increasingly prioritize profitability over other forest values. These trends imply that our model's estimates likely capture real-world behavior. Nonetheless, before selecting a carbon price, willingness-to-accept studies should be conducted to gauge how owners would actually respond to different subsidy levels.

The net aggregate carbon sink figures assumes a complete halt in harvesting by private forest owners for four years which would disrupt the forest industry and likely face strong resistance. The gains from a short-term program like ours therefore need to be balanced against the losses in terms of forest industry production capacity, substitution effects, and job opportunities. These concerns are reflected in the Committee on Environmental Objectives' recommendation to cap participation at 100,000 hectares, which would significantly reduce the program's potential contribution to the carbon sink.

Furthermore, we observe an increasing trend between site index and optimal deferral period. Correspondingly, deferral on low productivity land for the investigated 4-year period generally requires higher subsidy levels. Only the poorest sites deviate from this pattern, reflecting their low biomass and correspondingly low timber revenues. In contrast, J. Sartori et al. (2024) find that under a socially optimal carbon price, high-productivity sites exhibit shorter deferral periods than low-productivity sites. This result is largely explained by their social optimality framework, aligning the private solution with the marginal benefit to society from carbon sequestration. Our study focuses on the private solution under different subsidies and site indexes, and does not aim to determine the site indices for which it is socially optimal to increase rotation lengths. Our findings may hence be less informative for a social planner than Sartori's. Moreover, none of the studies consider the opportunity cost of extending rotations from a societal perspective. Future research should examine the relationship between SI and optimal deferral more closely in the context of mature Swedish forest land, particularly concerning the opportunity costs of forgone timber revenues.

Lastly, comparing our results for bare land and mature stands underscores the substantial impact of this distinction, as four to ten times larger carbon subsidies are required to incentivize harvest delays in the bare land case. Relaying solely on bare land models may therefore underestimate the

practical effectiveness of carbon benefit schemes, which have substantial policy-related implications.

6.2 Policy Design and Political Feasibility

The political feasibility and implications of our model should be carefully considered. We chose to link carbon benefits to the volume of carbon sequestrated, deviating from J. Sartori et al. (ibid.), who use fixed annual payments during the deferral period. Our model ties the benefits more directly to the actual carbon sink and reflects diminishing returns from deferral as forest growth slows with age. This setup may however increase administrative complexity and deter participation. Policymakers should consider these trade-offs when implementing a carbon payment scheme.

Furthermore, our decision to exclude a harvest tax is supported by our model results. As shown in Table 7 and 8, the resulting decline in the net carbon sink would make a program with taxation punitive. This could prompt private owners to sell their land to large industrial actors, who can offset losses with downstream profits. Punishing baseline management contradicts the goal of carbon payment programs, which is to increase the carbon sink. While introducing yearly carbon subsidies from year zero could help reduce the imbalance between the tax and the subsidy, it would likely be less effective in boosting short-term carbon sequestration, as a large share of the payments would go to non-mature stands with limited immediate impact. Given our focus on meeting short-term climate targets, our results hence suggests that the current design is more effective.

A broader discussion of the one-time carbon benefit program is also warranted, as all tested carbon subsidies eventually lead to harvest. The program offers only a temporary solution, and a forest planted in 2026 may sequester more carbon than one established later at a certain point in time. Nevertheless, compliance with EU legislation remains mandatory, and it can further be argued that the need for carbon sequestration is particularly urgent in the short term, given that its marginal benefits are likely greater now than they will be in the future decarbonized economy with reduced fossil fuel emissions. When comparing carbon subsidy levels to benchmarks, it is still important to account for if the resulting carbon sink is short-lived. As both the EU ETS and the social cost of carbon are designed to reflect the long-term damage of a permanent increase of CO_2 in the atmosphere, they may not be suited as a basis for determining compensation levels in this case.

6.3 Limitations and suggestions for future research

The model we employ is a theoretical simplification and it is important to discuss its limitations. One limitation is the exclusion of soil carbon. A substantial part of a forest's carbon is stored in the soil and this share is likely to be affected by logging practices. Ignoring these effects may lead to shorter rotation periods than what would be socially optimal. As biological research on soil carbon advances, economic models should incorporate these findings to provide more accurate assessments. On the other hand, our exclusion of forest damage risks, such as fires and storms, may lead to an overestimation of the optimal deferral period. As forests age, they become increasingly vulnerable to such risks. If the risk is perceived to be high, forest owners might be less inclined to delay harvests due to the possibility of losing their entire revenue (Ekholm 2019). It is however reasonable to assume that the occurrence of forest fires and extreme weather is expected to increase substantially as a consequence of climate change. Mitigating climate change may therefore nevertheless align with the long-term financial interests of forest owners.

Moreover, it is important to note that this study does not aim to provide a holistic assessment of a carbon sequestration benefit scheme, as it intentionally departs from the legal requirements set out in the LULUCF regulation. Numerous potential advantages and disadvantages of forestry fall outside the scope of our model but could be addressed in future research. Ecosystem services are for example difficult to quantify but are expected to hold substantial economic value. Conversely, a reduction in timber harvesting could lead to increased use of more carbon-intensive substitutes, such as cement instead of wood products, which may have a negative climate impact. Likewise, the increased carbon sink in Sweden may be offset by increased harvesting or deforestation elsewhere. A truly comprehensive analysis would need to account for these factors in order to weigh the marginal benefit of longer rotation periods against the associated economic trade-offs.

A full welfare analysis must also consider the opportunity cost of public spending on subsidies relative to alternative strategies for enhancing carbon uptake in the forest and land-use sector, including quantifying the expected fiscal outlay (for example, SEK per tCO_2 multiplied by projected tonnes sequestered) and comparing it to other mitigation or restoration programs. Future research could incorporate government-budget constraints and perform a full social cost–benefit analysis to determine whether carbon payments to forest owners remain the most cost-effective option under competing policy priorities.

Lastly, previous research (Guo and Gong 2017) has emphasized that assuming exogenous timber

prices can lead to unrealistic outcomes. To address this, their paper employs endogenous timber prices and uses a partial equilibrium model, where prices increase as timber supply declines. Our study elaborates on the Faustmann model, which renders this kind of modeling impossible. While we account for a range of timber prices in our sensitivity analysis, this approach might not be enough if price responses are substantial. There is considerable potential for future research that evaluates carbon sequestration schemes under the LULUCF framework while incorporating market feedback effects.

7 Conclusion

This study investigates how subsidies for carbon sequestration influence forest owners' decisions on harvest timing, profitability, and the resulting impact on Sweden's carbon sink. We employ a dynamic optimization model calibrated with empirical data to generate timely, policy-relevant insights for aligning private landowner incentives with broader climate goals. Specifically, the study aims to evaluate compensation schemes for carbon sequestration as a short-term measure to achieve the Swedish LULUCF target for the 2026–2029 period.

Our contribution to the current body of research is twofold. On a theoretical note, we elaborate on the work of J. Sartori et al. (2024) and further extend the Faustmann model with carbon benefits to analyze mature forest stands. Combined with a differentiation between pulpwood and sawlogs, we present a novel formula suited for short-term policy analysis. Secondly, we run the model using contemporary empirical growth and yield data from northern Sweden and private forest owners, divided into different soil productivity classes. The outcomes are evaluated under different carbon benefit sizes. Our empirical assessment of the potential of carbon sequestration incentives in Sweden fills a current gap in the literature.

The empirical estimates have implications for policymakers who strive to align private and public interests in forestry. We find that a carbon subsidy of 400 SEK/tCO_2 ($40), in line with the proposal by the Committee on Environmental Objectives (2025), extends the optimal harvest age with 14-19 years – well beyond the four-year target outlined in the LULUCF regulations. At this price, aggregate carbon sequestration in northern Sweden could increase by up to 7.5 million tCO_2 per year, or 29.4 million tCO_2 in total from 2026 to 2029 compared to a no-payment scenario. Sensitivity analyses confirm that this result holds robustly across plausible variations in discount rates and timber prices. Noteworthy, even relatively modest carbon subsidies (115-213 SEK/tCO_2) would suffice to achieve a four-year deferral period, assuming that forest owners commit to a fixed deferral duration at the initial decision point through binding contracts.

Answering whether a carbon subsidy scheme alone could meet Sweden's LULUCF targets requires a national-scale analysis comparing the country's current forest carbon stock with the 2016–2018 reference period. By focusing on northern Sweden, we limit our conclusions to regional impacts on the carbon sink under present (2025) and counterfactual conditions. Nevertheless, our results show that even at this regional scale the proposed scheme could make a substantial contribution, since the additional annual sequestration in our model exceeds the 3.5 million tonnes per year required

by the legislation by more than twofold.

Our results demonstrate that carbon sequestration benefits effectively can incentivize forest owners at a relatively modest cost. However, the introduction of carbon subsidies above the minimum level may come with other benefits, such as enhancing profitability for private forest owners in Sweden and strengthening the predictability of income. At a carbon subsidy of 400 SEK/tCO_2, an average forest owner with a mature stand could expect an increase in net present value of their land between 80,172 to 570,520 SEK, assuming no change in real timber prices. The aspect of profitability is particularly relevant in northern Sweden, where profitability is generally low or even negative over a full rotation. Nevertheless, purely profit-maximizing behavior might overstate real-world deferrals, as many private forest owners already exceed legal minimum harvest ages. Rising timber prices driven by reduced harvest volumes could produce a comparable outcome. For these reasons, our estimates of the net aggregate carbon sink should be viewed as upper-bound values and interpreted with caution.

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A Appendix

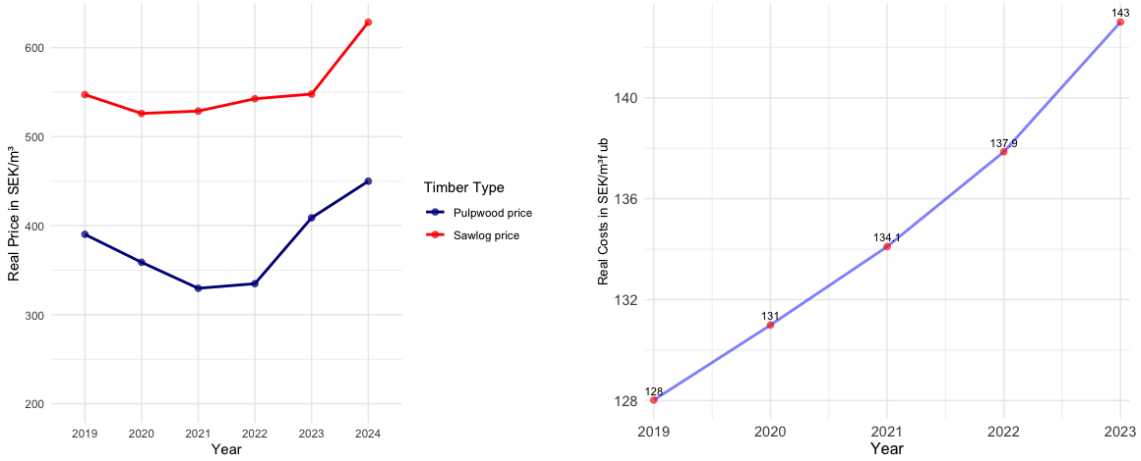
A.1 Price and cost calculations

Timber prices and harvest costs: Timber prices and harvest costs are determined exogenously by historical data from The Swedish Forest Agency. Swedish timber prices generally follow a stationary process, and our price variable is thus set to an average of the fixed prices (at 2023 price level) between 2019 and 2024.

The harvest costs, however, have seen a real increase during the last five years. Considering this, the cost variable is set to the average costs in large scale forestry in 2023. The net present value is calculated using a sawlog price of 553.5 SEK/m^3f ub, a pulpwood price of 378.8 SEK/m^3f ub, and a felling cost of 143 SEK/m^3f ub.

It should be noted that the felling costs likely are somewhat underestimated, as our calculations are based on large-scale operations that benefit from economies of scale. Additionally, we multiply net price by sawlog and pulpwood volumes, though in practice, a portion of the under-bark volume falls outside these categories.

Figure 3: Timber prices and felling costs



(a) Fixed timber prices, 2023 prices

(b) Fixed costs 2019-2023, 2023 prices

Regeneration cost: Our model incorporates regeneration costs as a separate parameter. We introduce a distinct regeneration cost parameter C_R, adjusted to site index. It is set to 14500 SEK/ha and 11400 SEK/ha for high- and low-productivity sites, respectively. The regeneration costs are based on standards provided by the Swedish Forest Agency (2009) and include expenses

for site preparation, planting and pre-commerical thinning, according to table 11. These costs represent a fixed average value for the north of Sweden and are discounted at a 3 percent rate based on 2023 price levels using data from the Swedish Forest Agency. A discount rate of 3 percent is applied to obtain the present value.

Table 9: Regeneration cost in present value

Action	Year	Cost (SEK/ha)	Present value (SEK/ha)
Site preparation	0	3108	3108
Planting	1	6168	5988
Pre-commercial thinning	12	3336	2340
Total present value	NA	12612	11436

Since the majority of soil in northern Sweden has low SI values (Petersson et al. 2024), the average regeneration cost will be applied to the analysis on low-productivity sites. For high-productivity soil, the cost parameter is set approximately 27 percent higher, following Guo and Gong (2017).

Based on this, and assuming a linear relationship, we calculate the regeneration cost for each site index according to:

$C_R = 11400 + 258 * (SI - 16)$

A.2 First and Second Order Conditions

First-Order Condition (FOC) for Optimal Deferral

We consider the problem of maximizing the net present value (NPV) of a mature forest stand by choosing the optimal deferral period N. The first order condition is obtained by splitting the optimization problem into three parts.

Differentiation of $A(N)$ We begin with the expression for timber profits at time N:

$$A(N) = e^{-rN} \cdot [\pi_s \cdot v_s(T_1 + N) + \pi_w \cdot v_w(T_1 + N)]$$

Applying the product rule:

$$A'(N) = -re^{-rN} \cdot (\pi_S \cdot v_S(T_1 + N) + \pi_W \cdot v_W(T_1 + N)) + e^{-rN} \cdot (\pi_S \cdot v'_S(T_1 + N) + \pi_W \cdot v'_W(T_1 + N))$$

Finally, we factor out the exponential term:

$$A'(N) = e^{-rN} \cdot [\pi_s v'_s(T_1 + N) + \pi_w v'_w(T_1 + N) - r\,(\pi_s v_s(T_1 + N) + \pi_w v_w(T_1 + N))]$$

Differentiation of $B(N)$ The carbon payment term is modeled as the sum of annual uptake values, so the marginal increase in carbon payments from delaying harvest by one year is:

$$B(N) = P_c \alpha \int_0^N [v_{\text{tot}}(T_1 + t) - v_{\text{tot}}(T_1 + t - 1)]\, e^{-rt}\, dt$$

To differentiate with respect to N, we apply the Leibniz rule for differentiating integrals with variable upper limits:

$$B'(N) = P_c \cdot \alpha \cdot [v_{\text{tot}}(T_1 + N) - v_{\text{tot}}(T_1 + N - 1)] \cdot e^{-rN}$$

Differentiation of $C(N)$ The present value of future infinite Faustmann rotations is given by:

$$C(N) = e^{-rN} \cdot \left[(\pi_s \cdot v_s(T) + \pi_w \cdot v_w(T)) \cdot \frac{e^{-rT}}{1 - e^{-rT}} - C_{\text{R}} \right]$$

Differentiating with respect to N, we apply the chain rule:

$$C'(N) = -r \cdot \left[(\pi_s \cdot v_s(T) + \pi_W \cdot v_w(T)) \cdot \frac{e^{-rT}}{1 - e^{-rT}} - C_{\mathrm{R}} \right] \cdot e^{-rN}$$

This captures the opportunity cost of postponing access to the infinite sequence of rotations.

The three parts compiled gives the following expression.

$$e^{-rN} \cdot \left\{ \begin{array}{l} \pi_s \cdot v_s'(T_1 + N) + \pi_w \cdot v_w'(T_1 + N) \\ - r \cdot [\pi_S \cdot v_{ub,S}(T_1 + N) + \pi_w \cdot v_w(T_1 + N)] \\ + P_c \alpha \cdot [v_{\mathrm{tot}}(T_1 + N) - v_{\mathrm{tot}}(T_1 + N - 1)] \\ - r \cdot [\pi_s \cdot v_s(T) + \pi_w \cdot v_w(T)] \cdot \left(\frac{e^{-rT}}{1 - e^{-rT}} \right) + r \cdot C_R \end{array} \right\} = 0$$

Division by e^{-rN} gives the finished expression.

Second Order Sufficiency Condition

The second-order sufficiency condition for the optimal N to be a maximum solution is evaluated by taking the second derivative of each part and evaluating them.

$$\begin{aligned} A''(N) = e^{-rN} \Big\{ & - r \left[\pi_s v_s'(T_1 + N) + \pi_w v_w'(T_1 + N) \right] - r \left[\pi_s v_S(T_1 + N) + \pi_w v_w(T_1 + N) \right] \\ & + \left[\pi_s v_s''(T_1 + N) + \pi_w v_w''(T_1 + N) - r \left(\pi_s v_s'(T_1 + N) + \pi_w v_w'(T_1 + N) \right) \right] \Big\} \end{aligned}$$

As forest growth slows with age, the growth functions are concave over the relevant time span. This suggests that the entire second derivative $A''(N)$ is negative.

$$B''(N) = P_c \cdot \alpha \cdot e^{-rN} \cdot [v_{\mathrm{tot}}'(T_1 + N) - v_{\mathrm{tot}}'(T_1 + N - 1) - r \cdot (v_{\mathrm{tot}}(T_1 + N) - v_{\mathrm{tot}}(T_1 + N - 1))]$$

Because of the declining forest growth rate, also $B''(N)$ is expected to be negative.

$$C''(N) = r^2 \cdot \left[(\pi_s \cdot v_s(T) + \pi_w \cdot v_w(T)) \cdot \frac{e^{-rT}}{1 - e^{-rT}} - C_R \right] \cdot e^{-rN}$$

As the land expected value is realistically larger than the regeneration costs, $C''(N)$ is likely to be positive.

The complete second derivative should be <0 for the second-order sufficiency condition to hold. As the positive nature of $C''(N)$ is believed to be counteracted by the negative $A''(N)$ and $B''(N)$, the condition is expected to hold. This is confirmed upon visual confirmation of the graph.

A.3 Forest Growth Model

Equation (5) is calculated using MP and FT

For site index values below 20 (SI<20), the following relationship hold:

$$MP = 0.97 \times (0.235 \times SI - 0.3) \times (0.035 \times SI + 0.3) - 0.55 \tag{10}$$

And the following for site index values above 20 (SI>20).

$$MP = 0.97 \times (0.235 \times SI - 0.3) - 0.55 \tag{11}$$

The stand age when the highest mean annual average increment is reached is determined by:

$$FT = 127.67 - 1.6456 \times SI \tag{12}$$

Equation (6) and (7) are calculated using $Vub(T)$. $Vub(T)$ is calculated with the following expression

$$Vub(t) = v_{ub} \cdot (1 - STA(t)) \cdot (1 - Bvol(t)) \tag{13}$$

$STA(t)$ is the deduction of small trees which at final felling is given by:

$$STA(t) = 0.01 + 1.05 \cdot e^{-0.177 \cdot D(t)} \tag{14}$$

$Bvol(t)$ is bark's share of total standing volume over bark. For medium thick bark series this is given by:

$$Bvol(t) = \frac{0.4501}{\big(D(t)\big)^{0.352}} \tag{15}$$

D(t) denotes the basal area weighted mean diameter over bark (in cm) and is calculated using the following equation

$$D(t) = 4.452 + 0.9926 \cdot MP + (15.703 + 0.9186 \cdot MP)\,\frac{t}{FT}$$

Equation (5) and (6) also incorporate the share of sawlog in the harvested volume under bark, $TUB(t)$ which is given by:

$$TUB(t) = 0.86 - \frac{0.6 \cdot X}{DGVUB(t)} + 0.009 \cdot DGVUB(t) - 0.01 \cdot X$$

The concept of the share of merchantable timber is lastly also used, $G3M(T)$, which is given by the expression:

$$G3M(t) = 1 - \frac{0.81}{DGVUB(t) - Y}$$

X and Y are empirically derived values. X represents the minimum top diameter under bark for sawlog. We use a value of 12 cm. Y is the minimum top diameter for pulpwood. We use a value of 5 cm.

Note: the calculations are made using the assumption that no pre-commerical thinning is performed which might cause a slight underestimation of the forest growth and carbon sink.

A.4 Data & Processing for Carbon Sink Quantification

All data used to calculate the aggregate carbon sink were obtained from SLU Riksskogstaxeringen (Petersson et al. 2024). All tables referenced here can be found in the report.

1. **Identifying total productive forest land**

   Total productive forest land (in 1,000 ha) was identified for private forest owners in both Northern (N) and Southern (S) Norrland. These figures served as the underlying resource base for subsequent calculations.

2. **Determining share of age classes D1 and D2**

   The proportion of harvest-classified forest area in Northern Sweden that belongs to D1 or D2 was then calculated using data from Table 3.3. Under Swedish forestry guidelines, D1 designates stands that have reached the minimum legal age for regeneration felling but remain below the recommended final-felling age, whereas D2 designates stands that have reached the recommended final-felling age under the 1979 Swedish Forest Act.

3. **Disaggregate by site index**

   The total area in hectares for individual owners in Northern and Southern Norrland, divided for soil productivity, was extracted from Table 3.11a. Soil productivity was translated into site index (e.g., 14, 16, 20, 24) using the tool "Bonitet - Skoghögsskolans system" based on the site productivity classification system developed by Hägglund & Lundmark (1970). The conversion table for Norway spruce was used, but its values largely overlap with those for Scots pine.

4. **Combining harvest class and site index data**

   The disaggregated data were then synthesized to determine the total number of hectares (and corresponding standing volume) that simultaneously met three criteria: (i) private ownership, (ii) location in Norrland, and (iii) classification in harvest classes D1 or D2. Each site index category was separately identified.

Note: our model underestimate the age of the D1 and D2 stands, since we assume that the full share of D1 plus D2 stands are at the lowest legal harvest age

A.5 Complete Results Tables

Table 10: Sensitivity of optimal rotation to the carbon subsidy, avg prices

SI	P_c (SEK/t)	T^* (yr)	N^* (yr)	NPV*(SEK/ha)
12	0	100	0.00	21430
12	400	100	16.21	23789
12	800	100	34.09	32084
12	1200	100	47.36	42497
14	0	95	0.00	33663
14	400	95	13.93	36286
14	800	95	31.94	47821
14	1200	95	45.16	62760
16	0	90	0.00	46632
16	400	90	13.47	50008
16	800	90	31.39	65589
16	1200	90	44.45	85880
18	0	85	0.00	60123
18	400	85	13.91	64819
18	800	85	31.62	85400
18	1200	85	44.46	111960
20	0	80	0.00	73882
20	400	80	14.89	80639
20	800	80	32.30	107301
20	1200	80	44.87	141135
22	0	75	0.00	79163
22	400	75	16.95	88978
22	800	75	33.94	120917
22	1200	75	46.17	160258
24	0	70	0.00	83159
24	400	70	19.13	96984
24	800	70	35.67	134698
24	1200	70	47.55	179905
26	0	67	0.00	89894
26	400	67	19.44	105852
26	800	67	35.50	147318
26	1200	67	47.01	196697
28	0	65	0.00	98290
28	400	65	18.84	115070
28	800	65	34.40	158937
28	1200	65	45.54	211289

Table 11: Sensitivity of optimal rotation to the carbon subsidy, high prices

SI	P_c (SEK/t)	T^* (yr)	N^* (yr)	NPV* (SEK/ha)
12	0	100	0.00	28579
12	400	100	8.78	29444
12	800	100	25.53	35966
12	1200	100	38.17	45350
14	0	95	0.00	43580
14	400	95	7.31	44472
14	800	95	24.16	53487
14	1200	95	36.76	66951
16	0	90	0.00	59436
16	400	90	7.39	60678
16	800	90	24.14	73041
16	1200	90	36.59	91430
18	0	85	0.00	75881
18	400	85	8.23	77880
18	800	85	24.79	94607
18	1200	85	37.02	118869
20	0	80	0.00	92609
20	400	80	9.54	95962
20	800	80	25.83	118208
20	1200	80	37.81	149383
22	0	75	0.00	99127
22	400	75	11.81	104859
22	800	75	27.71	132333
22	1200	75	39.37	168961
24	0	70	0.00	104106
24	400	70	14.17	113210
24	800	70	29.67	146475
24	1200	70	41.00	188958
26	0	67	0.00	112302
26	400	67	14.68	123182
26	800	67	29.74	160027
26	1200	67	40.73	206550
28	0	65	0.00	122438
28	400	65	14.27	133923
28	800	65	28.87	172909
28	1200	65	39.50	222217

A.6 Declaration of Artificial Intelligence (AI) Usage

In accordance with academic guidelines requiring the disclosure of artificial intelligence usage in academic work, we provide the following statement regarding the role of AI in the preparation of this thesis.

We used OpenAI's ChatGPT (GPT-4) in a limited and controlled manner as a tool to support certain tasks during the writing process. Specifically, AI was used for:

- Language editing and suggestions to improve the clarity and conciseness of sections in the thesis.
- Improved formatting of tables in LaTeX
- Simplifying programming tasks in R by suggesting functions or general code structures. All actual implementation, parameterization, debugging, and validation of the code were carried out independently by us.
- Validating our mathematical modeling approach by helping to verify derivations, identify potential inconsistencies, and confirm the logical structure of formulas. All final model specifications, assumptions, and derivations were developed, reviewed, and approved by us.

No AI-generated content has been included in the thesis without critical review, editing, and approval by us. All analyses, interpretations, arguments, coding, and conclusions reflect our own reasoning and academic work. The use of AI was strictly supportive and did not replace any substantive part of our research or writing process.

The use of AI in this project was limited to what is disclosed here. No other tools or services based on generative AI were used.