Compensation of carbon sequestration in forests: theory and practical applications

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Tiivistelmä/Referat – Abstract

We study the compensation required to increase carbon sequestration in privately owned forests as a part of effective climate policy. We develop a theoretically correct understanding of compensating additional carbon sequestration in a voluntary stand-level carbon offset scheme by creating incentives for extending the rotation from the privately optimal length. We examine the cost of extending the length of the rotation to a socially desired level. The resulting costs and the increase in carbon sequestration determine the level of compensation required to make the private forest owner indifferent between joining the compensation scheme and resuming privately optimal forest management. A correctly defined subsidy scheme is required as forests are expected to play a major role in meeting national climate change mitigation targets, and so far, the existing schemes have failed to attract voluntary participants.

The well-established univariate optimal rotation model (Faustmann 1894, Samuelson 1976) with a net carbon subsidy (van Kooten et al. 1995) is used to evaluate the compensation structure in the California Forest Offset Protocol and the New Zealand Emissions Trading Scheme, and to present a theoretically sound framework for subsidizing additional carbon sequestration in forests. An empirically more realistic size-structured forestry model with carbon storage (Assmuth et al. 2018) is used to verify the understanding of a correctly defined subsidy scheme when thinnings and multiple carbon pools are included.

The results of the theoretical modelling are compared to practical applications in California Cap-and-Trade and the New Zealand Emissions Trading Scheme. These practical applications have faced various problems and have been subject to numerous revisions, due to issues with baseline establishment, over-crediting, questionable additionality, and leakage. We show that if the compensation scheme follows the Californian structure, a significantly high compensation is required to create sufficient incentives for private forest owners to participate in the sequestration program. The exclusion of carbon stored in harvested wood products may have decreased voluntary participation of post-1989 forests in the New Zealand Emissions Trading Scheme. These schemes serve as an example for the rest of the world of constructing a carbon sequestration compensation scheme. Thus, it is paramount to evaluate the choices in policy design, by comparing the compensation structure to a theoretically sound way of incentivizing additional carbon sequestration.

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Carbon storage, additional carbon sequestration in forests, California Cap-and-Trade, New Zealand Emissions Trading Scheme, Forest Offset Protocol, Faustmann, size-structured forestry with carbon storage

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Tiivistelmä/Referat – Abstract

Tutkielma tarkastelee yksityisten metsänomistajien vaatimaa kompensaatiota metsien hiilensidonnan lisäämisestä osana tehokasta ilmastopolitiikkaa. Muodostamme teoreettisesti perustellun ymmärryksen metsien lisäisen hiilensidonnan kompensoinnista luomalla kannustimet yksityisesti optimaalisen kiertoajan pidentämiseen vapaaehtoisessa metsikkötason kompensaatiojärjestelmässä. Tarkastelemme kiertoajan yhteiskunnallisesti toivotulle tasolle pidentämisestä koituvia kustannuksia. Koituneet kustannukset ja lisäinen hiilensidonta määrittelevät vaaditun kompensaatiotason, jolla yksityinen metsän omistaja on indifferentti järjestelmään liittymisen ja yksityisesti optimaalisen metsänhoidon harjoittamisen välillä. Oikein määritelty tukijärjestelmä on välttämätön, sillä metsien oletetaan olevan suuressa roolissa kansallisten päästövähennystavoitteiden saavuttamisessa, ja olemassa olevat järjestelmät eivät ole saavuttaneet riittävästi vapaaehtoisia jäseniä.

Käytämme tunnetuinta metsikkötason optimikiertoaikamallia (Faustmann 1894, Samuelson 1976) laajennettuna nettohiilensidontatuella (van Kooten et al. 1995) Kalifornian päästökauppajärjestelmän kompensaatiorakenteen mallintamiseen ja Uuden Seelannin päästökauppajärjestelmän arviointiin. Muodostamme teoreettisesti perustellun ymmärryksen lisäisen hiilensidonnan tukemisesta metsissä. Käytämme empiirisesti realistisempaa kokoluokkarakenteista metsikkömallia hiilensidontatuella (Assmuth et al. 2018) vahvistaaksemme muodostetun ymmärryksen oikeaoppisesta tukiaisesta, kun huomioidaan harvennukset ja hiili useissa eri varastoissa.

Vertailemme teoreettisen mallinnuksen tuloksia käytännön sovelluksiin Kalifornian ja Uuden Seelannin päästökauppajärjestelmissä. Nämä käytännön sovellukset ovat kohdanneet lukuisia ongelmia vertailutason asettamisen, kyseenalaistetun lisäisyysperiaatteen, ylikreditoinnin ja hiilivuodon kanssa. Mikäli kompensaatiorakenne noudattaa Kalifornian päästökauppajärjestelmän rakennetta, vaaditaan huomattavan korkea kompensaatio riittävien kannustimien luomiseksi, jotta yksityinen metsänomistaja liittyisi järjestelmään. Puutuotteiden hiilivaraston sulkeminen Uuden-Seelannin päästökauppajärjestelmän ulkopuolelle on mahdollisesti laskenut vapaaehtoista osallistumista järjestelmään. Nämä käytännön sovellukset näyttävät esimerkkiä muulle maailmalle hiilensidonnan kompensaatiojärjestelmien rakentamisessa. Tämän takia on olennaista arvioida tehtyjä rakenteellisia ja poliittisia valintoja vertailemalla niitä teoreettisesti perusteltuun tapaan lisätä metsien hiilensidontaa.

Avainsanat – Nyckelord – Keywords

Hiilivarasto, metsien lisäinen hiilensidonta, Kalifornian päästökauppajärjestelmä, Uuden-Seelannin päästökauppajärjestelmä, päästökompensaatio, Faustmann, kokoluokkarakenteinen metsikkömalli

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1 Introduction

Climate change poses an urgent threat to our societies and the planet (IPCC 2018). Many IPCC scenarios require a large-scale deployment of negative emission technologies, as some emission sources are utmost difficult to eliminate (EASAC 2018). Forests represent a low-cost negative emission technology providing climate change mitigation and supporting sustainable development (IPCC 2007). Between 2007 and 2016, forestry, agriculture and other land use activities accounted for 13% of CO_2, 44% of CH_4 and 88% of N_2O global emissions (IPCC 2019). During this period, terrestrial vegetation sequestered 29% of total CO_2 emissions (IPCC 2019). Forests act as carbon sinks storing carbon in living trees, dead tree matter and timber products, and as emission sources when timber is felled. One hectare of forest land has the potential to sequester up to 4 tCO_2 per year (Daniels 2010). The net emissions of forests are affected by harvests, growth and the lifespan of timber products (van Kooten and Johnston 2016). While the full climate change mitigation potential of forestry has previously not been utilized due to a lack of proper policies (IPCC 2007), nations now expect forests to play a key role in reaching their climate change mitigation targets (Grassi et al. 2017). This thesis will examine, how a compensation for increasing carbon sequestration in privately owned forests should be determined and evaluate existing schemes, in order for nations to utilize their forest resources in meeting their mitigation targets.

In the absence of regulation, the positive externality of carbon sequestration provided by forests is not included in the decisions concerning land and resource use (Tahvonen and Rautiainen 2017). This leads to the private optimum falling short of the social optimum. One way to internalize this externality is to create a market-based mechanism for carbon offsets. This may be done by including forests into emission trading systems and subsidizing them for increased carbon sequestration with emissions trading units, as is the case in California and New Zealand. According to Daniels (2010), emissions trading schemes including carbon offsets could provide a cost-efficient method to achieve emission reductions. The inclusion could improve the overall profitability of forestry (Kelly et al. 2017) by creating income from increasing carbon sequestration during the rotation period in addition to income from conventional timber production (Daniels 2010; Kelly and Schmitz 2016).

Carbon offsets are emission reduction or removal units that may be used to offset the emissions of a regulated entity (Peterson St-Laurent et al. 2017). They have the potential to reduce costs of emission reductions by providing more time for technical development but may reduce the ambition of emission reductions by the polluters (van Kooten and Johnston 2016). Forests can provide carbon offsets by afforestation, reforestation and carbon sequestration increasing activities by enhancing forest growth and altering forest management (Peterson St-Laurent et al. 2017). When including forest offsets into an emissions trading system, additionality, permanence, leakage, carbon pricing as well as the accuracy and verifiability of measurement must be considered (Daniels 2010). Additionality in this case refers to the reduction of the atmospheric carbon dioxide occurring as a result of the policy instrument in question (van Kooten & Johnston 2016). Thus, business-as-usual forest management is defined as a baseline, and only carbon sequestration exceeding this baseline is subsidized. As the compensation for carbon sequestration is likely to be publicly funded, the question of additionality must be considered. Public expenditure includes an opportunity cost and authorities may prefer not to compensate non-additional carbon sequestration (Tahvonen and Rautiainen 2017).

The Program of the Finnish Government (Finnish Government 2019) aims to develop policies to increase carbon sequestration and storage in forests and soil and implement pilots for a carbon exchange. Such incentive systems have been implemented as a part of emissions trading schemes in California and New Zealand. These systems and their applicability in the Finnish context will be evaluated in this thesis. In California, forests are included *via* a voluntary Forest Offset Protocol (EDF 2018), while in New Zealand forests are integrated into the scheme with a division between voluntarily and mandatorily participating post-1989 and pre-1990 forests, respectively (Carver et al. 2017). The Forest Offset Protocol in California has been criticized for over-crediting, falsely defined baselines for carbon sequestration and emission leakage leading to non-additional offset credits entering the system (Haya 2019). Anderson et al. (2017) found that the Forest Offset Protocol has succeeded in incentivizing forest conservation in industrial forests. Kelly et al. (2017) criticize the Protocol for complexity and high transaction costs resulting in a high threshold for non-industrial private forest owners to participate in the Protocol. The initiation of the New Zealand Emissions Trading Scheme (NZ ETS) resulted in increased deforestation prior to the beginning of the scheme (Karpas and Kerr 2011). Carver et al. (2017) have criticized the Scheme for policy uncertainty and inaccurate measurement of carbon sequestration in forests. Evison (2017) reported that in 2014, only 42% of eligible post-1989 forests were participating in the NZ ETS. According to The New Zealand Ministry for Primary Industries (2019), the full and immediate compensation liability for harvest emissions has resulted in a conservative approach in carbon trading and lowered voluntary participation.

In this thesis we examine how the compensation for additional carbon sequestration in forests should be defined in a theoretically sound manner, evaluate the compensation structure in California and examine why the exclusion of harvested wood products from the NZ ETS has decreased voluntary participation. This will be done by analyzing a univariate optimal rotation model (Faustmann 1849, Samuelson 1976) with carbon sequestration, first presented by van Kooten et al. (1995). A study by Tahvonen and Rautiainen (2017) examines the model analytically when additionality of forests' carbon sequestration is considered. To obtain more empirically valid results for our theoretical framework, we extend our analysis to a size-structured stand-level model by Tahvonen and Rämö (2016), which is extended to include carbon storage by Assmuth et al. (2018). The question of additionality has not been included in the earlier study by Assmuth et al. (2018), thus, this thesis extends existing research and provides new insights on the concept of additional carbon sequestration in forests.

We examine the effects of carbon price levels on the forest rotation length and the profitability of forestry. We compare results of crediting all carbon sequestration in forest to only crediting additional carbon sequestration. Implementing a carbon subsidy generally increases the optimal rotation length (cf. van Kooten et al. 1995, Asante and Armstrong 2012, Hoel et al. 2014) and creates a surplus for the forest owner. We also examine a policy-relevant case where only the first rotation is extended by postponing the clearcut and the appropriate compensation is determined by the decrease in timber revenues.

We begin by providing an introduction of the emissions trading schemes in California and New Zealand. We then present the univariate optimal rotation model, the Californian compensation structure and construct a theoretically correct understanding of subsidizing additional carbon sequestration in forests. After examining the most well-established model, we compare the results of the theoretically correctly defined compensation with the size-structured forestry model and analyze the obtained numerical results. Lastly, we discuss the similarities and differences between the theoretical models and practical applications and draw conclusions.

2 Practical applications of compensating forest carbon sequestration

Many private companies and associations have created voluntary forest offset systems utilizing international offset projects verified by standards, such as, the Clean Development Mechanism and the Gold Standard (Climate Corporation 2020). So far, only a few countries have managed to create public schemes crediting forests' carbon sequestration by issuing offset credits. Two pioneer schemes including forest offsets, California Cap-and-Trade and the New Zealand Emissions Trading Scheme, will be presented in this chapter.

2.1 California Cap-and-Trade and the Forest Offset Protocol

The California Cap-and-Trade was launched in 2013 covering GHG emissions from the industrial and electricity sectors. The coverage was expanded in 2015 to cover emissions from transportation fuels, natural gas, imported electricity and fuel (CARB 2012). Agricultural and fugitive emissions as well as emissions from marine fuel and aviation remain outside the coverage of the program (CARB 2012). The Californian system features an emissions cap starting at 431 million tCO_2e, which decreases at an annual rate of 3.3%. After 2020, the decrease rate will increase to 5% (CARB 2015b). The system includes a hard price floor of $10USt^{-1} with a 5% plus inflation annual increase, a soft price ceiling to control unexpected price fluctuations and a banking and borrowing system to provide more temporal flexibility (CARB 2019). The price floor ensures that the system constantly creates correct incentives for emission reduction by not letting the allowance price decrease below the set limit. Banking refers to the possibility of saving current allowances for future compliance periods, while borrowing allows the participant to use allowances from the quotas of future compliance periods to account for emissions of the current period. The soft price ceiling is implemented *via* an allowance reserve, from which allowances will be gradually released to control unexpected price shocks (CARB 2019).

The California Cap-and-Trade system includes an Offset Compliance Program where credits are awarded to offset projects that reduce emissions (CARB 2012). Capped entities may then buy these credits to offset up to 8% of their emissions (CARB 2012). At least 50% of post-2020 created offset credits must provide direct environmental benefit to California (CARB 2006a), i.e. the provided offsets must be done within the state. Separate offset protocols exist for ozone depleting substances, livestock projects, urban forest projects, mine methane capture projects and forest projects (CARB 2014). All provided offsets must be *"real, permanent, quantifiable, verifiable, enforceable by the* *state board and in addition to any greenhouse gas emission reductions otherwise required by law or regulation and any other greenhouse gas emission reduction that otherwise would occur"* (CARB 2006b). Offset credits are tradable compliance instruments issued by the California Air Resources Board (CARB) representing an emission removal or reduction of one tCO_2e (Ramo 2014).

The Forest Offset Protocol includes forest carbon stocks in standing live and dead carbon, soil carbon and carbon in harvested wood products in use and in landfills (Anderson et al. 2017). Forest emissions are accounted from leakage, decomposition of timber products and site preparation activities (Anderson et al. 2017). According to the legislation (CARB 2015), the approved forestry activities for the protocol are reforestation, improved forest management (IFM) and avoided conversion (AC). Reforestation restores tree cover on a land that has previously been forestland. Forest management may be improved by, for example, improving productivity, extending rotation lengths or by maintaining or increasing tree stocks in understocked areas. Avoided conversion prevents the land use change from forestry to non-forestry use.

In the Forest Offset Protocol, the offset projects are credited for a limited period of time for baseline exceeding carbon sequestration. The crediting period is set to 25 years with the possibility of renewing the crediting period for an additional 25 years (CARB 2015). The forest owner is required to maintain the forest carbon stock for the duration of the monitoring period, 100 years after the last received credit (Kelly et al. 2017). During the monitoring period the stand may be harvested according to the principles of uneven-aged management, where at least 40% of canopy coverage is retained across the entire forest (CARB 2015). Forest owners are required to take into account the carbon released in every reporting period if trees are felled during the project duration (CARB 2015). After the monitoring period, the contract ends, and the forest owner may resume privately optimal forest management (e.g. rotation forestry) without compensation liabilities. To set the baseline for carbon sequestration, the forest owner specifies an estimation of the forest's carbon fluxes during a 100-year period without regulation (CARB 2015). This estimation must be financially feasible, in compliance with existing regulation and not be below the regional average (CARB 2015).

The forest offset projects may be located anywhere in the contiguous United States and Alaska (Anderson et al. 2017). In 2019 there were 39 forest projects participating, of which 16 were located in California, accounting for 20% of the total land area and 40% of the credits within the protocol. 15% of the projects participated *via* avoided conversion and 85% *via* improved forest management

(Anderson et al. 2017). The Forest Offset Protocol accounts for 80% of the total offset credits in the cap-and-trade (Haya 2019).

2.2 Forestry in the New Zealand Emissions Trading Scheme

The New Zealand Emissions Trading Scheme was launched in 2008, eventually covering electricity production, forestry, industrial processes, synthetic GHGs, waste and the production as well as import of liquid fossil fuels (Leining and Kerr 2018). According to Leining and Kerr (2018), agriculture has an obligation to only report their emissions. In 2016, the energy sector accounted for 40% and agriculture for 49% of New Zealand's gross emissions while forestry sector offset about 29%. The compliance period, excluding post-1989 forests, is one year. Emissions are reported annually, and a verification is only required if a regulated entity requests to use a unique emission factor. Banking of New Zealand Units (NZUs) is allowed (Leining and Kerr 2018).

The yearly allocation of NZUs is based on emission and output data reported from the previous year (Climate Change Response Act 2002). The industrial sector receives a yearly free allocation of 60% or 90% based on the emission intensity of production and their trade exposedness. The fishing industry and pre-1990 forests received a one-off free allocation at the time of registration (Climate Change Response Act 2002). The free allocation is made to protect the industries in New Zealand and to prevent leakage of emissions outside of the coverage of the NZ ETS (Leining and Kerr 2016) and it should continue until the most important trading partners have similar emission pricing in place (Ministry for the Environment 2016). Until 2015, the NZ ETS included an implicit emission cap *via* the linkage to the first Kyoto Protocol Compliance period (Leining and Kerr 2018). After de-linkage from the Kyoto Protocol in 2015 the scheme was left without an emission cap (Carver et al. 2017). The government is currently working towards a system of national auctioning of NZUs, which would impose a cap on emissions (Leining and Kerr 2018).

Forestland is divided into two main categories in the NZ ETS, mandatorily participating pre-1990 forests and voluntarily participating post-1989 forests (Carver et al. 2017). The NZ ETS aims to discourage deforestation of pre-1990 forests and incentivize increased rotation lengths and regeneration of stands of post-1989 forests (Carver et al. 2017). Accounted forest carbon pools are above and below ground live biomass, and coarse and fine woody litter (Manley 2012). According to Carver et al. (2017), owners of pre-1990 forests must surrender units if more than 2 hectares of land is deforested. Only deforestation of pre-1990 forests is limited by the regulation, as the forest owner has no surrender obligation if the stand is regenerated artificially. Carbon sequestration of pre-1990 forests is not credited and thus, we concentrate on owners of post-1989 forests, who may earn NZUs for increased carbon sequestration and are fully liable for the released credited carbon.

The change in the carbon stock of a participating post-1989 forest is calculated at the end of a 5-year period. If this change is positive (i.e. carbon sequestration) or negative (i.e. emissions), the forest owner earns or surrenders NZUs, respectively (Forestry New Zealand 2020a). The surrender obligation is limited to the amount of credits earned for increasing carbon sequestration (Carver et al. 2017). NZUs may be earned during the 5-year period by voluntarily reporting changes in forest carbon stock. Forest growth and change in the carbon stock are determined by look-up tables (forest size <100ha) or the Field Measurement Approach (forest size ≥100ha). Look-up tables give regional average growth factors for forests of different ages and species. (Forestry New Zealand 2020a) The Field Measurement Approach creates forest owner specific look-up tables by obligating them to measure forest growth on assigned sample plots in their forest (Ministry for Primary Industries 2018). Harvest residues are assumed to decay linearly over 10 years after harvest. The forest owner is requited to surrender NZUs for decaying harvest residues (Forestry New Zealand 2020b). Harvested wood products (HWPs) are excluded from the system (Manley 2012).

The requirement that participants must account for all changes in the forest carbon stocks and the exclusion of HWPs imposes the full liability of released carbon on the forest owner (Ministry for the Environment 2016, 2019). The Ministry for the Environment is working on implementing averaging accounting into the scheme. When averaging is used, the forest owner must surrender units only as the long-term average carbon stock decreases and is only credited for an increase in the long-term average carbon stock. This approach would allow more flexibility as the forest owner would not need to comply with NZUs at the end of each 5-year period, as long as the forest stand is regenerated (Ministry for the Environment 2016, 2019).

3 Univariate optimal rotation model with a carbon subsidy

We now present the theoretical framework for evaluating the presented practical applications. Carbon sequestration in forests is first presented by analyzing a univariate optimal rotation model (Faustmann 1849, Samuelson 1976) by adding carbon pricing (van Kooten et al. 1995). Here we analyze the optimization problem presented by Tahvonen & Rautiainen (2017), concentrating on the effects of subsidizing only additional, baseline exceeding, carbon sequestration.

3.1 Growth model and the optimization problem

Stand volume $F(t)$, ($m^3 ha^{-1}$) is a function of stand age *t* that satisfies

$$F \in C^3,\ F(0)=0,\ F'(0)=0,\ F(t)>0 \text{ and } F'(t)>0\ \forall\ t>0,\ F'(t)\to 0 \text{ and } F \to \hat{F} \\ \text{as } t\to\infty,\ F''>0 \text{ for } 0<t<\bar{t},\ F''<0 \text{ for } t>\bar{t} \text{ and } F''/F' \text{ is decreasing in } t, \tag{A1}$$

where $\hat{F}$ denotes the volume when the stand has reached the site-specific maximum volume and $\bar{t}$ is the culmination age where the stand growth is the fastest. A function satisfying assumptions A1 is written as

$$F(t)=\alpha_1(1-e^{-\alpha_2 t})^{\alpha_3}, \tag{1}$$

where $\alpha_1>0$ is the maximum level of *F*(*t*), i.e. the asymptote, and $\alpha_2>0$, and $\alpha_3>0$ denote empirical growth parameters. By the assumptions in A1 we know that $F(t)$ is a convex-concave function, where a young stand is described by the increasing convex part and the decreasing growth as $t\to\infty$ is described by the concave part after the stand reaches the culmination age $\bar{t}$. The development of an even-aged Norway spruce stand with parameter values of $\alpha_1=526.7031$, $\alpha_2=0.0548$ and $\alpha_3=8$ (calibrated to a high fertility stand in Bollandsås et al. 2008) is illustrated in Figure 1.

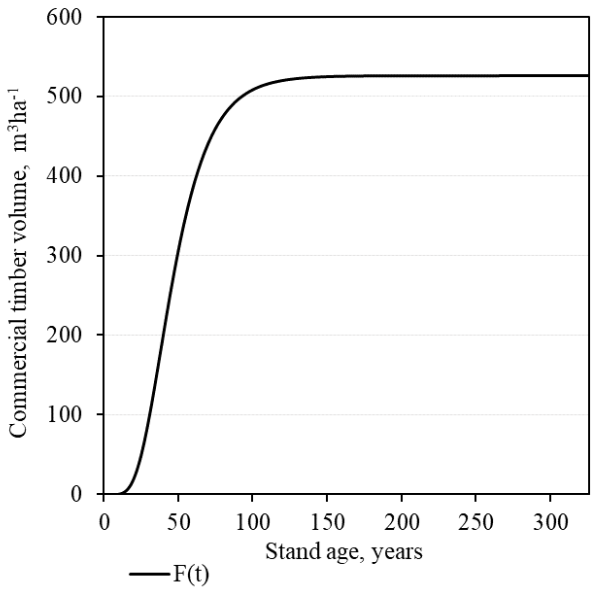

Figure 1. Time development of stand volume of Norway spruce at a site of high fertility.

Let $w \geq 0$ denote the regeneration cost (€ha^{-1}) and $r \geq 0$ the interest rate. Parameter p denotes the stumpage price (€m^{-3}) and the stand volume is given by the function $F(t)$. The net present value of timber revenues is written as

$$J_T(t) = \frac{-w + e^{-rt} pF(t)}{1 - e^{-rt}}, \tag{2}$$

where J denotes the bare land value (BLV). Let $\tau = \delta p_c$ denote the price of carbon (€m^{-3}), where the carbon content of a cubic meter of wood is denoted by δ and p_c is the social price of carbon (€tCO_2^{-1}). The present value of income from subsidized net carbon sequestration is given as

$$J_C(t) = \frac{\tau \int_0^t F'(s) e^{-rs} ds - \tau \beta F(t) e^{-rt}}{1 - e^{-rt}}, \tag{3}$$

where parameter β $(0 \leq \beta \leq 1)$ is the present value of decay of timber products, written as $\beta = \alpha(\alpha + r)^{-1}$. We assume a decay rate of timber products, $\alpha = 0.139$, which is roughly in line with the average of timber product decay in Finland (Assmuth et al. 2018). Equation (3) subsidizes all carbon sequestration in the stand. To subsidize only additional carbon sequestration, we can apply a lump sum tax (Tahvonen and Rautiainen 2017) to remove non-additional subsidies. The lump sum tax is defined as $J_C(t^*)$, where t^* denotes the length of the optimal rotation when carbon sequestration has no value, i.e. Faustmann optimal rotation, obtained by maximizing equation (2).

The objective function, as presented by Tahvonen & Rautiainen (2017) is $J(t) = J_T(t) + J_C(t)$ and can be given as

$$\max_{t\geq 0} J(t) = \frac{-w + \tau \int_0^t F'(s)e^{-rs}ds + e^{-rt}(p - \tau\beta)F(t)}{1 - e^{-rt}}, \tag{4}$$

where we maximize bare land value by the optimal choice of rotation length *t*. Following the proof from Tahvonen and Rautiainen (2017), the first order optimality condition for (4) is obtained by taking the time derivative of $J(t)$ and setting it equal to zero, which yields

$$J'(t) = \frac{\left[\tau F'(t)e^{-rt} - re^{-rt}(p-\tau\beta)F(t) + e^{-rt}(p-\tau\beta)F'(t)\right](1-e^{-rt}) - re^{-rt}\left[-w + \tau\int_0^t F'(s)e^{-rs}ds + e^{-rt}(p-\tau\beta)F(t)\right]}{(1-e^{-rt})^2} = 0. \tag{5}$$

Noting that $(1-e^{-rt})^2 > 0 \ \forall \ t > 0, \ r > 0$ and dividing by $(1-e^{-rt})e^{-rt}$ yields

$$\tau F'(t) - r(p-\tau\beta)F(t) + (p-\tau\beta)F'(t) \ - r\left[\frac{-w + \tau\int_0^t F'(s)e^{-rs}ds + e^{-rt}(p-\tau\beta)F(t)}{1-e^{-rt}}\right] = 0.$$

We note that $\frac{-w + \tau\int_0^t F'(s)e^{-rs}ds + e^{-rt}(p-\tau\beta)F(t)}{1-e^{-rt}} = J(t)$ and simplify the equation to

$$\tau F'(t) - r(p-\tau\beta)F(t) + (p-\tau\beta)F'(t) - rJ(t) = 0.$$

The first order condition thus becomes $J'(t) = y(1-e^{-rt})^{-1} = 0,$ where

$$y \equiv [p + (1-\beta)\tau] F'(t) - r[(p-\tau\beta)F(t) + J(t)] = 0. \tag{6}$$

According to this condition, it is optimal to harvest the stand when the value of marginal growth is equal to the interest cost of postponing the harvest. We now define $\mu \equiv \hat{F}(p-\tau\beta) - w + \tau\int_0^\infty F'(s)e^{-rs}ds$ and analyze the basic features of the optimal rotation period. For it to be optimal to clearcut the stand, the clearcut revenues of a mature stand and the net value of carbon sequestration must exceed the regeneration cost, i.e. $\mu > 0$. If $\mu < 0$, it cannot be optimal to clearcut the stand.

Proposition 1. *The optimal rotation is finite and unique given* $\mu > 0$ *and assumptions (A1).*

Proof. From (6). If $w > 0$, $J'(t) \to \infty$ as $t \to 0^+$. If $w = 0$, $J(t) \to 0$ as $t \to 0^+$, however, $J(t) > 0$ $\forall$ finite $t > 0$. Therefore, when $w = 0$, $J'(t) \geq 0$ as $t \to 0^+$ and $J'(t) > 0$ with low levels of *t*. When

$$t \to \infty,\ y(t) \to -r\left[\hat{F}\left(p - \tau\beta\right) - w + \tau\int_0^\infty F'(s)e^{-rs}ds\right] < 0,$$

when (A1) holds. The continuity of $y(t)$ implies that finite values of *t* exist when $J'(t) < 0$ and there must be a strictly positive value of *t* when the sign of $J'(t)$ changes from positive to negative (Figure 2). Hence, at least one finite optimal rotation must exist.

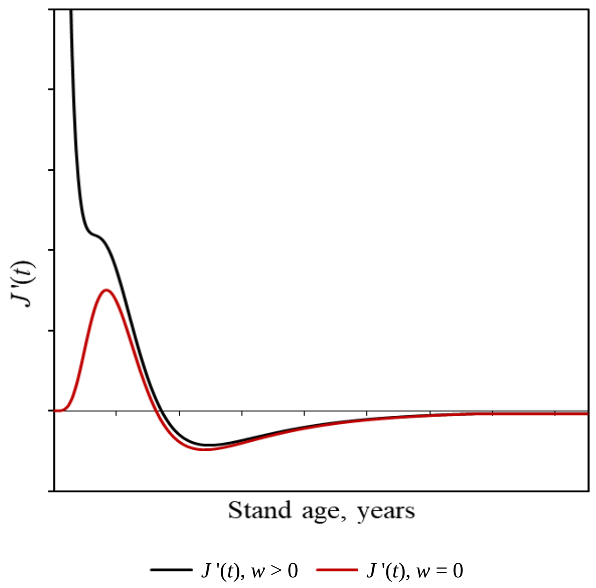

Figure 2. Time development of $J'(t)$ with $w > 0$ and $w = 0$.

To show uniqueness of the optimal rotation, we derive the second order condition from (6), which yields

$$J''(t) = \frac{p + (1-\beta)\tau \ F''(t) - r[(p - \tau\beta)F'(t) + J'(t)]}{1 - e^{-rt}}. \tag{7}$$

Multiplying by $(1-e^{-rt})$, noting that $J'(t) = 0$ and rearranging, we can simplify the expression to

$$\frac{F''(t)}{F'(t)} - \frac{r(p - \tau\beta)}{p + (1-\beta)\tau}, \tag{8}$$

which shows us the sign of $J''(t)$. The obtained optimal rotation is both finite and unique because by (A1), $F''(t)/F'(t)$ is decreasing in time (Figure 3). Thus, with $J'(t) = 0$, any larger value of t cannot exist. ■

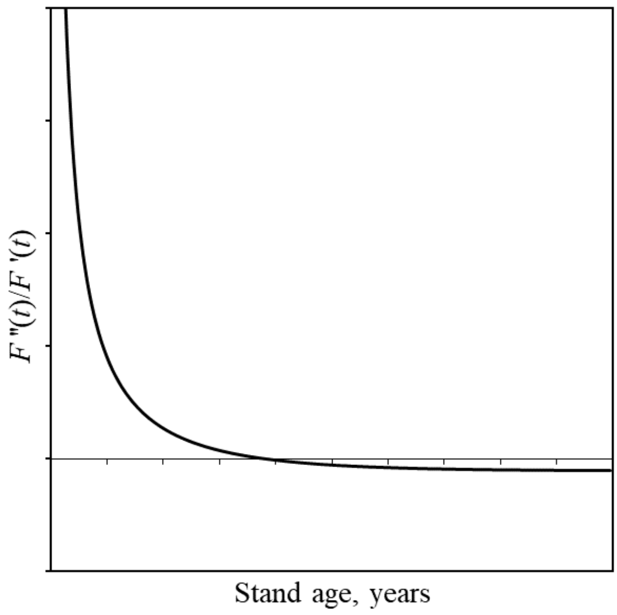

Figure 3. Time development of $F''(t)/F'(t)$.

Proposition 2. *Given* $\mu > 0, \partial y / \partial t^* \neq 0$ *and (A1), a positive price of carbon increases the length of the optimal rotation period if* $\beta = 1$ *and* $r > 0$, *and decreases it if* $\beta < 1,\ r = 0$ *and* $w > 0$.

Proof. Let us write the optimality condition (6) as

$$y(t) = \tau \left\{ (1-\beta)F'(t) - r\frac{\int_0^t F'(s)e^{-rs}ds - \beta F(t)}{1-e^{-rt}} \right\} + pF'(t) - r\frac{pF(t)-w}{1-e^{-rt}} = 0.$$

Setting $\beta = 1$, in $y(t)$ and differentiating with respect to τ yields

$$\frac{\partial y}{\partial \tau} = -r\frac{\int_0^t F'(s)e^{-rs}ds - F(t)}{1-e^{-rt}} > 0,$$

when $r > 0$. The assumption $\partial y / \partial t^* \neq 0$ and proposition 1 imply that $\partial y / \partial t^* < 0$. We use the implicit function theorem (Sydsæter et al. 2008) and write

$$\frac{dt}{d\tau} = -\frac{\partial y / \partial \tau}{\partial y / \partial t} = -\left\{ -r \frac{\int_0^t F'(s)e^{-rs}ds - F(t)}{\partial y / \partial t^*(1-e^{-rt})} \right\} > 0, \tag{9}$$

which implies that a positive carbon price has an increasing effect on the length of the optimal rotation period when $\beta = 1$ and $r > 0$. Next, let us assume $\beta < 1$, $r = 0$ *and* $w > 0$. When $r \to 0$, $r(1-e^{-rt})^{-1} \to t^{-1}$. Thus, when $r = 0$, the optimality condition (6) becomes

$$\tau \left\{ (1-\beta) \left[F'(t) - \frac{F(t)}{t} \right] \right\} + p \left[F'(t) - \frac{F(t)}{t} \right] + \frac{w}{t} = 0. \tag{10}$$

Taking a partial derivative of (10) with respect to τ yields

$$\frac{\partial y}{\partial \tau} = (1-\beta) \left[F'(t) - \frac{F(t)}{t} \right] < 0,$$

where $(1-\beta) > 0$ when $\beta < 1$, and $\left[F'(t) - F(t)t^{-1} \right] < 0$ when $w > 0$. To examine the effect of a positive carbon price under these assumptions, we again use the implicit function theorem and write

$$\frac{dt}{d\tau} = -\frac{\partial y / \partial \tau}{\partial y / \partial t} = -\frac{(1-\beta) \left[F'(t) - \frac{F(t)}{t} \right]}{\partial y / \partial t^*} < 0, \tag{11}$$

implying that when $\beta < 1$, $r = 0$ and $w > 0$, a positive carbon price decreases the length of the optimal rotation. ■

Proposition 3. *Given* $\mu > 0$, $\partial y / \partial t^* \neq 0$ *and (A1), the optimal rotation is longer the higher is the present value of decay of timber products if* $r > 0$ *and* $w > 0$.

Proof. Differentiating the optimality condition (6) with respect to β yields

$$\frac{\partial y}{\partial \beta} = \tau \left\{ -F'(t) + r \frac{F(t)}{1-e^{-rt}} \right\} > 0.$$

By the implicit function theorem, the effect of β on the length of the optimal rotation is

$$\frac{dt}{d\beta} = -\frac{\partial y / \partial \beta}{\partial y / \partial t} = -\frac{\tau \left\{ -F'(t) + r \frac{F(t)}{1-e^{-rt}} \right\}}{\partial y / \partial t^*} > 0, \quad (12)$$

which implies that when $r > 0$ and $w > 0$, the faster is the release of carbon after harvesting the stand, the longer the optimal rotation becomes. ■

3.1.1 Parameter values and computational methods

Maple 2019 software is used for analyzing carbon storage in the univariate optimal rotation model. Stand regeneration cost is €1500 ha^{-1} and we use an interest rate of 2%. The stumpage price equals €40m^{-3}. The carbon content per m^3 of wood (δ) is 0.7 tCm^{-3}. With the given interest rate the present value of decay of timber products is $\beta = 0.874$. We parameterize a growth function, equation (1), for Norway spruce in two different fertility sites. For a site of high fertility we use $\alpha_1 = 526.7031$, $\alpha_2 = 0.0548$ and $\alpha_3 = 8$, and for a low fertility site $\alpha_1 = 304.6683$, $\alpha_2 = 0.0296$ and $\alpha_3 = 7.1533$ are used.

3.1.2 Numerical results for the univariate optimal rotation model

We begin by presenting numerical results for the univariate optimal rotation model in equations (1) – (4). Table 1 presents numerical results for maximizing bare land value at stand level with growth function parameter values for a Norway spruce stand at a site of high fertility with a 2 % interest rate when varying the price of carbon in equation (4). Subsidizing carbon sequestration in forest increases the optimal rotation length (column a) from 52 years with no carbon pricing to infinity with a carbon price of €113 tCO_2^{-1}. An infinitely long rotation implies that the optimal forest management regime shifts from rotation forestry to pure carbon storage, i.e. no harvesting of timber. While the value of bare land (column b) increases as a result of the carbon subsidy, the increased rotation length leads to a decrease in timber revenues (column d). This decrease in timber income reveals the cost of increased carbon sequestration for the forest owner. To show additionality, we determine the baseline for carbon sequestration applying the optimal rotation given carbon sequestration has no value. By comparing column e and column g, it is clear that carbon pricing results in a net gain (column h) for the forest owner even when only additional carbon sequestration is subsidized. The importance of the additionality principle is emphasized by showing the net gain of the forest owner if all carbon sequestration would be credited (column i). By comparing columns h and i, we note that disregarding additionality would be costly and unnecessary as already subsidizing additional sequestration results in a net gain for the forest owner.

Table 1. Numerical results for the univariate optimal rotation model in a forest of high fertility.

	a	b	c	d	e	f	g	h	i
Price of carbon *(€/tCO₂)*	Optimal rotation *(years)*	Bare land value *(€/ha)*	NPV of additional net carbon sequestration *(tCO_2/ha)*	NPV of timber revenues *(€/ha)*	Cost of additional storage *(€/ha)*	Unit cost of additional storage *(€/tCO_2)*	Subsidy for additional storage *(€/ha)*	Net gain from additional subsidy *(€/ha)*	Net gain from subsidizing all carbon storage *(€/ha)*
0	52	4830	-	4830	-	-	-	-	-
10	54	5511	4	4811	18	5	37	18	681
40	61	7789	16	4501	329	21	635	306	2959
80	77	11470	37	3218	1611	44	2946	1335	6640
113	∞	16830	83	-	4830	58	9341	4511	12001

Note: 2% interest rate

Figure 4 illustrates the effect of interest rate on the optimal rotation length with different carbon prices. The effect of carbon pricing on the rotation length is higher with a higher interest rate, i.e. the optimal rotation approaches infinity at a lower carbon price. When the optimal rotation becomes infinitely long, forest management shifts from rotation forestry to pure carbon storage. With a 5% interest rate, the optimal rotation becomes infinitely long with a carbon price of €71 tCO_2^{-1} and with a 1% interest rate, a carbon price of €204 tCO_2^{-1} makes the rotation infinitely long. A higher carbon price increases revenue from carbon sequestration before clearcut but decreases clearcut revenues due to a higher compensation liability for released carbon. The interest cost of postponing the clearcut decreases as clearcut revenues decrease. This effect is further strengthened by a higher interest rate. Thus, the effect of carbon pricing is stronger with higher interest rates.

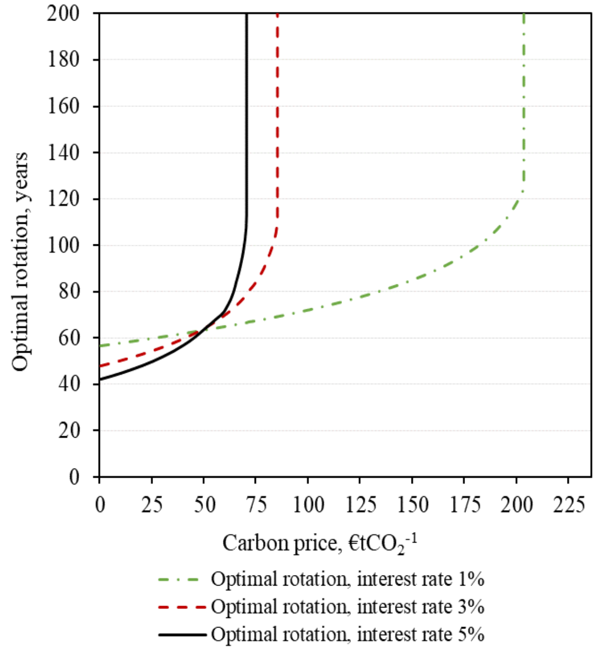

Figure 4. Effect of interest rate on the optimal rotation length with a positive carbon price.

The dependence of bare land value on the rotation age with carbon prices of €20 and €80 tCO_2^{-1} and interest rates of 1%, 3% and 5% is depicted in Figure 5. A lower interest rate results in a higher bare land value, while a lower price of carbon leads to a lower bare land value. This implies that the choice of interest rate has a large impact on the numerical results.

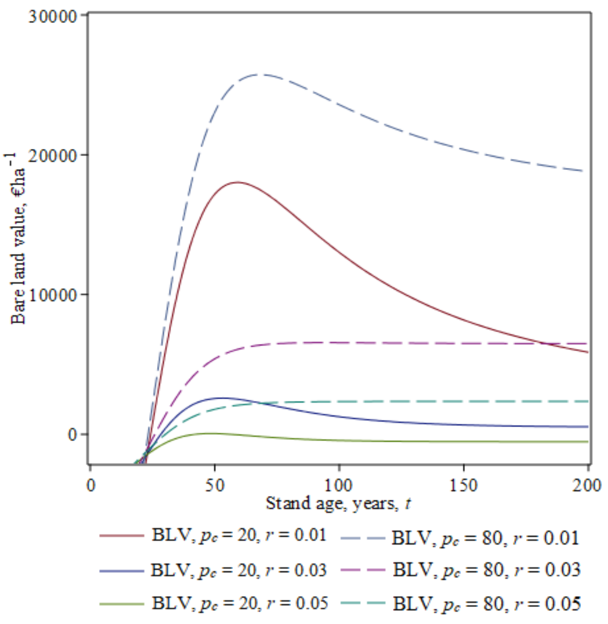

Figure 5. Dependence of bare land value on the rotation age with different carbon prices and interest rates.

3.2 Theoretically correct compensation

The high net gain for the forest owner in the results for the univariate optimal rotation model with carbon storage (Table 1) implies a need for a theoretically sound model of compensating carbon sequestration with the additionality principle. Here the subsidy for increasing carbon sequestration will be determined by examining the opportunity costs of not applying privately optimal forest management.

According to the theory of environmental economics, in the case of externalities, the social planner may intervene in the market by implementing regulation to incentivize the internalization of externalities (Phaneuf and Requate 2017, p. 3). In this case, we examine one externality: carbon sequestration and its release when timber is harvested. Carbon sequestration and post-harvest emissions represent two sides of the same externality. According to the so-called Tinbergen rule, a determinate policy system should have an equal number of objectives and instruments (Tinbergen 1952). Hence, next we will implement a net subsidy on carbon sequestration including a liability for carbon released at harvest.

In this model we apply the additionality principle and only subsidize carbon sequestration incentivized by the regulation. Tahvonen and Rautiainen (2017) suggest paying a subsidy for baseline carbon to avoid bringing forward clearcuts in anticipation of a mandatory scheme and imposing a full compensation liability on harvest emissions to ensure additionality. We follow a similar logic in our proposed voluntary scheme because otherwise the cost burden would be excessively high at the time that the forest owner decides to join the scheme with a regeneration ready stand. The compensation liability at the end of the rotation ensures that the additionality criterion is met. We consider a case where the privately optimal rotation length is denoted by t^* and is obtained by maximizing equation (4) with $\tau = 0$, i.e. the Faustmann optimum. The private optimum differs from the socially desirable rotation length ($\hat{t}$) as it does not consider the value of carbon sequestration. Thus, the social planner intervenes and offers the possibility to extend the length of the first rotation to $\hat{t}$ by entering the proposed compensation scheme (Figure 6). The length of the extension is denoted by $\tilde{t} = \hat{t} - t^*$ and the decision to participate in the scheme by postponing the first clearcut is made with a regeneration ready stand, i.e. $t = t^*$.

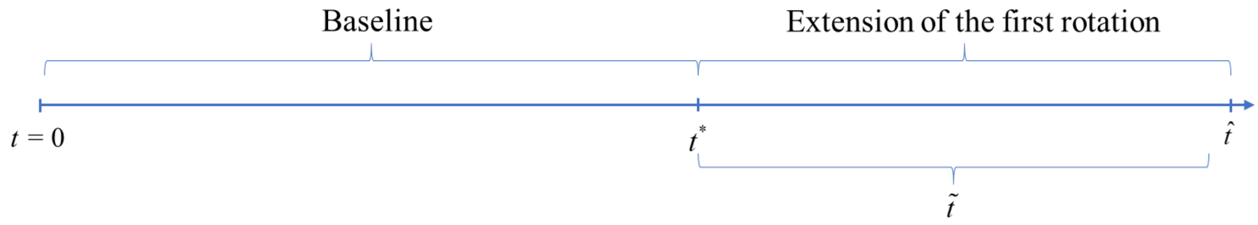

Figure 6. Timeline of the scheme with a correctly determined compensation.

Let us first pay a subsidy for carbon sequestration exceeding the baseline (t^*) and write

$$\tau \int_{t^*}^{\hat{t}} F'(s) e^{-r(s-t^*)} ds, \qquad (13)$$

where additional carbon sequestration is subsidized from t^* to $\hat{t}$. Let us pay a subsidy for baseline carbon that remains stored in the stand at t^* and impose a compensation liability for all emissions released by harvesting at $\hat{t}$. The net subsidy is given as

$$-\tau\beta\left\{e^{-r\tilde{t}} F(\hat{t}) - F(t^*)\right\}. \qquad (14)$$

In the proposed scheme the forest owner has the possibility to clearcut the stand at $\hat{t}$, generating a timber income of

$$e^{-r\tilde{t}}\left\{pF\left(\hat{t}\right) + J_t\left(t^*\right)\right\}, \qquad (15)$$

where the clearcut income at $\hat{t}$ and the maximized bare land value are discounted to t^*. The cost of the proposed scheme for the forest owner consists of (14) and the opportunity cost caused by not applying the privately optimal rotation length t^*, which can be written as

$$pF\left(t^*\right) + J_t\left(t^*\right). \qquad (16)$$

We may now present the final equation in which the objective is to determine a carbon price implying that the forest owner is indifferent between joining the scheme and applying the private optimum.

Thus, fully compensating the cost of additional carbon sequestration without causing unnecessary fiscal costs. The net revenues or costs of participating in the scheme for the forest owner are given as

$$\tau(\hat{t}) = e^{-r\tilde{t}}\left\{pF\left(\hat{t}\right) + J_t\left(t^*\right)\right\} - \left\{pF\left(t^*\right) + J_t\left(t^*\right)\right\} + \tau\int_{t^*}^{\hat{t}} F'(s)e^{-r(s-t^*)}ds - \tau\beta\left\{e^{-r\tilde{t}}F(\hat{t}) - F(t^*)\right\} = 0, \quad (17)$$

where the price of carbon (τ) is a function of the length of the extended first rotation $(\hat{t})$. The subsidy per additional ton of CO_2 sequestered is determined by the clearcut revenues obtained at the end of the extension and the bare land value of all future rotations, credited additional carbon sequestration, the difference of carbon released at clearcut and the credited baseline carbon, and the opportunity cost of not applying the private optimum.

3.2.1 Numerical results for the theoretically correct compensation

Table 2 presents results for equation (17), where the price of carbon is a function of the socially desired rotation length ($\hat{t}$). The aim is to solve for a price of carbon resulting in a zero gain/loss for the forest owner from participating in the scheme. We use $t^* = 52$ as the baseline for carbon sequestration and examine different alternatives for $\hat{t}$. As $\hat{t}$ increases from $\hat{t} = 77$ to $\hat{t} = \infty$ (i.e. forest management for carbon storage only), the required subsidy (column a) increases from €33 tCO_2^{-1} to €60 tCO_2^{-1}. While the net present value of additional carbon sequestration (column b) increases with an increase in $\hat{t}$, the net present value of timber income (column c) and average annual commercial timber yield (column d) decrease resulting in an increase in the subsidy for additional carbon sequestration (column f). The opportunity cost of not applying the privately optimal rotation length is a constant €17790 ha^{-1}. A lump sum subsidy (column e) paid for baseline carbon sequestration depends on the price of carbon (column a) and varies between €6548 ha^{-1} and €11805 ha^{-1}. As the timing of the first clearcut is postponed, also the emissions are released later in time, resulting in a declining emission tax (column g) as $\hat{t}$ is increased. The fiscal costs (column h) increase in $\hat{t}$ as the emission tax (column g) decreases and the subsidies (column e) and (column f) increase.

Table 2. Numerical results for solving carbon price as a function of the extension of the first rotation.

	a	b *	c	d	e	f	g	h **
Postponement of first clearcut (*years*)	Required subsidy (*€/tCO2*)	NPV of additional net carbon sequestration (*tCO_2/ha*)	NPV of Timber revenue (*€/ha*)	Average annual commercial timber yield (*m3/ha*)	Subsidy for baseline carbon (*€/ha*)	Subsidy for additional sequestration (*€/ha*)	Emission tax (*€/tCO2*)	Fiscal cost (*€/ha*)
0	0	-	17790	6.3	-	-	-	-
25	33	82	14255	6.1	6548	2709	5722	3535
50	47	98	9294	5.1	9317	4583	5404	8496
100	56	100	3499	3.5	11104	5625	2438	14291
∞	60	101	-	-	11805	5985	-	17790

Note: * *(f/a)*, ** *(e+f-g)*, t^* = 52 years, r = 2 %

3.2.2 Sensitivity analysis of the model

Figure 7 illustrates the results of a sensitivity analysis for equation (17) to see how the results depend on the values of r, p, w, β, α_1, α_2, and α_3. In all figures, the required carbon price level used in the compensation is an increasing function of the socially desired rotation age $(\hat{t})$ which saturates at some level of $\hat{t}$. Figure 7a shows that as the interest rate increases, the required compensation decreases due to the optimal rotation being more sensitive to carbon pricing with higher interest rates (Figure 4). A higher interest rate also lowers the opportunity cost, as the maximized bare land value decreases. With a higher stumpage price (Figure 7b) a higher compensation is required due to the high profitability of timber production. With a higher regeneration cost (Figure 7c), a lower compensation is required because timber production is less profitable. The opportunity cost, equation (16), decreases more compared to the net present value of timber income, equation (15), as a result of the optimal rotation (t^*) being shorter (Figure 7c). A higher present value of decay of timber products (Figure 7d) results in a decrease in the required subsidy due to a relatively higher increase in the lump sum subsidy compared to the increase in the tax burden when the stand is clearcut. In Figure 7e differences in stand fertilities are compared. A noticeably lower compensation is required to achieve a given extension of the first rotation at a site of low fertility.

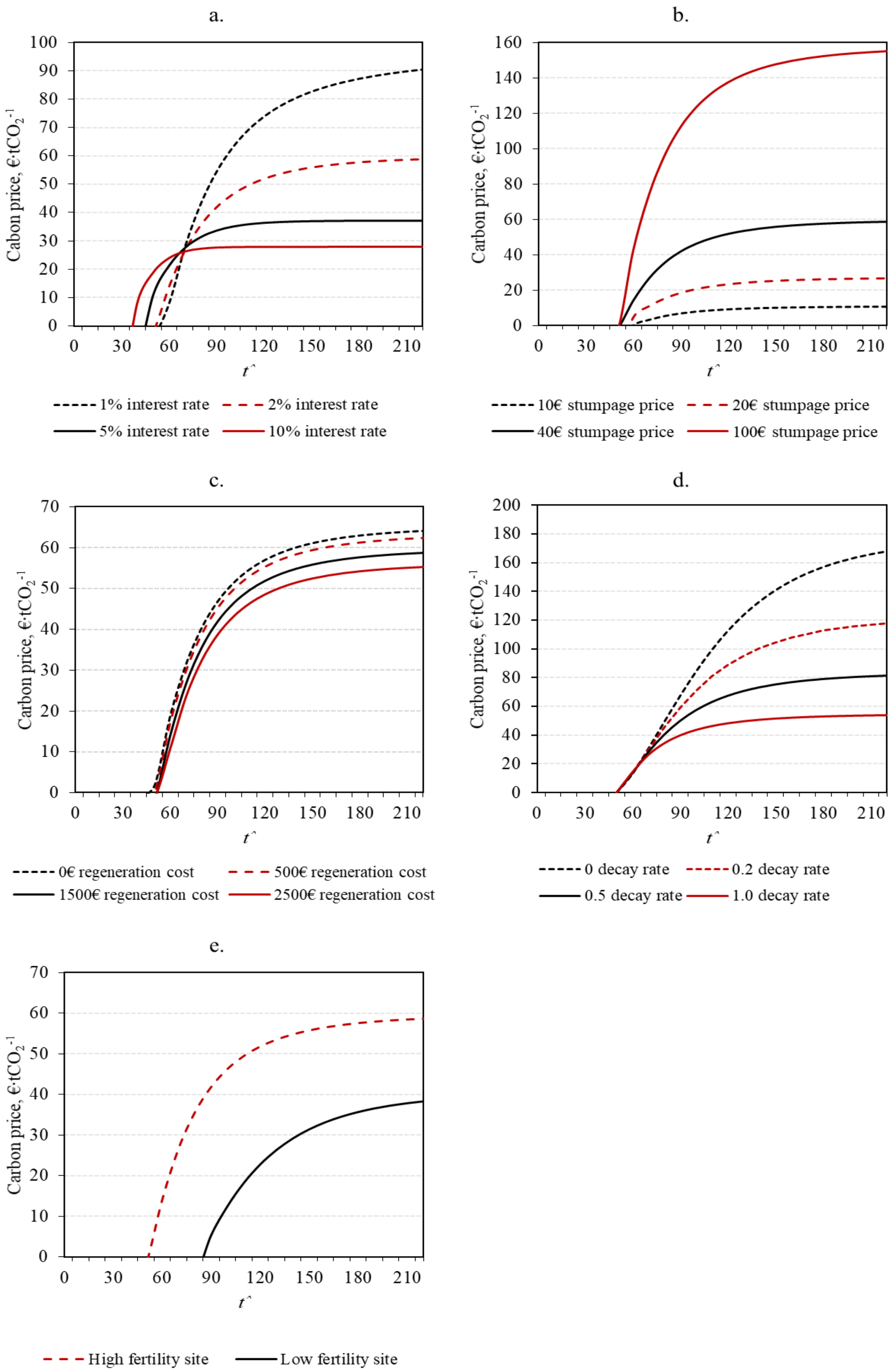

Figure 7. Sensitivity analysis of the key parameters in the theoretically correct compensation model.

3.3 New Zealand Emissions Trading Scheme

We now use the model presented in equations (1) – (4) to evaluate the net compensation structure for post-1989 forests in the New Zealand Emissions Trading Scheme. Forest owners are liable for all carbon released at harvest. In our model the present value of decay of timber products (β) can be used to see, how the exclusion of harvested wood products affects the compensation required for the forest owner to be willing to participate in the scheme.

Table 3 shows, how the present value of decay of timber products affects the results. We note that the faster the carbon is released after harvest, the longer is the optimal rotation (column a) and the higher is the decrease in bare land value (column b) and the net present value of timber revenues (column c). Thus, the cost of providing additional carbon sequestration (column d) increases from €28 ha^{-1} when $\beta = 0$ to €89 ha^{-1} when $\beta = 1$ and the total subsidy (column f) increases from €64 ha^{-1} to €171 ha^{-1}.

Table 3. Effect of the present value of decay of timber products.

	a	b	c	d	e	f
Decay rate (β)	Optimal rotation *(years)*	Bare land value *(€/ha)*	NPV of timber revenues *(€/ha)*	Total cost of additional storage *(€/ha)*	Unit cost of additional storage *(€/tCO$_2$)*	Subsidy for additional storage *(€/ha)*
β = 0	54	8382	4802	28	6.2	64
β = 0.5	55	7148	4780	50	6.7	104
β = 1	56	5923	4741	89	7.3	171

Note: p_c = 20, r = 2 %

Figure 8 shows the effect of parameter β on the optimal rotation length. If $\beta = 1$ all carbon is released at harvest and if $\beta = 0$ all carbon is stored indefinitely in timber products. The faster the carbon is released from harvested wood, the stronger is the effect of carbon pricing on the optimal rotation length. This supports our analytical finding that the faster is the release of carbon, the longer the optimal rotation becomes. If all carbon is released at harvest, a carbon price of €108.4 tCO_2 results in an infinitely long optimal rotation, i.e. managing the forests for carbon storage only. This is due to the nature of the net subsidy system implemented in the model. At the point when the optimal rotation becomes infinitely long, the cost of released carbon exceeds the income from harvested timber. Thus, the optimal management regime shifts from clearcut to pure carbon storage. With a gross subsidy system ($\beta = 0$), the effects of carbon pricing on the optimal rotation are minor, as the forest owner has no liability for carbon released at harvest. If half of the carbon is released at harvest, i.e. $\beta = 0.5$, the optimal rotation lengthens significantly as the price of carbon increases. However, to fully conserve the forest with this parameter value, a carbon price of €501 tCO_2 would be required.

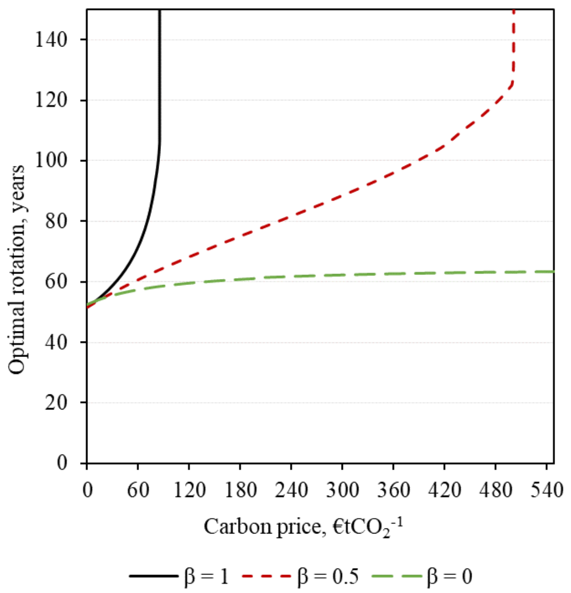

Figure 8. Effect of the present value of decay of timber products on the optimal rotation with a 2 % interest rate.

3.4 Compensation accounting in the California Forest Offset Protocol

To examine the compensation scheme implemented in California, we modify the univariate optimal rotation model to resemble the Californian Forest Offset accounting structure. Additional, i.e. baseline-exceeding, carbon sequestration is credited for the duration of a crediting period $\left(\hat{t} - t^*\right)$ of 25 or 50 years, where t^* and $\hat{t}$ denote the privately optimal rotation length and the stand age at the end of the crediting period, respectively. The forest may be clearcut only after a 100-year monitoring period $\left(t^* + \tilde{t}\right)$ beginning from the last issued offset credit (Figure 9), where $\tilde{t}$ denotes the combined length of the crediting and monitoring period, i.e. 125 or 150 years. Only the length of the first rotation is extended and after the monitoring period, the forest owner may resume applying privately optimal forest management. The Forest Offset Protocol accounts for harvest emissions during the contract when thinnings are allowed according to the principles of uneven-aged management. However, after the contract ends the forest owner has no liability for harvest emissions. The utilized model does not include thinnings, thus, we model the Protocol as a gross subsidy system, with no liability for clearcut emissions.

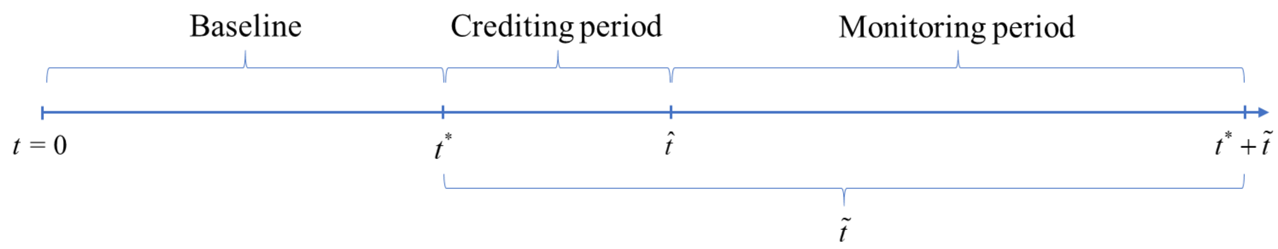

Figure 9. Timeline of the California Forest Offset Protocol.

The baseline forest management is based on the Faustmann optimal rotation (t^*) when $\tau = 0$. To model the choice offered by the California Forest Offset Protocol, we offer the forest owner the opportunity to postpone the harvest from the private optimum to the end of the monitoring period (i.e. $t^* + \tilde{t}$). Carbon sequestration between t^* and $\hat{t}$ is credited as

$$\tau \int_{t^*}^{\hat{t}} F'(s) e^{-r(s-t^*)} ds, \tag{18}$$

where the value of carbon sequestration is discounted to the moment t^*, when the decision to postpone the first clearcut is made. The income if the forest is harvested at $t^* + \tilde{t}$ is the sum of crediting the additional carbon sequestration, clearcut revenues and the value of bare land discounted to the moment t^*, and is written as

$$\tau \int_{t^*}^{\hat{t}} F'(s) e^{-r(s-t^*)} ds + e^{-r\tilde{t}} \left[pF\left(t^* + \tilde{t}\right) + J_t\left(t^*\right) \right]. \tag{19}$$

To see the cost of the extension, *C*, for the forest owner, we deduct the opportunity cost of not applying the privately optimal rotation (t^*) from the income at $t^* + \tilde{t}$ and write the final equation as

$$C = \tau \int_{t^*}^{\hat{t}} F'(s) e^{-r(s-t^*)} ds + e^{-r\tilde{t}} \left[pF\left(t^* + \tilde{t}\right) + J_t\left(t^*\right) \right] - \left[pF\left(t^*\right) + J_t\left(t^*\right) \right]. \tag{20}$$

Equation (20) presents the change in the forest owner's income if he joins the California Forest Offset Protocol by postponing the timing of the first clearcut from the private optimum (t^*) to $t^* + \tilde{t}$ and additional carbon sequestration is credited for the duration of the crediting period, $\hat{t} - t^*$. After the monitoring period, the contract ends and the forest owner has no compensation liability.

3.4.1 Numerical results for compensation accounting in California Forest Offset Protocol

We now present the results of our modelling of the Californian Forest Offset Protocol compensation structure presented in equation (20). Figure 10 illustrates the net revenues or costs of participation in the Offset Protocol for the forest owner. With the parameter values presented earlier and an interest rate of 2%, the baseline solution is to apply a rotation age of 52 years (yielding a bare land value of €4830 ha^{-1}). By evaluating equation (20), we may observe at which price of carbon the forest owner's net revenues or costs from joining the protocol are equal to zero, i.e. all costs are compensated. Line a presents the case where the crediting period lasts 25 years and the forest may be clearcut after the monitoring period at the stand age of 177 years. Line b presents the case where the crediting period is 50 years and the forest may be clearcut at the stand age of 202 years. To compensate the costs of participating in the Protocol with a 25 or 50-year crediting period, a carbon price of €191 tCO$_2^{-1}$ and €169 tCO$_2^{-1}$ is required, respectively.

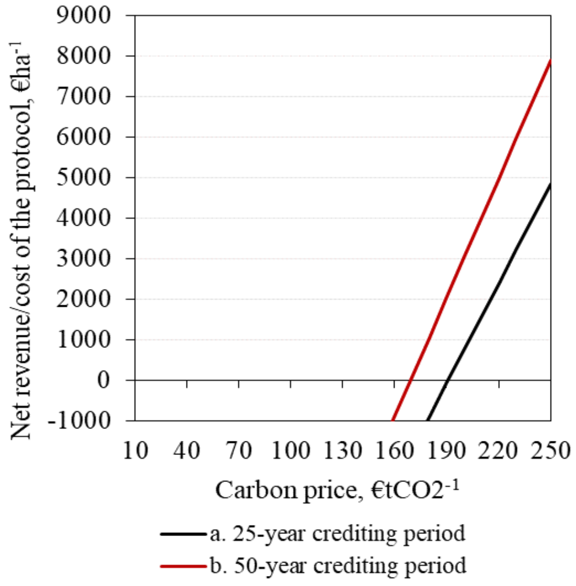

Figure 10. Net revenues/costs of joining the Protocol with crediting periods of 25 and 50 years with a 2 % interest rate.

The baseline set for the compensation scheme plays a large role in examining the change in timber income. The California Forest Offset Protocol has been criticized for baselines established lower than the actual forest state at the time of entering the Protocol (Haya 2019). Theoretically, the effect of the baseline can be examined by decreasing the lower bound of the integral set at t^* in equation (20). The model now begins crediting carbon sequestration before the optimal rotation t^*. Figure 11 illustrates the effect of the baseline on the change in forest income with a 25-year crediting period by decreasing the lower bound from 52 years to (b) 42, (c) 32 and (d) 22 years. We note that by an earlier initiation of crediting carbon sequestration, a much lower carbon price is needed to maintain the profitability of forestry with the Californian structure. The carbon stocks in forests corresponding to the lower bounds of crediting in Figure 11 are: (b) 156 tCO_2ha^{-1}, (c) 78 tCO_2ha^{-1}, (d) 20 tCO_2ha^{-1}, while at t^*, (a), the forest carbon stock is $227tCO_2ha^{-1}$. Carbon that is sequestered between the lowered baseline and the carbon stock at t^* represents non-additional crediting leading to a decrease in the required subsidy per tCO_2 sequestered. While these non-additional credits make the scheme more appealing for the forest owner, they simultaneously jeopardize its integrity.

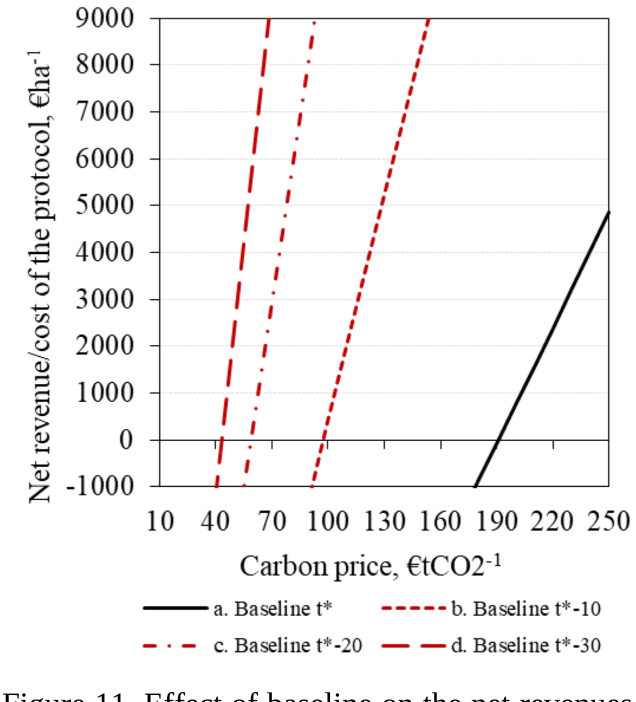

Figure 11. Effect of baseline on the net revenues/costs of the protocol for the forest owner with a 2 % interest rate.

The key results for the compensation structure of the California Forest Offset Protocol are presented in Table 4. The required compensation (column a) was presented above with the net revenue/cost curves and here we report the precise carbon prices (€tCO_2^{-1}) required for the forest owner to be willing to join the protocol according to our model. The first three rows present the baseline results and the results for the two possible lengths of the crediting period (25 and 50 years). The last three rows present results for cases where the baseline is set lower than the actual carbon stock in the forest at the time of project initiation. The required subsidy decreases from €191 tCO_2^{-1} to €169 tCO_2^{-1} with the crediting periods of 25 and 50 years, respectively. If the baseline is set lower and non-additional carbon sequestration is credited, the required subsidy decreases from €97 tCO_2^{-1} to €43 tCO_2^{-1} when the crediting begins 10 years or 30 years before the actual private optimum (t^*). The net present value of credited carbon sequestration (column b) increases if the crediting period is longer or the baseline is set below the actual carbon stock at the time of project initiation. The net present value of timber revenues (column c) decreases radically from the private optimum (€17 789 ha^{-1}) to €2126 ha^{-1} with a 25-year crediting period and to €1290 ha^{-1} with a 50-year crediting period. This significant decrease is due to the length of the monitoring period, which postpones the clearcut from 52 years (baseline) to 177 years (25-year crediting period) or to 202 years (50-year crediting period) simultaneously decreasing the average annual commercial timber yield (column d) from 6.3 m^3ha^{-1} to 2.6 m^3ha^{-1}. The total subsidy for carbon sequestration (column e) in the modelled scenarios is €15 664 ha^{-1} with the 25-year crediting period and €16 500 ha^{-1} with the 50-year crediting period. This total subsidy combined with the net present value of timber income is equal to the opportunity cost of €17 790 ha^{-1} with all rotation lengths and the non-additional crediting when the baseline is lowered has no effect on the total subsidy. From the point of view of fiscal costs, it is thus insignificant if non-additional carbon sequestration is credited when the subsidy is defined based on the opportunity cost. However, non-additional crediting creates false offset units to the market, decreasing its effectiveness by allowing the capped polluters to release more emissions.

Table 4. Numerical results of the univariate optimal rotation model with California Forest Offset Protocol structure.

	a	b	c	d	e
Length of crediting period (*years*)	Required subsidy (*€/tCO2*)	NPV of credited net carbon sequestration (*tCO₂/ha*)	NPV of Timber revenue (*€/ha*)	Average annual commercial timber yield (*m3/ha*)	Subsidy for carbon sequestration (*€/ha*)
-	-	-	17790	6.3	-
25	191	82	2126	3.0	15664
50	169	98	1290	2.6	16500
Crediting period 25 years. Baseline lowered: *					
*t** - 10	97	161	2126	3.0	15664
*t** - 20	59	266	2126	3.0	15664
*t** - 30	43	361	2126	3.0	15664

Note: *t** = 52 years, *r* = 2 % , * additionality criterion not fulfilled

Due to structural differences, the required subsidies (€tCO_2^{-1}) calculated for the Californian Forest Offset Protocol differ significantly from the ones obtained with our proposed compensation structure (Table 2). The timing of the first clearcut is postponed more in the Forest Offset Protocol than in our proposed scheme, while carbon sequestration during the monitoring period is not subsidized. This results in higher costs for the forest owner leading to a higher required subsidy (€tCO_2^{-1}). However, the resulting fiscal costs (column h in Table 2 and column e in Table 4) are similar. While California is a gross subsidy scheme in the case of clearcuts at the end of the extension, our proposed structure represents a net compensation scheme, i.e. the forest owner is liable for clearcut emissions. Our structure pays a subsidy for carbon stored in the stand at the time of project initiation, as carbon that is stored in the stand longer than in the business as usual scenario also has a value. Additionality in our scheme is achieved by the full liability for emissions released at the end of the extended rotation. Thus, although the fiscal costs of the schemes are similar, the proposed scheme avoids the issues of non-additional crediting that are present in the Californian Forest Offset Protocol and ensures that all offset credits represent actual additional carbon sequestration. When the aim is to subsidize carbon sequestration with the prevailing price of carbon in the emissions trading scheme, it appears that the Californian structure fails to compensate the costs of extending the length of the rotation thus making the Protocol unattractive for forest owners.

4 Size-structured forestry model with a carbon subsidy

To verify the results of the theoretically correct model (Chapter 3.2) using a more realistic forestry model, we now begin examining a size-structured model with a carbon subsidy presented by Assmuth et al. (2018). The model is an extension of a generalized size-structured model by Tahvonen and Rämö (2016), where the choice between rotation forestry (i.e. forestry based on clearcuts) and continuous cover forestry is optimized simultaneously with the timing and intensity of thinnings (i.e. partial harvests). In boreal forestry, commercial thinnings may represent a significant share of timber revenues and altering thinning strategies plays a large role in increasing economically optimal carbon storage (Assmuth et al. 2018; Pihlainen et al. 2014). Thus, it is important to verify the results obtained with the univariate optimal rotation model, with this empirically more detailed model. We will first present the original model as presented by Assmuth et al. (2018), go through the modifications made for our numerical analysis, and finally present results.

4.1 Growth model and the optimization problem

The stand state at the beginning of period *t* is given by $\mathbf{x}_t = \left[x_{1t},\ x_{2t},\ ...,\ x_{nt}\right]$, where x_{st} denotes the number of trees in size class *s* at the beginning of period *t*, $s = 1,\ 2,\ ...,\ n$ and $t = t_1,\ t_1 + 1,\ ...,\ T + 1$. The fraction of trees moving to size class *s*+1 in period *t* is denoted by $\beta_s(\mathbf{x}_t),\ s = 1, 2, ...,\ n$. In the largest size class the fraction of trees moving to the next size class is zero, i.e. $\beta_n(\mathbf{x}_t) \equiv 0$. Let $\mu_s(\mathbf{x}_t),\ s = 1,\ 2,\ ...,\ n$ denote the natural mortality in size class *s* in period *t*. The fraction of trees remaining in the same size class can now be written as $1 - \beta_s(\mathbf{x}_t) - \mu_s(\mathbf{x}_t),\ s = 1,\ 2,\ ...,\ n$. Ingrowth, denoted by $\phi(\mathbf{x}_t)$, describes natural regeneration by determining the number of trees entering the first size class. Let the number of harvested trees from size class *s* at the end of period *t* be $h_{st},\ s = 1\ , 2,\ ...,\ n,\ t = t_1,\ t_1 + 1,\ ...,\ T$. The following equations describe the stand development:

$$x_{1,t+1} = \phi(\mathbf{x}_t) + [1 - \beta_1(\mathbf{x}_t) - \mu_1(\mathbf{x}_t)]x_{1t} - h_{1t}, \tag{21}$$

$$x_{s+1,t+1} = \beta_s(\mathbf{x}_t)x_{st} + [1 - \beta_{s+1}(\mathbf{x}_t) - \mu_{s+1}(\mathbf{x}_t)]x_{s+1,t} - h_{s+1,t}, \tag{22}$$

$$x_{n,t+1} = \beta_{n-1}(\mathbf{x}_t)x_{n-1,t} + [1 - \mu_n(\mathbf{x}_t)]x_{nt} - h_{nt}, \tag{23}$$

where $t = t_1,\ t_1 + 1,\ ...,\ T$.

The stand is clearcut if $T \in [t_1, \infty]$ is finite. After a clearcut the stand is artificially regenerated creating a cost of $w \geq 0$ (€ha^{-1}). The time period between regeneration and ingrowth into the smallest size class is denoted by t_1. Annual interest rate is denoted by *r* and the discount factor is $b = 1(1+r)^{-1}$. The period length in years is denoted by Δ. Thinning, $R(\mathbf{h}_t)$, and clearcut revenues $R(\mathbf{x}_T)$ are dependent on the size and number of the harvested trees. The periodic revenues are given as

$$R(\mathbf{h}_t) = \sum_{s=1}^{n} h_{st} \left(v_{\sigma,s} p_{\sigma} + v_{\varpi,s} p_{\varpi} \right), \quad t = t_1,\ t_1 + 1,\ ..., T, \tag{24}$$

where $v_{\sigma,s}$ and $v_{\varpi,s}$ denote the volumes of sawlog and pulpwood per tree in size class *s*, and p_{σ} and p_{ϖ} denote their roadside prices in €m^{-3}. A fixed harvesting cost, C_f, includes, for example, the transportation of machinery to the logging site. Variable harvesting costs, $C_i(\mathbf{h}_t)$, where *i* denotes clearcut (*cl*) or thinning (*th*), are given separately. Binary variable $\delta_t = \{0,\ 1\}$, $t = t_1,\ t_1 + 1,\ ...,\ T$ and the Boolean operator $h_t = \delta_t h_t$ take into account that the fixed costs may result in it not being optimal to harvest the stand in every period. When $\delta_t = 1$, the harvest levels $h_{st} \geq 0,\ s = 1,\ 2,\ ...,\ n$ can be freely optimized, and when $\delta_t = 0$, it must be that $h_{st} = 0,\ s = 1,\ 2,\ ...,\ n$.

Society internalizes the positive externality of carbon sequestration by implementing a Pigouvian subsidy for carbon sequestration and charging for emissions released from harvested timber and due to natural mortality. Denote the price of CO_2 by $p_c \geq 0$ (€tCO_2^{-1}) and the volume of merchantable timber in the stand at the beginning of period *t* by $\varpi_t = \sum_{s=1}^{n} x_{s,t}(v_{\sigma,s} + v_{\varpi,s})$. A density factor, ρ, converts the stem volume of merchantable timber into stem dry mass which is converted into whole-tree dry mass, including non-merchantable tree matter, by an expansion factor η. Thus, $B_t(\mathbf{x}_t) = \rho\eta\varpi_t$ gives the total tree biomass in the stand and $B_{t+1}(\mathbf{x}_{t+1}) - B_t(\mathbf{x}_t)$ the net biomass growth in period *t*.

The dry mass of harvested sawlog and pulpwood at the end of period *t* are given by $y_{\sigma,t} = \rho \sum_{s=1}^{n} h_{st} v_{\sigma,s}$ and $y_{\varpi,t} = \rho \sum_{s=1}^{n} h_{st} v_{\varpi,s}$, respectively. The dry mass of dead tree matter from natural mortality during period *t* is described by $d_{m,t} = \rho\eta \sum_{s=1}^{n} \mu(\mathbf{x}_t)_{s,t} x_{s,t}(v_{\sigma,s} + v_{v,s})$ and the dry mass of harvest residues by $d_{h,t} = (\eta - 1)(y_{\sigma,t} + y_{\varpi,t})$. Harvesting does not instantaneously release the whole carbon content of timber as timber is used for products that have varying decay profiles (Liski et al. 2001). Annual decay rates of sawlog, pulpwood and dead tree matter are denoted by $g_j(j = \sigma,\ \varpi,\ d)$, respectively. We assume that the society has a positive time preference for net emissions. Thus, the present value of future emissions from a unit of timber assortment *j* is $p_c \alpha_j(r)$ where $\alpha_j(r) = g_j(g_j + r)^{-1}$ is the present value of decay of timber products (cf. Assmuth and Tahvonen 2018). The value of net carbon sequestration (i.e. carbon sequestration and carbon released when the stand is harvested) in period *t* can be given as

$$Q_t = p_c \theta \{B_{t+1}(\mathbf{x}_{t+1}) - B_t(\mathbf{x}_t) + \left[1 - \alpha_\sigma(r)\right] y_{\sigma,t}(\mathbf{h}_t) + \left[1 - \alpha_\varpi(r)\right] y_{\varpi,t}(\mathbf{h}_t) + \left[1 - \alpha_d(r)\right]\left[d_{m,t}(\mathbf{x}_t) + d_{h,t}(\mathbf{h}_t)\right]\}, \tag{25}$$

where θ denotes the conversion factor of dry mass units to CO_2. The first term represents biomass net growth and the next three terms take into account the carbon stored and released from sawlog and pulpwood products and dead tree matter, respectively. The problem of optimizing harvests over an infinite time horizon as presented by Assmuth et al. (2018) is

$$J(\mathrm{x}_0, T) = \max_{\{h_{st}, \delta_t, T \in [t_1, \infty)\}} \frac{-w + \sum_{t=0}^{T} Q(\mathbf{x}_t, \mathbf{h}_t) b^{\Delta(t+1)} + \sum_{t=t_1}^{T} [R(\mathbf{h}_t) - C(\mathbf{h}_t) - \delta_t C_f] b^{\Delta(t+1)}}{1 - b^{\Delta(t+1)}} \tag{26}$$

subject to

(21), (22), (23) and

$$\delta_t \in \{0,\ 1\},\ t = t_1,\ t_1 + 1,\ ...,\ T, \tag{27}$$

$$x_{st} \geq 0,\ s = 1,\ 2,\ ...,\ n,\ t = t_1,\ t_1 + 1,\ ...,\ T + 1, \tag{28}$$

$$h_{st} = \delta_t h_{st} \geq 0,\ s = 1,\ 2,\ ...,\ n,\ t = t_1,\ t_1 + 1,\ ...,\ T, \tag{29}$$

$$\mathbf{x}_{T+1} = 0, \tag{30}$$

$$x_{s,t_1} \text{ given.} \tag{31}$$

4.2 Parameter values and computational methods

In the model the harvest intensities are continuous, while the harvest timing variables are integers. Thus, we apply bi-level optimization to solve a mixed-integer nonlinear programming problem. Knitro 10.3 optimization software is used for solving the lower level problem of continuous harvest intensity, while the upper level problem of harvest timing variables is optimized with a genetic algorithm. The applied growth model is an empirical transition matrix model for boreal single- and mixed-species stands estimated by Bollandsås et al. (2008) using Norwegian National Forest Inventory data. The model includes species-specific functions for ingrowth, mortality, and diameter increment. This thesis studies a pure Norway spruce stand at latitude 61.9°N on an average productivity site (SI=15), where the height of the dominant trees at an age of 100 years is 24 meters. The parameter values for all size classes (12) are presented in Table 5. The period length used in the model is $\Delta = 5$ years. The time for the emergence of trees into the smallest size class after planting is 4 periods (20 years) and we assume an initial stand of 2250 trees.

Table 5. Size-class specific parameter values (SI=15).

Size class	Diameter *(cm)*	Basal area *(m^2)*	Sawlog volume *(m^3)*	Pulpwood volume *(m^3)*
1	7.5	0.004	0	0.014
2	12.5	0.012	0	0.067
3	17.5	0.024	0	0.167
4	22.5	0.04	0.234	0.081
5	27.5	0.059	0.446	0.065
6	32.5	0.083	0.684	0.06
7	37.5	0.11	0.963	0.05
8	42.5	0.142	1.253	0.05
9	47.5	0.177	1.574	0.043
10	52.5	0.216	1.9	0.039
11	57.5	0.26	2.214	0.033
12	62.5	0.307	2.565	0.031

Natural mortality in period *t* in size class *s* is calculated as $\mu_{st} = \left[1 + e^{-\left(-2.492 - 0.020 M_s + 3.2 \cdot 10^{-5} M_s^2 + 0.031 A_t\right)}\right]^{-1}$,

where M_s denotes the diameter of size class *s* and A_t ($m^2 ha^{-1}$) is the total stand basal area in the beginning of period *t*. The fraction of trees moving to the next size class during period *t* can be given as

$$\beta_{st} = \frac{1.2498 + 0.0476M_s - 11.585 \cdot 10^{-2} M_s^2 - 0.3412L_{st} + 0.906 \cdot SI - 0.024A_t}{50}, \tag{32}$$

where L_{st} denotes the total basal of the size class *s* in the beginning of period *t*. Natural regeneration during period *t* depends on the site index (SI) and the total basal area and is given per period *t* as

$$\phi_t = \frac{54.563(A_t + a)^{-0.157} \cdot SI^{0.368}}{1 + e^{(0.391 + 0.018A_t - 0.066 \cdot SI)}}, \tag{33}$$

where $a = 0.741$.

Fixed harvesting costs are assumed to be €500 ha^{-1}. Variable harvesting and hauling costs, given separately for thinnings and clearcuts, by an empirically estimated function by Nurminen et al. (2006) depend on the volume and number of harvested trees and are given as

$$C_i = C_{i0}C_{i1}\sum_{s=1}^{n} h_{st}\left(C_{i2} + C_{i3}v_s - C_{i4}v_s^2\right) + C_{i5}\left(C_{i6}\sum_{s=1}^{n} h_{st}v_s + C_{i7}\left(\sum_{s=1}^{n} h_{st}v_s\right)^{0.7}\right), \tag{34}$$

where $i = th,\ cl$. C_{i0} (€) denotes the harvesting cost per minute and C_{i1} is the number of minutes spent cutting one tree and moving to the next one. C_{i5} and its coefficient denote the cost and duration of hauling, respectively. Values for these parameters are presented separately for thinnings and clearcuts in Table 6. The cost of artificial regeneration cost is €1500 ha^{-1}. The sawlog and pulpwood roadside prices are €58.44 m^{-3} and €34.07 m^{-3}, respectively.

Table 6. Harvesting cost parameter values.

i	C_{i0}	C_{i1}	C_{i2}	C_{i3}	C_{i4}	C_{i5}	C_{i6}	C_{i7}
th	2.1	1.15	0.412	0.758	0.18	1	2.272	0.535
cl	2.1	1	0.397	0.758	0.18	1	1.376	0.393

The stem wood density factor is $\rho = 0.3774$ tons of dry matter per m^3 while $\eta = 2.1566$ converts stem dry mass into whole-tree dry mass. The CO_2 content of a wood dry mass unit is $\theta = 1.83333$ tCO_2 t^{-1} (Niinimäki et al. 2013). Decay rates for sawlog and pulpwood products, $g_\sigma = 0.06611$ and $g_\varpi = 0.47070$, were calculated based on data presented in Liski et al. (2001). For dead tree matter, we use a decay rate calculated from data presented by Mäkinen et al. (2006), Palviainen et al. (2004), Palviainen et al. (2010) and Shorohova et al. (2008). The obtained decay rate of dead tree matter is $g_d = 0.1168$, which is somewhat lower than the one used in Assmuth et al. (2018).

4.3 Setup for the numerical analysis

We now present the setup for our numerical analysis with the size-structured model that is used to compare the results obtained with the univariate optimal rotation model and the theoretically correct setup in chapter 3. Again, we postpone the first clearcut, assume that privately optimal forest management is continued afterwards, and let the required subsidy be determined by the cost of extending the length of the first forest rotation. To examine the cost of extending the first rotation length past the private optimum (T^*) we define $\Delta(T^*+1) = 5(20+1) = 105$ years as the baseline. Similarly, as in the previously presented model, we now create a structure where this privately optimal rotation length is extended to a socially desired rotation length ($\hat{T}$) to increase carbon sequestration. The length of the extension of the first rotation is denoted by $\tilde{T}$ (Figure 12).

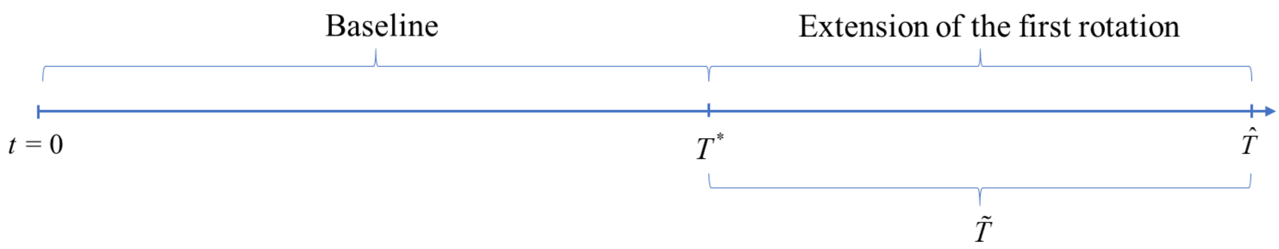

Figure 12. Timeline of the numerical analysis with the size-structured model.

The decision to enter the proposed scheme is again made at $\Delta(T^*+1) = 105$ and all values are discounted accordingly. The baseline values are obtained by maximizing the objective function in equation (26) with $p_c = 0$. As a result, we obtain the optimal harvest timings and volumes, rotation length, carbon flows, bare land value and clearcut revenues. The baseline forest management up to

T^{*}, i.e. the timing and intensity of thinnings, is assumed to remain unchanged as the first clearcut is postponed. Thus, we constrain the harvest timings and volumes of the baseline phase with equality constraints defined as

$$y_{\sigma,\,8} + y_{\varpi,\,8} = 158.391 \text{ m}^3,$$
$$y_{\sigma,\,11} + y_{\varpi,\,11} = 88.2951 \text{ m}^3,$$
$$y_{\sigma,\,13} + y_{\varpi,\,13} = 113.749 \text{ m}^3,$$
$$y_{\sigma,\,16} + y_{\varpi,\,16} = 159.755 \text{ m}^3,$$

which are the optimal harvest volumes at the end of specific periods during the baseline phase obtained by the unconstrained optimization.

During the baseline phase we assume that the forest does not regenerate naturally (i.e. we let $\phi_t = 0$ in equation (21)). This is due to understory cleaning in conventional forestry, where saplings are cleared from the forest prior to harvests (Tapio 2014). As we now begin extending the rotation length and forbid harvests during the extension, it is assumed that the forest is left untouched for the duration of the extension. I.e. the forest begins to regenerate naturally according to equation (33) without understory cleaning beginning from the stand age of 105 years. After understory cleaning is suspended, we assume that it takes 20 years for the first naturally regenerated trees to enter the first size class. Thus, the first naturally regenerated trees enter the smallest size class 125 years after stand regeneration.

Now the timing of the first clearcut is postponed from 105 years (private optimum), after which the forest owner is assumed to resume applying optimal forest management. The compensation for increasing net carbon sequestration is paid as a lump sum subsidy at the moment when the decision to postpone the first clearcut is made. The implemented structure compensates the cost of increasing net carbon sequestration in the forest but avoids over crediting and unnecessary fiscal costs. We will first define the net present value of timber revenues if the forest owner enters the scheme at $\Delta(t + 1) = 105$. We then define the functions for carbon sequestration and present the final equation for determining the correct subsidy per additional ton of CO_2.

The change in the net present value of timber income if the forest owner joins the protocol is given as

$$
\begin{aligned}
Y(\hat{T}) = & \left[R(\mathbf{x}_{\hat{T}}) - C_{cl}(\mathbf{x}_{\hat{T}}) - \delta_{\hat{T}} C_f + J(\mathbf{x}_0, T^*) \right] b^{\Delta \tilde{T}} \\
& - \left[R(\mathbf{x}_{T^*}) - C_{cl}(\mathbf{x}_{T^*}) - \delta_{T^*} C_f + J(\mathbf{x}_0, T^*) \right],
\end{aligned} \tag{35}
$$

where the first term presents the revenues after the extension, ie. clearcut income and the maximized bare land value discounted from the duration of the extension ($\tilde{T}$). Discounting the bare land value takes into account that all future rotations now begin later in time due to the postponement of the first clearcut. The second term considers the opportunity cost of not applying privately optimal forest management. In the opportunity cost, the clearcut revenues and the maximized bare land value can be obtained immediately, as we are at the moment $\Delta(t+1) = 105.$ The present value of net carbon sequestration of all future rotations is given as

$$
Q_\infty(T^*) = \frac{\sum_{t=0}^{T^*} Q(\mathbf{x}_t, \mathbf{h}_t) b^{\Delta(t+1)}}{1 - b^{\Delta(T^*+1)}}. \tag{36}
$$

The present value of net carbon sequestration when joining the protocol is the sum of sequestration during the first rotation discounted to the moment when the decision is made. To take into account the effect of the extension on the net sequestration of future rotations, we discount $Q_\infty(t)$ from the length of the extension ($\tilde{T}$). The present value of net carbon sequestration can now be given as

$$
\sum_{T^*}^{\hat{T}} Q(\mathbf{x}_t, \mathbf{h}_t) b^{\Delta(t - T^* + 1)} + Q_\infty(T^*) b^{\Delta \tilde{T}}. \tag{37}
$$

To establish additionality, we deduct the baseline carbon sequestration from the net sequestration of the first rotation given in equation (37). Additional net carbon sequestration when the first clearcut is postponed can now be written as

$$
Q_{ad}(\hat{T}) = \sum_{T^*}^{\hat{T}} Q(\mathbf{x}_t, \mathbf{h}_t) b^{\Delta(t - T^* + 1)} + Q_\infty(T^*) b^{\Delta \tilde{T}} - \left[Q(\mathbf{x}_{T^*}) + Q_\infty(T^*) \right]. \tag{38}
$$

The subsidy for increasing carbon sequestration (€tCO_2^{-1}) that makes the forest owner indifferent between resuming privately optimal forest management and joining the scheme can now be given as

$$\frac{Y(\hat{T})}{Q_{ad}(\hat{T})}, \tag{39}$$

where we divide the cost of postponing the first clearcut (€) with the achieved additional carbon sequestration (tCO_2).

4.4 Results

Privately optimal forest management with a 2% interest rate is presented in Figure 13a and the development of carbon stocks in the accounted pools in Figure 13b. The results are obtained by maximizing the objective function in equation (26) without assigning a value for carbon sequestration. This gives us the optimal forest management when externalities are excluded from the optimization, which is used as a baseline for carbon sequestration as we extend the length of the first rotation and subsidize additional carbon sequestration. Figure 13a illustrates the development of merchantable stand volume (m^3 ha^{-1}) and number of trees per hectare. 20 years after regeneration, 2250 saplings emerge into the first size class. The assumption that the forest does not regenerate naturally (i.e. $\phi_t = 0$) due to understory cleaning results in a decrease in the number of trees during the rotation, until the stand is regenerated after a clearcut. Thinnings are shown in Figure 13a as the decrease in stand volume, and after a clearcut the stand volume decreases to zero. All optimal thinnings are thinnings from above (i.e. the largest trees are harvested) and the first thinning is carried out at the stand age of 45 years and the subsequent thinnings at 60, 70 and 80 years of stand age. From Figure 13a, we see that carbon stored in living trees is by far the most significant carbon pool in the forest. It decreases as the forest is harvested, while after the harvest, carbon is stored in timber products and dead tree matter.

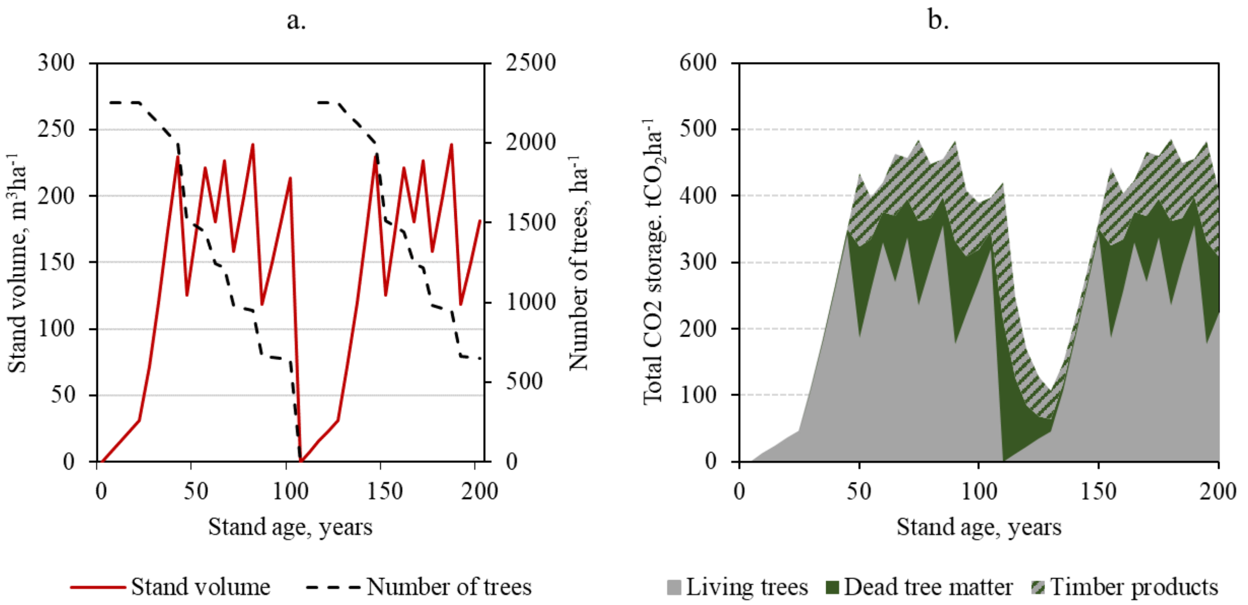

Figure 13. Baseline forest development with a 2% interest rate.

Figure 14 depicts the size class structure one period prior to harvest. Before the first thinning (Figure 14a), the majority of trees are in size classes 1–3 (diameter midpoints 7.5–17.5cm) and the largest standing size class is 5 (27.5cm). In the first thinning, size classes 4 and 5 are harvested. At the age of 100 years (Figure 14b), one period before clearcut, the size class structure is more evenly distributed, with some trees in size class 7.

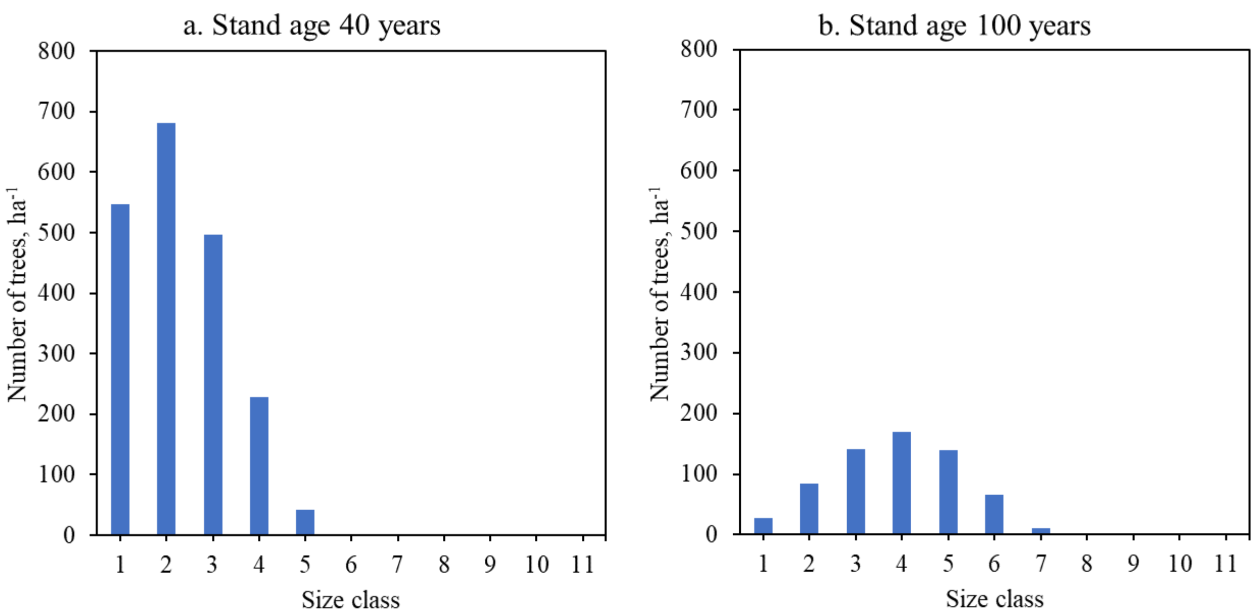

Figure 14. Baseline forest size class structure with a 2% interest rate.

When the decision to postpone the first clearcut is made, active forest management (i.e. understory cleaning) is suspended, and after 20 years the first naturally regenerated trees emerge in the first size class (Figure 15). The decision to postpone the timing of the first clearcut does not affect the timing of the thinnings carried out in the optimal baseline solution. As active forest management is suspended at the stand age of 105 years, stand volume begins to increase rapidly until the stand is clearcut at the age of 155 years (Figure 15a). When the first clearcut is postponed, the amount of carbon in living trees increases as the stand volume increases until the stand is clearcut and a share of carbon is transferred to the carbon pools of dead tree matter and timber products (Figure 15b).

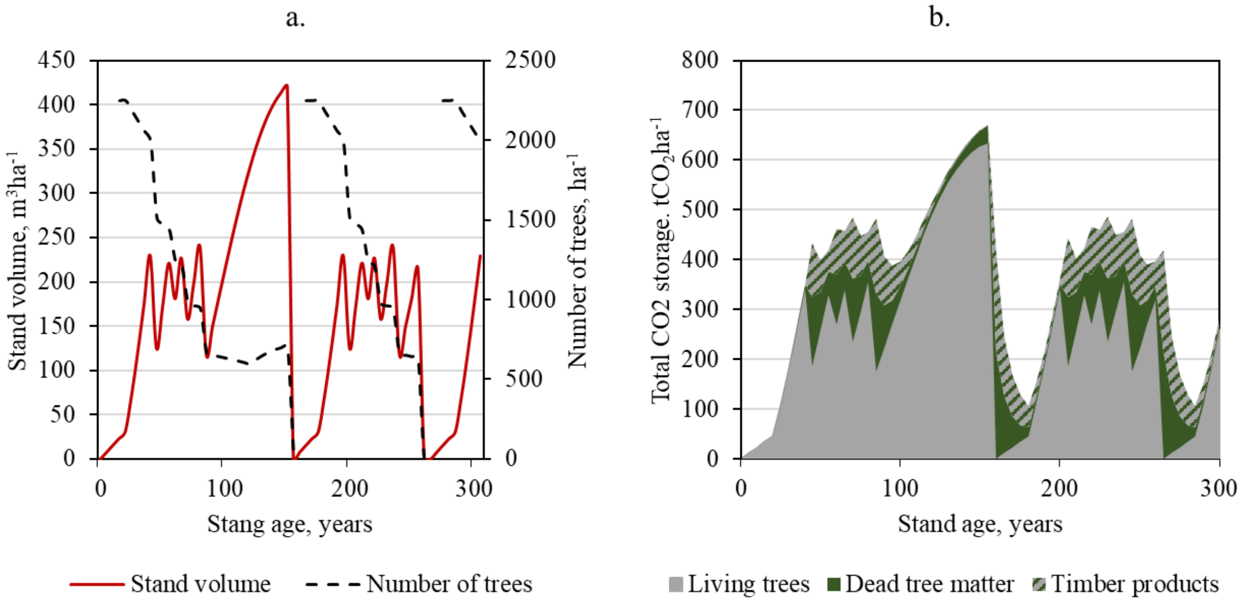

Figure 15. Forest development when the first clearcut is posponed to stand age of 155 years with a 2 % interest rate.

If the forest is conserved, i.e. all management is suspended, the number of trees begins to stabilize at the steady state value of 820 trees per hectare at the stand age of 400 years. Stand volume reaches its steady state value of 360 m^3ha^{-1} at the stand age of 425 years (Figure 16a). At the steady state, natural mortality is equal to natural regeneration ($\mu_s = \phi_t$). Figure 16b presents the development of total CO_2 storage per hectare without harvests after the baseline period. As the forest begins to regenerate naturally after 105 years of stand age, the amount of carbon stored in living trees increases rapidly until 170 years. When the stand is no longer harvested, no carbon is transferred to the carbon pool of timber products and the carbon stored in timber products is gradually released between 105 and 300 years of stand age. A small amount of carbon remains in the carbon pool of dead tree matter due to natural mortality but again most of the carbon is stored in living trees.

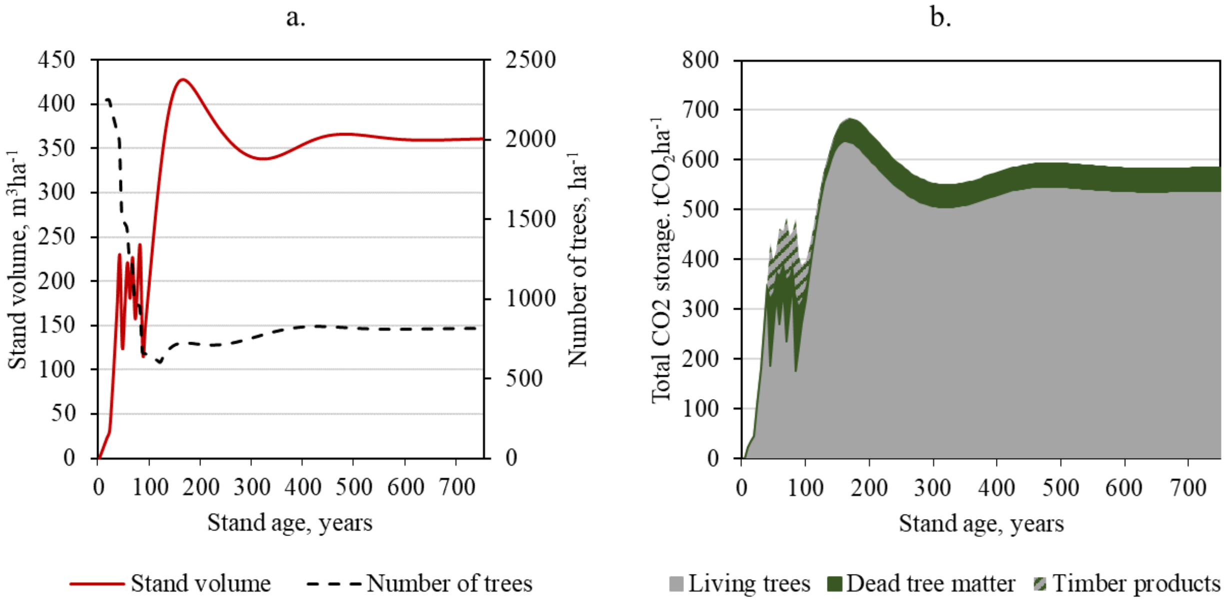

Figure 16. Forest development without clearcut with a 2% interest rate.

Figure 17 shows the size class structure development as the first clearcut is postponed. The trees in the baseline size class structure (Figure 17a) begin to transform towards older size classes and when conventional forest management is suspended at 105 years of stand age, new trees begin to emerge into the first size class at the stand age of 125 years (Figure 17b). At the stand age of 175 years, the number of trees in the smallest size class is dominant and the other size classes begin to even out (Figure 17c). The largest trees have now moved to size class 11 (57.5cm). The steady state is reached at around 400 years of stand age and Figure 17d presents the steady state size class structure.

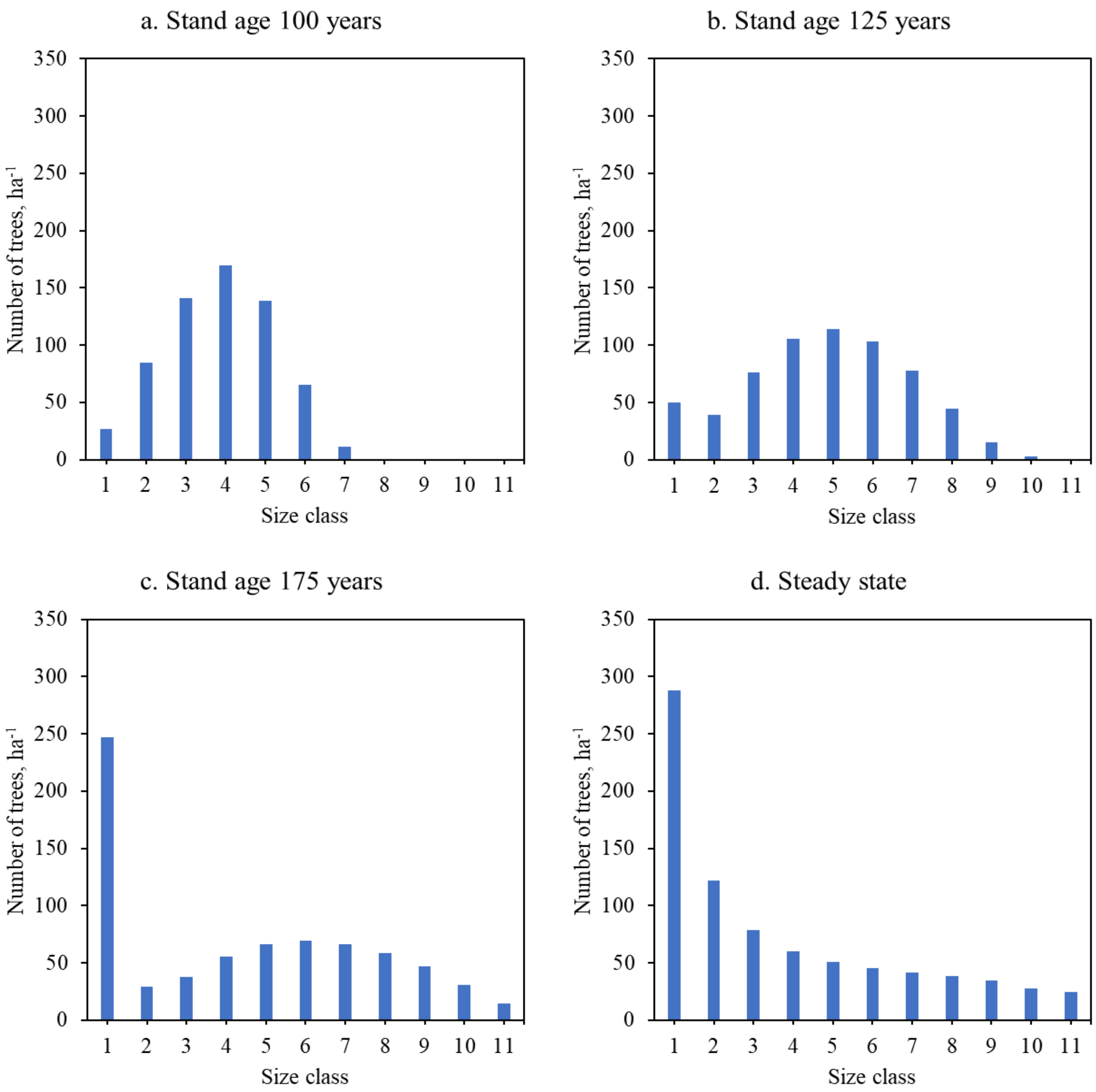

Figure 17. Forest size class structure development without clearcut with a 2% interest rate.

Table 7 presents the results of extending the first rotation past the privately optimal rotation length of 105 years. We calculated results for 5 different lengths of postponement of the first clearcut: 25, 50, 75, 100 years, and ∞, i.e. forest management for pure carbon storage, after which the forest owner resumes applying the optimal rotation length of 105 years. The required subsidy (€tCO_2) (column a) is defined by dividing the decrease in the NPV of timber revenues (column d) by the achieved additional carbon sequestration of the extension (column c), while (column f) presents the per hectare subsidy. The present value of total net carbon sequestration (column b) for the baseline consists of the emissions that would be released after clearcutting the stand at the private optimum and the net present value of total sequestration of all future rotations (201 tCO_2ha^{-1}). For the extensions, net carbon sequestration exceeding the baseline year is discounted to $\Delta(t+1)=105$. The present value of total net carbon sequestration increases from -56 tCO_2ha^{-1} (baseline) to 210 tCO_2ha^{-1} (pure carbon storage). The net present value of timber revenues (column d) consists of the clearcut revenues and the maximized bare land value (€7566 ha^{-1}), which are both discounted to the moment $\Delta(t+1)=105$. The NPV of timber revenues decreases from €18 835 ha^{-1} (baseline) to €0 ha^{-1} (pure carbon storage). This reveals the cost of postponing the first clearcut or of forest management for carbon storage only. The present value of additional net carbon sequestration (column c) is obtained by deducting the baseline total net carbon sequestration (-56 tCO_2ha^{-1}) from the total carbon sequestration (column b). Dividing the decrease in timber revenues from the baseline with the achieved additional carbon sequestration gives us the required subsidy (€tCO_2^{-1}), which ranges from €60 tCO_2^{-1} to €71 tCO_2^{-1}.

Table 7. Numerical results for the size-structured model with different extensions of the first rotation.

	a	b	c	d	e	f
Postponement of first clearcut *(years)*	Required subsidy *(€/tCO$_2$)*	Present value of total net carbon sequestration, *(tCO$_2$/ha)*	Present value of additional net carbon sequestration *(tCO$_2$/ha)*	NPV of timber revenue *(€/ha)*	Average annual commercial timber yield *(m^3/ha)*	Subsidy for additional sequestration, *(€/ha)*
0	-	-56	-	18835	7.3	-
25	60	-8	48	15953	6.9	2881
50	62	72	128	10866	6.1	7969
75	68	123	179	6602	5.2	12232
100	72	152	208	3866	4.5	14969
∞	71	210	266	0	0	18835

Note: Privately optimal rotation length 105 years. Interest rate 2 %.

When thinnings are included and the forest resources are accurately described by the size-structured model, the required compensation (€60 – €71 tCO_2^{-1}) is higher compared to the results obtained for the univariate optimal rotation model (€33 – €60 tCO_2^{-1}) but still significantly lower than for the California Forest Offset Protocol (€169 and €191 tCO_2^{-1}). The difference between the results of the size-structured and the univariate optimal rotation model are caused by the difference in the bare land value (€7566 ha^{-1} and €4830 ha^{-1}, respectively) when thinnings are included. The resulting opportunity cost is higher in the size-structured model when the first clearcut is postponed and thinnings are forbidden during the extension. The required subsidies (€tCO_2^{-1}) obtained with the size-structured model still remain far below the required subsidies of the California Offset Protocol implying that the understanding created with the univariate model holds.

The present values of net carbon sequestration in Table 7 can also be presented as a function of the length of the first rotation. This is presented in Figure 18. It begins from a negative value because with privately optimal forest management the forest would be clearcut at $\Delta(t+1)=105$ resulting in carbon being released from the stand. As the length of the first rotation increases from 105 years (private optimum) to infinity (pure carbon storage), the present value of net carbon sequestration increases from -56 to 210 tCO_2ha^{-1}.

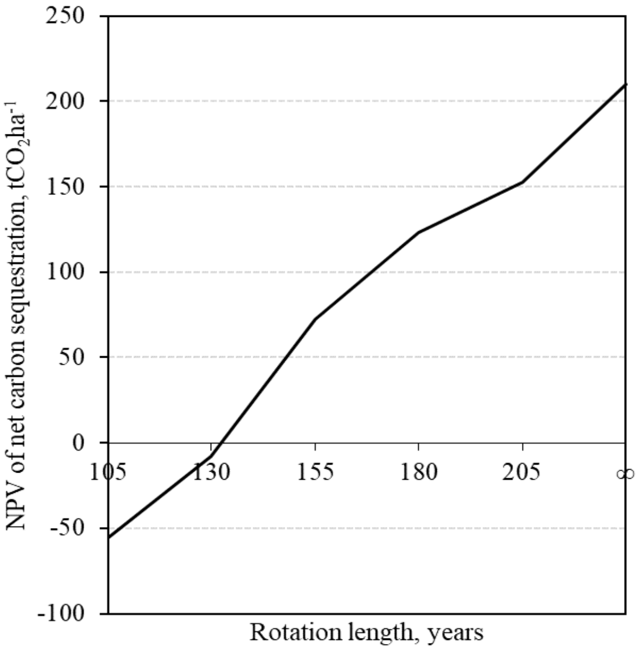

Figure 18. Development of the present value of net carbon.

5 Discussion

We used a univariate optimal rotation model to evaluate the structure of the California Forest Offset Protocol. The results were presented in Figures 10 and 11 and Table 2. By comparing the obtained results of carbon prices required to compensate the loss of income (€191 tCO_2^{-1} with a 25-year crediting period and €169 tCO_2^{-1} with a 50-year crediting period) to the prevailing carbon price of €15.03 tCO_2^{-1} in California in May 2020 (CARB 2020), we note that the offset protocol does not seem to be an attractive option to private forest owners. The protocol offers the forest owner the possibility to renew the crediting period for an additional 25 years. However, even with the 50-year crediting period, the required compensation per additional ton of carbon sequestration is unrealistically high compared to the prevailing carbon price (€15.03 tCO_2^{-1}). A study by Kelly et al. (2017) evaluates the willingness of non-industrial private forest owners to participate in the California Forest Offset Protocol. They find that private forest owners are reluctant to participate due to high transaction costs, complexity, and varying forest management motives. This result combined with our findings of unrealistically high carbon prices required to compensate the costs imply a need for revising the Protocol structure.

It should be noted that thinnings are not included in the univariate optimal rotation model but are allowed in California with certain restrictions. Income obtained from thinning the forests is obtained earlier in time hence, it is not subject to such heavy discounting as the income that is obtained after clearcutting at the end of the rotation period. Intuitively, this might slightly improve the viability of the Forest Offset Protocol in California in our examination. However, our size-structured model for the theoretically sound case also results in lower required subsidies compared to the Californian structure. The required subsidy in the univariate optimal rotation model ranges from €33 to €56 tCO_2 when the extension length is increased from 25 to 100 years, while in the size-structured model it ranges from €60 to €71 tCO_2. This implies that including harvests into our model of the Californian structure would not make the protocol significantly more appealing to the forest owner.

Another aspect that possibly makes the protocol in California more appealing to the forest owners is the setting of the baseline. The baseline is set according to average forest inventory and analysis data provided by the U.S. Forest Service (Anderson et al. 2017). Thus, it is possible for the baseline carbon stock of a specific forest to be higher than these average values. Haya (2019) examined a harvesting scenario modeled for a participating forest in Alaska and noted that the baseline for the project was set at 95 tCO_2ha^{-1}, while the actual carbon stock at the time of project initiation was 141 tCO_2ha^{-1}.

The forest was thus credited for 46 tCO_2ha^{-1} of non-additional baseline carbon. To mimic this, in Figure 11 we examined the effect of setting the baseline below the optimum rotation. The results of Haya (2019) are close to the baseline for carbon sequestration being set 10 years below the optimal rotation in our model. We note that if the optimal carbon stock of a forest is above the average stock of the region, a much lower carbon price is required to make the protocol an acceptable option for the forest owner. This non-additional crediting combined with allowed thinnings in California could explain the current participation of forest owners in the protocol.

In the New Zealand ETS, emissions from harvested wood products (HWPs) are fully accounted for at the time of harvest. This is based on international accounting rules of the Kyoto Protocol's first commitment period, while the accounting rules for the second commitment period recognizes that a fraction of carbon is stored in wood products with various lifespans (Ministry for the Environment 2016). The decision to not include carbon stored in harvested wood products imposes the full liability for all released carbon on the forest owner (instead of the buyers and users of timber). However, HWPs are intended to be recognized in the national accounting under the Paris Agreement in the 2021–2030 period (Ministry for the Environment 2016). The liabilities for emissions from HWPs could be deferred by including emissions from the decay of timber products into the look-up tables for the second forest rotation (Ministry for primary industries 2019).

The effect of carbon stored in HWPs is captured in the univariate optimal rotation model by parameter β. The effects of varying the value of the present value of decay of timber products was presented in Figure 8 and Table 3. Based on our observations with the univariate optimal rotation model, the inclusion of HWPs into the forest emission accounting under the ETS would decrease the cost of producing offset units for the forest owner units by deferring a share of the emission liability from the forest owner to other actors. This would lower the required compensation per provided offset unit, lowering the fiscal cost of emission reductions. The higher cost of providing offset units may increase the threshold for voluntary participants with post-1989 forests to join the NZ ETS. However, in this case another policy would be needed to ensure that other actors compensate the emissions that would not require compensation from the forest owners.

The inclusion of carbon stored in timber products may improve the incentives of voluntary participation. The New Zealand Ministry for Primary Industries (2019) also report that many forest owners are using a conservative approach in carbon trading due to the risks associated with the full emission liability. In a report based on a survey and afforestation modelling, they conclude that including averaging and HWPs into the ETS could make it more attractive to voluntary participants. Averaging refers to the forest owner bearing the compensation liability for emissions only when the long-term average carbon stock is decreased: thus, allowing harvests without compensation liability if the forest is artificially regenerated. The inclusion of these two factors would increase the amount of credits that would not have to be surrendered for emissions released at harvest as a part of the liability would be deferred from the forest owners (Ministry for primary industries 2019). Our findings on the effects of parameter β support this argument. A shared liability for harvest emissions would decrease the costs of carbon sequestration for the forest owners and thus make the scheme more attractive for voluntary participation.

The issues in the two examined emissions trading schemes call for a scheme which is built on a theoretically correct model of timber production and carbon storage. One such model is presented in equation (17), where the price of carbon is defined by the cost of the extended first rotation. The proposed scheme pays a subsidy for baseline carbon in order to avoid perverse incentives of bringing forward clearcuts in anticipation of the scheme. This subsidy is then taxed away with the full compensation liability at the end of the extended first rotation, ensuring that the additionality criteria is met. The results (Table 2) reveal that implementing a scheme with the proposed structure, would result in relatively low fiscal costs of increasing carbon sequestration (€3535–17790 ha^{-1}) with a reasonably high carbon price (€33–59.5 tCO_2^{-1}). Such levels of the social cost of carbon are expected to be reached by 2030–2050 (Nordhaus 2014), implying that a policy intervention with the presented compensation structure would be a viable option in the near future.

The understanding developed using the univariate optimal rotation model was further tested by applying the empirically more realistic size-structured model with a carbon subsidy. The results obtained with this model assure that the understanding created in chapter 3 is correct, and it would be recommendable to apply a theoretically sound model of additional carbon sequestration compensation instead of the two existing schemes. As a result of postponing the first clearcut (Table 7), carbon sequestration in the forest stand increases due to natural regeneration and trees growing into larger size classes. Postponement of the first clearcut results in costs for the forest owner as the net present value of timber income decreases. These costs determine the required subsidy per ton of additional CO_2 sequestered. The required compensation increases from €60 to €71 tCO_2^{-1} depending on the length of the extension.

This thesis examines incentivizing additional carbon sequestration only at stand level. In reality, landowners have the possibility of altering land use, for example, from forestry to agriculture and *vice versa* leading to deforestation or afforestation. Tahvonen and Rautiainen (2017), show that even though subsidizing only additional carbon sequestration (instead of total carbon sequestration) in forests may not affect rotation decisions at stand level it may have a distorting effect on land use decisions in a market-level model. They also note that if the emission liability is levied on the buyer of wood, the market price of wood decreases leading to the same bare land value in forests.

Increasing forest rotation lengths or altering forest management practices may also affect the supply of timber. A decrease in timber supply may be substituted by increasing harvests elsewhere leading to carbon leakage (Gan and McCarl 2007). Murray et al. (2004) estimate that carbon leakage in the United States may range from 10% to 90%. The California Forest Offset Protocol assumes that 20% increased carbon sequestration is replaced by increased harvests elsewhere (CARB 2015a), which may result in crediting non-additional carbon sequestration (Haya 2019). Accounting for leakage to ensure additionality by decreasing the amount of subsidized carbon could further decrease the attractiveness of the Protocol.

The ongoing public discussion on forests' carbon sequestration in Finland and globally reveals the need for proper economic analysis on the matter. In the past few years, we have witnessed the emergence of multiple private compensation schemes, as the public authorities have failed to implement national schemes in time. These private ventures vary widely in quality of the accounting methods and clearly require intervention *via* a more extensive scheme. In addition, possible carbon leakage would be easier to control in a more extensive scheme. In many of the private schemes, the offset credits are created abroad, leading to a lost opportunity of taking advantage of the co-benefits of increasing carbon sequestration domestically *via* extended rotation lengths or forest management for pure carbon storage. Such co-benefits include, for example, water quality, recreational use, and biodiversity (Anderson et al. 2017). The theoretically correctly defined compensation structure in both of our models (univariate and size-structured) results in a lower required carbon price to make joining attractive compared to the modelled structure of the California Forest Offset Protocol. Thus, it would be preferable to apply a theoretically correct compensation scheme instead of the scheme in California if a carbon exchange system would be implemented in Finland or the EU.

In this thesis, we limited the possibility of increasing carbon sequestration in forests solely to postponing the first clearcut in rotation forestry. Assmuth et al. (2018) and Pihlainen et al. (2014) find that also altering the optimal thinning path is key in increasing carbon sequestration in a cost-efficient manner. Altering the thinning path and allowing continuous cover forestry could increase biodiversity in addition to increasing carbon sequestration (Assmuth et al. 2018). This calls for extending our study in the future to cover the possibility of land-use changes, leakage and continuous cover forestry.

6 Conclusions

The aim of this thesis was to compare a theoretically correct manner of increasing carbon sequestration in forests by implementing a subsidy scheme with the additionality principle to practical applications in California and New Zealand. This was done by first presenting the basic results and characteristics of carbon storage within the Faustmann (1849) model framework, creating a correct understanding of a subsidy scheme with the additionality principle, evaluating the exclusion of HWPs in New Zealand and mimicking the compensation structure of the California Forest Offset Protocol. To verify the results of this basic and well-established model, we verified the theoretically sound understanding created with the Faustmann framework with an empirically more realistic size-structured model.

The scheme structure in California appears suboptimal due to high costs imposed on the forest owner due to the separation of a crediting and monitoring period. The costs of the monitoring period are not sufficiently compensated during the crediting period with reasonably high prices of carbon. In the New Zealand Emissions Trading Scheme, the decision to exclude harvested wood products as a carbon pool in the system, imposes the full liability for emissions on the forest owner, leading to a higher required subsidy level for the scheme to be attractive. The theoretically correct way of compensating increased carbon sequestration in forests presented in this thesis, and tested with two different models, results in lower prices of carbon being sufficient to compensate the costs of postponing the first clearcut. The fiscal costs of increasing carbon sequestration are lower when the compensation is correctly calculated, determined by the decrease in timber income. Such a structure is recommendable when different nations or coalitions, e.g. Finland or the EU, consider increasing forests' carbon sequestration as a part of meeting their climate change mitigation targets.

This thesis provided a comprehensive understanding of how the correct compensation should be determined but a more thorough analysis on implementing such a scheme is still needed. In our view, the proposed compensation structure should be included in the existing emissions trading scheme structures, for example, in the European Union. The inclusion of such an extension into the EU ETS requires more political and economic analysis as it would likely overlap with current regulation and could possibly flood the market with more emission units. These issues call for a market-level analysis on how the market would react to these offset units and how the existing credits should be retired as new, actual emission reduction units, would enter the market.

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