Ecological Economics 199 (2022) 107492

Contents lists available at ScienceDirect

Ecological Economics

journal homepage: www.elsevier.com/locate/ecolecon

Payment for CO_2 sequestration affects the Faustmann rotation period in Norway more than albedo payment does

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ARTICLE INFO

Keywords:
Policy instruments
Climate policy
Economic optimization
Bio-economic model

ABSTRACT

Albedo and CO_2 sequestration are the two most important climate forcing factors in forestry. After harvest the albedo in boreal forests increases which has a cooling effect. Likewise, CO_2 captured in the photosynthesis reduce atmospheric CO_2 and thereby have a cooling effect. These effects have value to society, and they may affect optimal management.

This article investigates the effect on economical optimal forest management – here the optimal harvest age – by payment for these forcers. The albedo effect is evaluated using the standard climate metric global warming potential (GWP) with a time horizon of 100 years, i.e. in terms of CO_2 equivalents. Alternative measures are discussed. The cooling effect of albedo change at time of harvest for the total Norwegian harvest corresponds to about 1.3% of the current Norwegian GHG emissions. The variation in albedo effect across the southern part of the country is modest.

The CO_2 sequestration effect is much larger than the albedo. At the time of harvest the CO_2 content in forest is more than 40 times the albedo effect. The carbon effect will therefore dominate the effect on the harvest age. Payments for climate services will prolong the rotation period. With the current quota price in the EU ETS – about 80 € ton^{-1} CO_2 equivalents – and current stumpage value, carbon capture and storage will be more profitable than commercial timber production for young stands. For stands close to maturity, the payment scheme will have little effect.

1. Introduction

As forest grows, forest management alters the vegetation and snow cover in boreal forests. Not only the carbon balance affects the climate, but so does also the change in albedo: the share of short-wave incoming radiation that is reflected back to the atmosphere by the surface. Depending on its color and brightness, a change in land surface can have a positive (cooling) or negative (warming) effect on climate. Planting coniferous trees as a climate mitigation measure has been questioned in areas with snow since the darkening of the surface may contribute to warming. And vice versa, the albedo effect may lower or even completely offset the lost carbon sinks following expanded timber harvesting (Arora and Montenegro, 2011; Bala et al., 2007; Betts, 2000; Betts et al., 2007; Bonan, 2008; Gibbard et al., 2005; Schwaiger and Bird, 2010; Thompson et al., 2009a).

In addition to the effects of carbon and albedo, there is a range of other biogeophysical climate effects in forestry such as altering fluxes of heat, momentum, and moisture exchanges (Bright et al., 2015). These effects are mainly local/regional. The use of products made from timber will also have other climate effects in addition to the emission of carbon when the final product is decaying or being combusted. For example, bioenergy may lead to emissions of a range of near-term climate forcers (NTCF, Myhre et al. (2013)) such as aerosols, carbon monoxide and volatile organic compounds – some leading to warming and some to cooling. These effects will not be covered explicitly here, but can be significant (Arvesen et al., 2018).

Since forests cover a large share of the land area in Norway and other Nordic countries (about 54% according to Forest Europe (2015)), the potential impact is large from large-scale changes in management. In Norway there are close to 130,000 forest holdings (Statistics Norway, 2018) and almost 80% of the productive forest area is owned by non-industrial private owners (Steinset, 2015).

The main aim of this study is to investigate how the harvest decision may be affected when the owner receives payments for the climate services carbon sequestration and albedo with application to boreal forests in Norway. A secondary aim is to assess the magnitude of the

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https://doi.org/10.1016/j.ecolecon.2022.107492
Received 8 November 2021; Received in revised form 18 May 2022; Accepted 22 May 2022

potential albedo effect from harvest across the southern part of Norway (south of about 65°N).

The effects on optimal harvest age from climate forcing payment have been studied earlier, both in Norway and other countries – see below. The novelty in this paper is that it covers a major part of the forested area in Norway. In addition, it includes a more consistent payment scheme than previously studied in Norway.

The article is organized as follows. First, a presentation of the theoretical framework used here – including a literature review – is given. This is followed by a description of how the albedo effects were calculated. Finally, the main results are presented and discussed.

2. Pricing of climate effects and optimal rotation length

2.1. Optimal forest management and climate effects pricing

The point of departure in this study is the classical Faustmann's formula (Faustmann, 1849; Faustmann, 1995). The fundamental assumption is that the forest owner is maximizing the net present value (NPV) of the forest. The optimal harvest age is found where the marginal stumpage value, with respect to time, equals the capital cost of holding the standing stock plus the opportunity cost of bare land. The classical approach further assumes full information over the future, i.e. that prices and discount rate are known.

There is ample evidence that forest owners also hold other objectives than income maximization alone (see e.g. Conway et al., 2003; Eggers et al., 2014; Favada et al., 2009; Joshi and Arano, 2009; Kuuluvainen et al., 1996; Løyland et al., 1995; Petucco et al., 2015). For example, Kuuluvainen et al. (1996) explored the objectives of Finish forest owner, and their analysis revealed three main types of objectives: “nontimber values”, “sales income and economic security” and “self-employment opportunities.” Still, timber price seems to be the most important determinant of timber supply in the short run (Amdam et al., 2000; Kuuluvainen et al., 2006).

Hartman (1976) extended the Faustmann framework by including preferences for non-timber services, e.g. amenity values (Amacher et al., 2009). However, the framework was not expanded to a more complete preference-based life-cycle model. A “utility-based Faustmann model” – maximizing utility in a life-cycle framework including consumption-saving decision-making – was developed by Tahvonen (1998). The model was used by Kuuluvainen and Tahvonen (1999) and Favada et al. (2009).

With the increased attention to climate change and greenhouse gases in the 90-ies, the Faustmann model was extended to include sequestration of carbon and payment thereof (Binkley and van Kooten, 1994; Hoen, 1994; Hoen and Solberg, 1997; van Kooten et al., 1995). The approach has been further refined (e.g. Asante and Armstrong (2012); Hoel et al. (2014)) and been used in modelling (e.g. Köthke and Dieter (2010); Raymer et al. (2009); Raymer et al. (2011)). The main result is that carbon payment increases the optimal rotation length.

The studies sited above all use the Faustmann framework in even-age forestry. Uneven-aged or continuous cover forestry has received attention the last decades mainly due to its expected environmental improvements. Lexerød and Eid (2006) show, however, that in Norway the share of the current forests suitable for selective cutting is limited (< 20% of the area). This means that uneven-aged forestry for a large part is relevant only for the next “rotation”.

Models for economic evaluation of continuous cover forestry has been available for more than a decade, e.g. the T model (Gobakken et al., 2008). In their analyses they found that the optimal choice of management system mainly depends on the initial diameter distribution. Tahvonen and Rämö (2016) using the same basic forest growth functions were the first to systematically analyze the two harvesting regimes in a NPV framework. Their model has been extended to include carbon payment (Assmuth et al., 2018). The results suggests that increased carbon payment does not have a large effect on the harvest intervals in the steady state of the uneven-aged regime. At 4% interest rate, continuous cover forestry is optimal for all levels of carbon payments studied.

Although the research community has acknowledged that albedo depends on land cover and that afforestation and deforestation may have a large effect (Betts, 2000), it took more than a decade before the effects on the optimal rotation period was first studied by Thompson et al. (2009a) and Thompson et al. (2009b). They used the emissions equivalent of the shortwave forcing (EESF) from Betts (2000) to “translate” the albedo effect into CO_2 equivalents (CO_2e). They found that for their modeled stands a forcing price (albedo + CO2 sequestration) would lead to prolonged rotation length. Matthies and Valsta (2016) also found that the carbon effect dominates. This is the opposite of Sjølie et al. (2013) where the albedo effect dominated completely, and rotation length was shortened to almost zero at the highest carbon prices (US$ 100 ton^{-1} CO_2e). They used estimates from Bright et al. (2011) on changes in radiative forcing and EESF.

The EESF (Betts, 2000) was developed to study permanent or constant changes in surface albedo such as deforestation and afforestation over an implicit time horizon. Other often used examples are changes in roof and pavement albedo (Akbari et al., 2009). Using the EESF for yearly changes in shortwave forcing, as applied by Sjølie et al. (2013), “would have severely overestimated CO_2-equivalent emissions” (Bright and Lund, 2021).

Both EESF and the widely used global warming potential (GWP) are based on the ratio between cumulative forcing of albedo change and CO_2. The GWP is used here, and as will be shown later, it is based on an explicit time horizon. They are both suited for dynamic albedo scenario studies (i.e. studies where the albedo effect changes over time like in forests), but need to be carefully implemented. For reviews of CO_2-equivalence metrics the reader is referred to Lintunen and Rautiainen (2021) and Bright and Lund (2021).

The choice of the baseline for payments is a major methodological difference between some of the studies. Lintunen et al. (2022); Thompson et al. (2009a) used bare ground as the reference. Sjølie et al. (2013) on the other hand used a mature stand (albedo in a forest with a closed canopy) as the reference: the forest owner is paid for the albedo consequence of harvest. The marginal incentive is the same in both cases, and thus, the optimal rotation length would be the same. As pointed out by Lintunen et al. (2022), the choice of reference will have “strong impact on land value.” This could in principle mean that forestry become not profitable when albedo payment is based on bare ground albedo.

It can also be argued that these two approaches are inconsistent compared to the sequestration payment, which is based on the flux of carbon. A third option is therefore to have a reference free payment by basing the payment directly on the (estimated) albedo. This approach is used here, in addition to a fixed premium at the time of harvest. To my knowledge, this approach has not been studied earlier.

In a social setting, an efficient policy equates marginal social abatement costs across all forcing agents and actors at all points in time (Rautiainen et al., 2011), and should further equal marginal social damage. By using so-called integrated assessment models, it is possible to – simply put – estimate the marginal damage for different forcers (Lutz and Howarth, 2014; Lutz and Howarth, 2015; Lutz et al., 2016; Rautiainen and Lintunen, 2017).

The value of the forcing agents will normally increase over time due to increased climate change and thereby increased marginal damage. Lutz and Howarth (2015) show that the optimal albedo price trajectories, generated in the DICE model, vary with the climate metric used (global warming potential, GWP and global temperature change potential, GTP) and the time horizon of the metric. GWP leads to higher forcing prices than GTP, and the albedo price falls with longer time horizon.

Lintunen et al. (2022) took this a step further by also including the effects of climate change on forest productivity and albedo. They ran the

DICE model to model the social cost of carbon used to value sequestration and emission of CO_2 from forestry, and the social cost of forcing used to value the effects of (changes) in forest albedo along with the temperature response and annual discount rate. The global temperature anomaly in the scenario used is similar to IPPC's representative concentration pathway (RPC) 6.0. The forest model resembles the model used in this paper.

As will be shown below, some of their main conclusions coincide with the conclusions in this paper. This despite the rather large difference in how the pricing of carbon and albedo is handled. For example, Lintunen and Rautiainen (2021) show that the multiplier for converting forcing into emission equivalents are not constant over time and depends on the socio-economic assumption (pure rate of time preference – PRTP) in the social cost framework. In this paper, the conversion factor is assumed to be constant.

Two conclusions from Lintunen et al. (2022) that also find support in the current work are first that the rotation period for current stand are hardly affected by payments for CO_2 and albedo, and second that the optimal rotation period for stands established today in principle will be infinite with the foreseeable forcing prices.

The current study adds to the literature in more ways. First, it uses a dynamic albedo model where the albedo effect is decreasing non-linearly with the stand age. Second, I use the GWP concept to evaluate the albedo effects. The use of GWP versus EESF should in principle not affect the results if done in the proper way. GWP is widely used in other contexts and is somewhat easier to understand. Third and as mentioned above, a payment scheme is tested that is directly based on the cooling effect of albedo instead of the change from some reference (bare ground or closed canopy).

The standard GWP measure is based on the cumulative forcing while the reference free scheme is flow based. This means that the marginal effect or incentive will change. A priori, the effect of this is unknown. Finally, the estimation of the albedo effects covers a major part of the forested area in Norway. As will be shown, the variability in the GWP from albedo is low, and thus the spatial variation in the effect on the rotation period is low. To my knowledge, this has not been shown before.

2.2. Albedo payment at time of harvest + CO_2 sequestration payment

Policies can normally not have retroaction power, and we need to consider the state of the stand at the time of policy implementation. Let us assume that a payment scheme for carbon fluxes and albedo in forest is implemented when the stand has an age of t_0 ($\geq$0). Under this scheme, the owner is paid for the yearly sequestration of CO_2 in the forest stand (including branches, roots etc). At time of harvest, it is assumed that carbon is oxidized, and thus, the owner has to pay a tax. Some of the carbon sequestered ends up in products with a long lifetime and some of the carbon substitute fossil carbon in products. The owner is paid for these climate services. Together this means that the value of a stand at some point in time is not only dependent on the stand age, but also the age when the carbon payment was introduced.

The net present value of this stand may be expressed by:

$$NPV(t,t_0) = [p_h h(t) - p_c((\delta-\varepsilon)\{h(t)-h(t_0)\} + GWP_{\Delta\alpha}(TH))]e^{-r(t-t_0)} - C(t) + \int_{t'=t_0}^{t} p_c \delta \dot{h}(t') e^{-r(t'-t_0)} dt' + SEV e^{-r(t-t_0)} \quad (1)$$

where t_0 ($\geq$0) is the stand age when the scheme is implemented, t ($\geq t_0$) is the stand age, p_h is the stumpage value (NOK m^{-3}), h(t) is timber production (m^3 ha^{-1}) with time derivative denoted $\dot{h}$, p_c is the forcing price (NOK ton^{-1} CO_2e) paid for CO_2 sequestration, CO_2 emission and the forcing effect of albedo change, $GWP_{\Delta\alpha}$(TH) is the albedo change effect (ton CO_2e ha^{-1}) for a given time horizon, TH, δ is the expansion factor mapping timber volume to total tree biomass (ton CO_2e m^{-3}), ε is the substitution effect, i.e. how much fossil carbon the use of harvested timber replaces (ton CO_2e m^{-3}), SEV is the value of bare ground (NOK ha^{-1}), r is the discount rate and C(t) represents the costs of establishing the stand. These costs are assumed to occur at stand age zero years, i.e. the function has a non-zero value only for $t = 0$. Since this is a fixed cost, the time derivative is treated as being zero everywhere.

The value of bare ground (SEV) should here be taken to mean the value of the ground used for forestry, i.e. the net present value of infinite rotations. The albedo effect has the same climate effect as a negative emission, and it is therefore a negative number.

The integral in the equation is the payment for CO_2 sequestration, while p_c (δ - ε) (h(t) – h(t_0)) is the net payment the forest owner must make at the time of harvest for releasing CO_2. We can view this as a deposit – refund system. It is a simplification that ε (the substitution and storage effect) and δ (the expansion factor) are treated as independent of stand age. The share of long-lived products with a high fossil carbon replacement effect is however rather low (Lunnan et al., 1991), and a more complex model would probably not change the results much.

If the objective of the forest owner is to maximize the NPV, the interior solution can be found by differentiating eq. [1] with respect to time, setting equal to zero and solving for t. The first order condition, after rearranging the terms, is:

$$(p_h + p_c\varepsilon)\dot{h}(t) = r[p_h h(t) - p_c((\delta-\varepsilon)\{h(t)-h(t_0)\} + GWP_{\Delta\alpha}(TH)) + SEV] \quad (2)$$

The left-hand side is the marginal revenue while the right-hand side is the opportunity costs of delaying harvest. The first term in the square brackets on the right-hand side is the value of timber, the second is the value of carbon in the timber adjusted for substitution effects and the albedo effect, while the last term is value of bare land. By delaying harvest, the sum of these multiplied by the rate of return yield the capital cost or marginal cost of waiting.

If there are no points where the equation above holds, assuming the second order conditions holds, we have a corner solution, i.e. to harvest now or never. In this case we need to check which of NPV(t_0, t_0) and NPV (t_0, ∞) is the largest.

The marginal effect of increased forcing price can be found by differentiating eq. [2] with respect to p_c and rearranging terms:

$$\frac{\partial t^*}{\partial p_c} = \frac{r\left[(\varepsilon-\delta)\{h(t^*)-h(t_0)\} - GWP_{\Delta\alpha}(TH) + \frac{\partial SEV}{\partial p_c}\right] - \varepsilon\dot{h}(t^*)}{(p_h+p_c\varepsilon)\ddot{h}(t^*) - r[p_h + p_c(\varepsilon-\delta)]\dot{h}(t^*)} \quad (3)$$

The denominator is the second order derivative and is thus negative. We are, however, not able to sign the numerator and the total effect of forcing price is therefore ambiguous. Normally we have that $\varepsilon < \delta$ and assuming non-decreasing production we also have $h(t^*) > h(t_0)$ and $\dot{h}(t^*) \geq 0$. The partial effect of pricing carbon sequestration, storing in final products and substitution, is a prolonging of the rotation age. Pricing the effect of albedo change at harvest have a negative effect on the harvest age, i.e. shorter rotation. This is in line with the literature cited above. Ceteris paribus, payment for an additional service or product in the forest will not decrease the value of bare ground. Thus, the last term in the square brackets is non-negative.

2.3. Continuous forcing payments

It can be argued that the above payment scheme is inconsistent. The payment for the albedo effect is based on the change in albedo compared to a reference situation – albedo before harvest – and is awarded at the time of harvest. The payment for carbon on the other hand is based on annual sequestration and emission. A more consistent model is to treat both albedo and carbon effects in the same way. One way to do this is to treat the albedo effect as an annual effect in level. In such a situation the net present value of a forest stand is:

$$NPV(t,t_0) = [p_h h(t) - p_c(\delta-\varepsilon)\{h(t)-h(t_0)\}]e^{-r(t-t_0)} - C(t) + \int_{t'=t_0}^{t} p_c\left(\delta\dot{h}(t') - GWP_\alpha(t')\right)e^{-r(t'-t_0)}dt' + SEVe^{-r(t-t_0)} \quad (4)$$

Where $GWP_\alpha(t)$ is the annual albedo effect, i.e. reference free directly based on radiative forcing, expressed in CO_2e, and the other terms as defined above. The estimation of $GWP_\alpha(t)$ is explained below.

The first order condition for this problem is, after rearranging the terms:

$$(p_h + p_c\varepsilon)\dot{h}(t) - p_c GWP_\alpha(t) = r[p_h h(t) - p_c\{(\delta-\varepsilon)\{h(t)-h(t_0)\}\} + SEV] \quad (5)$$

Again, the left-hand side is the marginal revenue from postponing the harvest (marginally) while the right-hand side is the opportunity cost of capital in the forest, i.e. the alternative cost. If we differentiate eq. [5] with respect to the forcing price (p_c), evaluated at the optimal harvest age (t^*), we find the following comparative static:

$$\frac{\partial t^*}{\partial p_c} = \frac{r\left[(\varepsilon-\delta)\{h(t^*)-h(t_0)\} + \frac{\partial SEV}{\partial p_c}\right] - \varepsilon\dot{h}(t^*) + GWP_\alpha(t^*)}{(p_h+p_c\varepsilon)\ddot{h}(t^*) + p_c G\dot{W}P_\alpha(t^*) - r[p_h + p_c(\varepsilon-\delta)]\dot{h}(t^*)} \quad (6)$$

As above the denominator is less than zero. Also here we are unable to sign the nominator. The first term is marginal capital cost, while the two last are the marginal sequestration and albedo effect, respectively. A priori, we cannot determine the size of these effects and the total effect is therefore ambiguous.

3. Method and data

3.1. Albedo and climate metrics

The climatic effect of albedo can be estimated using standard climate metrics (Bright et al., 2011). Here the global warming potential (GWP) is used, and in the case the effect is evaluated at the time of harvest, this can be estimated by:

$$GWP_{\Delta\alpha}(TH) = \frac{AGWP_{\Delta\alpha}(TH)}{AGWP_{CO_2}(TH)} \quad (7)$$

where $AGWP_{\Delta\alpha}(TH)$ is the absolute global warming potential for albedo change given a time horizon of TH years and $AGWP_{CO2}(TH)$ is the corresponding metric for CO_2. $AGWP_{CO2}$ can be estimated by combining the radiative efficiency of CO_2, A_{CO2}, with an impulse response function, IRF_{CO2} (Aamaas et al., 2013). A_{CO2} is estimated to 1.7693E-12 W m^{-2} ton^{-1} CO_2 (Forster et al., 2007; Joos et al., 2013; Myhre et al., 1998), while parameters for IRF_{CO2} are taken from the multi-model mean in Joos et al. (2013). A time horizon (TH) of 100 years is used when estimating optimal rotation length, but "[T]here is certainly no conclusive scientific argument that can defend 100 years compared to other choices, and in the end the choice is a value-laden one" (Shine, 2009). Estimates of $GWP_{\Delta\alpha}(TH)$ for shorter time horizons are also presented.

The $AGWP_{\Delta\alpha}(TH)$ is estimated by (Bright et al., 2011; Cherubini et al., 2012):

$$AGWP_{\Delta\alpha}(TH) = \int_0^{TH} E_\alpha \frac{AR_F}{AR_E}\Delta RF_\alpha^{TOA}(t)dt \quad (8)$$

where AR_F is the affected area (1 m^2), AR_E is the area of earth's surface (5.10072 E+14 m^2), E_α is the climate efficacy of albedo (1.94, Cherubini et al. (2012)) and ΔRF_α^{TOA} is the change in local radiative forcing measured at the top of the atmosphere at time t after harvest, i.e. net upwelling short wave radiation due to the change in ground albedo as a consequence of harvest. This is estimated using a simple 1-layer atmospheric approach (Bright and Kvalevåg, 2013):

$$\Delta RF_\alpha^{TOA}(t) = -RF^{TOA}(t)K_T(t)\Delta\alpha(t)TF_a \quad (9)$$

$RF^{TOA}(t)$ is the local incoming extraterrestrial solar flux at the top of the atmosphere, $K_T(t)$ is the fraction of RF^{TOA} that reaches the earth surface (clearness index), $\Delta\alpha(t)$ is the change in surface albedo after harvest and TF_a is an atmospheric transmittance factor (fraction of upwelling shortwave radiation exiting the atmosphere).

Eqs. 13–15 in Bright et al. (2012) are used for estimating $RF^{TOA}(t)$. Regarding TF_a, a value of 0.854 is used (Lenton and Vaughan (2009); Bright et al. (2013); Bright and Kvalevåg (2013)). The clearness index ($K_T(t)$) is estimated from data taken from NASA's Surface Meteorology and Solar Energy website – as described below.

Bright et al. (2013) estimated models for monthly average forest albedo in South-Eastern Norway as a function of monthly mean temperature and stand age. Similar age effects (both form and magnitude) are found in Finland (Kuusinen et al., 2014a; Kuusinen et al., 2014b). Bright et al. (2013) report separate parameter estimates for the three main species in Norway: Norway spruce (*Picea abies*), Scotch pine (*Pinus sylvestris*) and birch (Betula sp.). Here the focus is on Norway spruce since this is the most important species in Norway accounting for 70% of the annual harvest in 2020 (Statistics Norway, 2020). The change in albedo following a harvest is estimated by:

$$\Delta\alpha_s(t) = \alpha_s(\tau_t, t) - \alpha_s(\tau_t, \infty) \quad (10)$$

where t is time after harvest, $\alpha_s(\bullet)$ is estimated albedo based on Bright et al. (2013), s is the tree species of the stand, and τ_t is monthly mean temperature at time t. The last term on the right hand side represents the albedo in a mature stand. Holding other elements constant (i.e. a constant term and a temperature term), the albedo is negative exponential function of the stand age (t), i.e. converges toward a lower asymptote. For spruce and pine there is no noticeable change after a stand age of 50 years. For birch this happens two to three decades later.

In the case of continuous albedo forcing payment, $GWP_\alpha(t)$, the same methodology is used except that that the last term on the right hand side of eq. [10] is dropped. An alternative view of the difference is to remove all Δ in eqs. [8] and [9]. We are estimating the yearly ("flow") effect of albedo, but still converting this to equivalent effects of CO_2 emissions over a time horizon (TH). In mathematical terms, we have:

$$GWP_\alpha(t) = \frac{AGWP_\alpha(t)}{AGWP_{CO_2}(TH)} = -\frac{E_\alpha\frac{AR_F}{AR_E}RF^{TOA}(t)K_T(t)\alpha(t)TF_a}{AGWP_{CO_2}(TH)} \quad (11)$$

We can view this as the derivative of $GWP_{\Delta\alpha}(TH)$ with respect to time which here means stand age. $GWP_{\Delta\alpha}(TH)$ is independent of the rotation length while $GWP_\alpha(t)$ explicitly depends on the stand age. In the first case the effect is in the form of a capital cost similar to the value of bare ground (SEV), while the latter can be viewed as a flow effect similar to the annual increment. A priori, it is hard to size the two effects.

3.2. Weather data

Monthly average temperatures for each month over the time horizon is needed in order to estimate albedo. This since the albedo equations are nonlinear in temperature and the mean temperature for a given month may vary from year to year, i.e. $E[\alpha(\tau,t)] \neq \alpha(E[\tau],t)$. In order to account for this and that the future weather is uncertain, a Monte-Carlo approach is adopted.

Weather data from 217 climate stations in southern Norway were downloaded from the eKlima web portal of the Norwegian Meteorological Institute (http://eklima.no). The locations of the weather stations are shown in Fig. 1, while simple statistics are shown in Table 1. A

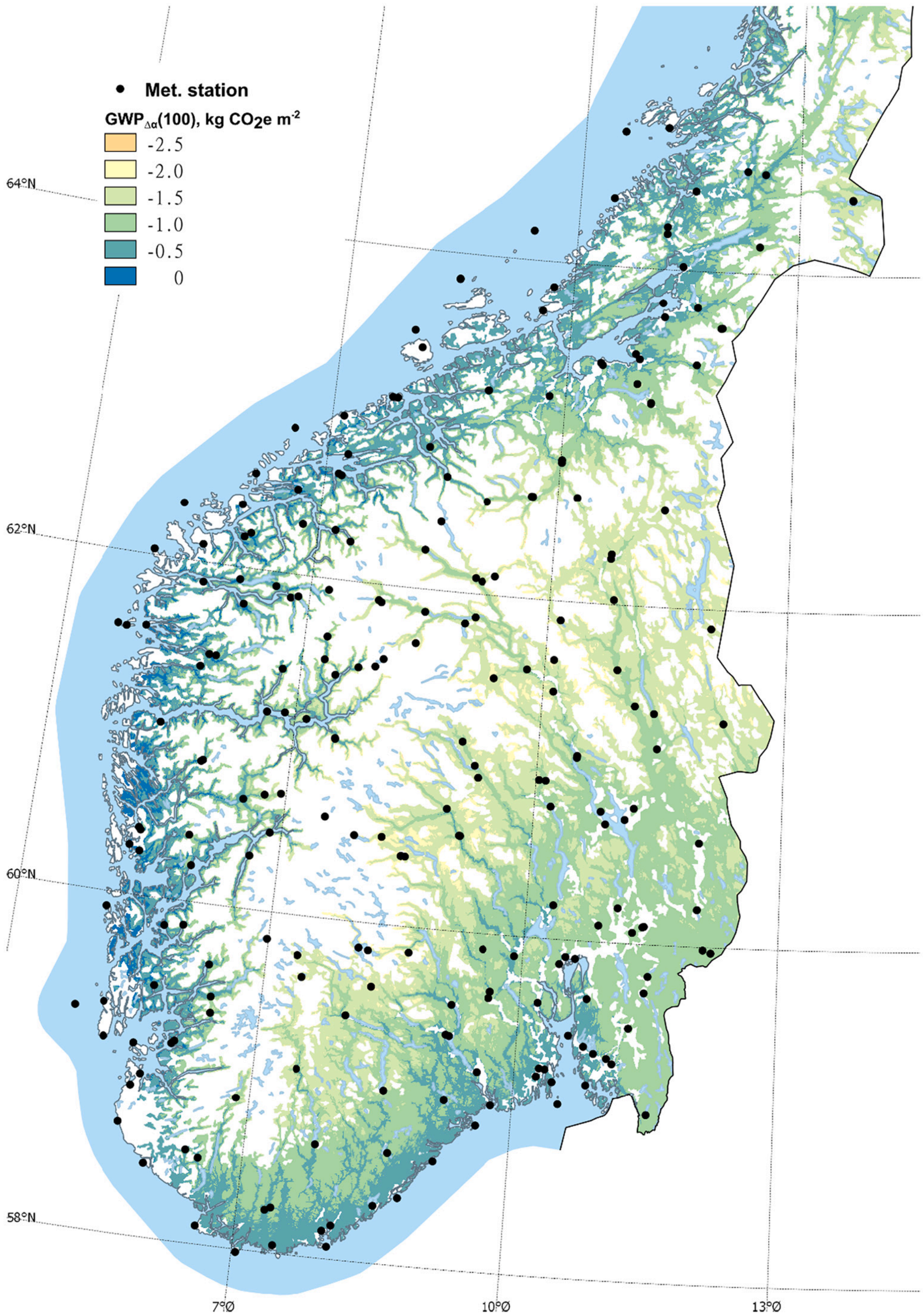

Fig. 1. Estimated GWP$_{\Delta\alpha}$(100), i.e. GWP due to albedo change after harvest, for spruce with a time horizon of 100 years. The figure also shows the location of the weather stations included in the analyses. Map sources: https://kartverket.no (Norwegian Mapping Authority). White areas are areas without forest cover according to the land cover map.

Table 1
Simple statistics for the weather stations included in the analyses.

	Longitude (°E)	Latitude (°N)	Elevation (m.a.s.l.)	Annual mean temp (°C)	Time series length (years)
Min	4.6817	57.9828	1	0.1	10
Max	13.7181	64.8350	798	8.1	54
Mean	8.6948	61.1192	168	5.2	25

simple regression (OLS) of annual temperature at the stations against year shows an yearly increase of 0.027°C (standard error = 0.0022) with $r^2 = 0.025$. The average increase in annual temperature during the period covered by the data is thus about 1.5°C. The low coefficient of determination indicates however a large portion of unexplained variation (across stations and years).

For each weather station, series of monthly mean temperatures of 100 years length are constructed by random sampling of years in the time series. As can be seen from Table 1 the series length varied from 10 to 54 years. A uniform distribution is used in the sampling, i.e. it is assumed that the likelihood for reoccurrence in the future of a given year is equal for all years in the historical weather data. This procedure is repeated 1000 times. If the temperature increases also in the future, the procedure used here will overestimate the albedo effect.

3.3. Clearness index, K_T

The fraction of incoming solar raditation at the top of the atmosphere (R^{TOA}) that reaches the ground, $K_T(t)$, is estimated by using the monthly averaged insolation clearness index downloaded from NASA's Surface Meteorology and Solar Energy website (https://eosweb.larc.nasa.gov/sse/). The data cover the period 1984–2005 and is reported for a 1 × 1 degree grid. Linear interpolation (using proc. g3grid in SAS, SAS Institute Inc (2011)) is used on the average monthly data in order to estimat $K_T(t)$ for each weather station.

3.4. National GWP map – Meta-analysis

The weather stations are well distributed over the analyses area – as can be seen from Fig. 1. Still, we do not know how representative they are for the weather conditions in the forests since weather stations normally are located near infrastructure etc. Since the average altitude of the weather stations is only 168 m.a.s.l. and temperature normally decreases as altitude increases, the estimates based on data from the weather stations may underestimate the forest albedo. This is accounted for by using the results from the above procedure to estimate generalized equations that can be applied to spatial (map) data:

$$GWP_{\Delta\alpha,i,s} = \beta_{0,s} + \beta_{1,s}X_i + \beta_{2,s}Y_i + \beta_{3,s}Z_i + e_{i,s} \quad (12)$$

Where $GWP_{\Delta\alpha,i,s}$ is the estimated albedo effect for weather stations i and tree species s, X_i is the longitude (°E or UTM33 Easting), Y_i is the latitude (°N or UTM33 Northing), Z_i is the elevation (m.a.s.l), $\beta_{0,s}$-$\beta_{3,s}$ are parameters to be estimated, and $e_{i,s}$ is residual error. The functions are estimated using OLS (SAS Institute Inc, 2011).

By combining these estimates with a digital terrain model and land cover map from the Norwegian Mapping Authority (https://kartverket.no), albedo effects maps for the forested area of South Norway are produced. This also enables us to compare the results from the estimations at weather stations with the estimates for the total forested area. The spatial data is handled in QGIS (https://qgis.org).

3.5. Forest production functions, prices, costs, etc.

Timber production functions are estimated on the basis of standard production tables for Norway spruce (Braastad, 1975). To keep the model as simple as possible no thinnings are assumed. For simplicity, a functional form with an asymptote – the Gompertz function – is chosen:

$$h_{SI}(t) = a_{SI}e^{-b_{SI}e^{-c_{SI}}} + \xi \quad (13)$$

Where $h_{SI}(t)$ is standing stock (m^{-3} timber ha^{-1}), SI is site index (H_{40}, dominant height (m) at breast height age of 40 years), t is stand age, a_{SI} (the asymptote), b_{SI} and c_{SI} are parameters to be estimated and ξ is residual error. The functions are estimated using proc. nlin in SAS (SAS Institute Inc, 2011). Gizachew et al. (2012) used a functional form with a similar shape.

The functional form used will ease the numerical optimization, but the results must be interpreted with some care. If the carbon pricing leads to increased rotation length, this will tend to infinity when the carbon price is high enough relative to the timer price. This since the production functions are non-decreasing. The intuition is that if carbon storage is more valuable than timber as a raw material, we should keep the carbon in the forests. The main point in this paper is not to estimate the exact optimal rotation length or how fast it eventually tends to infinity – this depends on the curvature properties – but to see if the rotation length increases or decreases with payment for climate services and the magnitude of these changes.

The data from the yield tables and the estimated functions are shown in Fig. 6 in the appendix. Parameter estimates can also be found in the appendix.

Biomass functions in Lehtonen et al. (2004) and Repola (2009) show that stems constitutes about 50% of the total. Combined with a base density of 400 kg dry matter m^{-3}, a carbon content in wood of 50% and the CO_2 to C ratio of 44/12, this gives an expansion factor (δ) of 1.46 ton CO_2e m^{-3} timber.

There exists a comprehensive literature on the substitution effects of forest based products, but there are few that look at the total impact of wood use, i.e. the total effects in terms of per m^3 timber (Leskinen et al., 2018). They report a weighted substitution effect for the production phase of 0.5 kg C kg^{-1}C in timber. This corresponds to 0.37 ton CO_2 m^{-3} timber, and this is used in this study (ε).

For simplicity, an age independent average stumpage value is used. Bergseng et al. (2018) used 250 NOK m^{-3} (23 € m^{-3}) in their example calculations. Statistics Norway (2020a) reports an average timber price for Norway spruce of 396 NOK m^{-3} (37 € m^{-3}) delivered roadside for the period 2006–2018 – measured in 2018 NOK. Harvesting cost is taken from Vennesland et al. (2013) and inflated to the 2018 price level using the consumer price index. Together this yields a stumpage value (pH) of 264 NOK m^{-3} timber (24 € m^{-3}). The average cost of planting (C(0)) in the period 2010–2019 is reported by Statistics Norway (2020b) to be about 1 NOK m^{-2} (0.1 € m^{-2}).

4. Results and discussion

4.1. The climate effect of harvest

The simple statistics for the results for the weather stations are shown in Table 2. We see that there is a wide variation in the effect in relative terms. As will be shown below, the variation is low when compared to the carbon effects. The weather stations cover climate condition ranging from costal climate influenced by the Golf stream to more continental climate inland (Table 1).

The cooling effect, in terms of CO_2-equivalents is largest for birch, and it is 20% lager than for spruce. The effect for pine is 6% lower than for spruce. Birch is statistically different at 1% level from the two other species. If we assume that the results for the different species are independent (in the statistical sense), the difference in mean $GWP_{\Delta\alpha}$ between spruce and pine is significant at 1%. If we on the other hand do a pairwise comparison, the difference is not significant at any reasonable test level. From the table we also see that the median value is not far from the mean value. This is an indication of a symmetric distribution of the estimated effects.

Using the meta-analysis approach outlined above, the results from the weather station based estimates are scaled up to wall-to-wall estimates for the forested area in southern Norway. Parameter estimates and fit metrics for eq. [12] are show in the appendix. The overall fit is good with an r^2 of 0.86–0.87. The simple statistics for the estimated albedo effects are shown in Table 3 and a map is shown in Fig. 1.

The average $GWP_{\Delta\alpha}$ for Norway spruce is −0.84 and −1.28 kg CO_2e m^{-2} for the station mean and forested area mean, respectively (see Tables 2 and 3). This is roughly one fourth to one fifth of the levels reported by Bright et al. (2012). Their estimates are −5.67 to −3.99 kg CO_2e m^{-2}. The difference is due to different albedo estimates and is part of the

Table 2
Simple statistics of estimated $GWP_{\Delta\alpha}(100)$, kg CO_2e m^{-2}, at the 217 weather stations included.

Species	Minimum	Maximum	Mean	Median	Standard deviation
Spruce	−1.85	−0.31	−0.84	−0.78	0.38
Pine	−1.78	−0.28	−0.79	−0.73	0.37
Birch	−2.31	−0.29	−1.01	−0.94	0.51

Table 3
Simple statistics of estimated $GWP_{\Delta\alpha}(100)$, kg CO_2e m^{-2}, for the forested pixels (500 m by 500 m) on the map ($N = 458,159$).

Species	Minimum	Maximum	Mean	Median	Standard deviation
Spruce	−2.79	−0.27	−1.28	−1.25	0.40
Pine	−2.70	−0.24	−1.22	−1.20	0.39
Birch	−3.56	−0.26	−1.59	−1.56	0.53

scientific development. Sjølie et al. (2013) estimates are about 55 times those of Bright et al. (2012) which also are based on albedo estimates from Bright et al. (2011). The ratio (55) corresponds to 1/ $AGWP_{CO2}(100)$ using the same IRF_{co2} as Bright et al. (2012). This indicates that Sjølie et al. (2013) have made an error when applying EESF or else implicitly assumed a time horizon of 0 years. The latter would be inconsistent with other assumptions and parameters in their model that are based on e.g. the use of the LCA methodology which normally are based on a time horizon of 100 years. Either way, this indicates that the albedo effect was massively overestimated in Sjølie et al. (2013). Still, their claim that "policies that only consider GHG fluxes and ignore changes in albedo will not lead to an optimal use of the forest sector for climate change mitigation" may still be valid.

If we estimate the maximum CO_2 amount in the forest stand based on the estimated asymptotes in Table 4 (parameter a) and the expansion factor mentioned above, we get a result between 73 and 127 kg CO_2e m^{-2}. These figures would represent the maximum bare ground carbon effects. Although not directly comparable, these figures indicate that the carbon effect is dominating over the albedo effect.

The Norwegian Agricultural Authority monitors the compulsory reforestation after harvests. In this they also estimate the harvested area each year. In their latest report, the estimated harvested area in 2016 was close to 500 km^2 (Norwegian Agricultural Authority, 2020). 96% of the area was harvested as clear-cuts, shelterwood harvest and seed-tree harvests. If we for simplicity assume that all area was harvested in a way that removes a sufficiently large share of the canopy, we can combine the estimated distribution on tree species reported in Norwegian Agricultural Authority (2020) with the estimated average albedo effect in Table 3. This suggests that the harvest in 2016 contributed with a cooling effect equivalent to a point emission of 0.67 million ton CO_2. This corresponds to a bit over 1% of the current greenhouse gas emissions in Norway.

According to Statistics Norway (2020) the commercial harvest was about 10 mill. m^3 in 2016. The carbon content in this timber is equivalent to about 7.7 million ton CO_2 and about twice this amount if we also include the rest of the tree biomass. This is the short-term carbon storage effect of harvesting in the sense that this is the instantaneous reduction in standing stock in the forest. If we, however, use the same time horizon as the for the albedo effect above, i.e. 100 years, the climate effect would be (slightly) negative for the timber. The trees will grow back and over the rotation the amount of carbon stored in trees and soil will be about the same as before the previous harvest. See e.g. Cherubini et al. (2011) for a discussion on the so-called GWP_{bio}. In addition, some of the timber harvested will substitute fossil carbon and some will be stored for a long time in products like construction lumber.

The choice of time horizon will affect the estimated equivalent CO_2 emission effect. Fig. 2 shows the station mean $GWP_{\Delta\alpha}$ for time horizons between 0 and 100 years along with 95% confidence intervals.

For spruce, the albedo effect with at time horizon of 20 years is 3.3 times the effect with 100 years as the time horizon. For TH = 50, the ratio is 1.7. Although the relative differences are large, the $GWP_{\Delta\alpha}$ are in absolute values modest compared to the possible carbon effects mentioned above.

The small confidence intervals show that there are small differences in the effect across the part of Norway included in this study. Fig. 1 also show little variation across the country. Lintunen et al. (2022) discusses regional and global implications of their findings from Kuusamo, Finland at almost 66°N. They argue that the albedo effect will be larger north of Kuusamo and lower to the south. Although the current study only covers up to 65°N, there is no clear north–south effect. Distance to the coast and altitude seems more important for the albedo effect. Of course, this does not mean that there is no latitude effect in Finland.

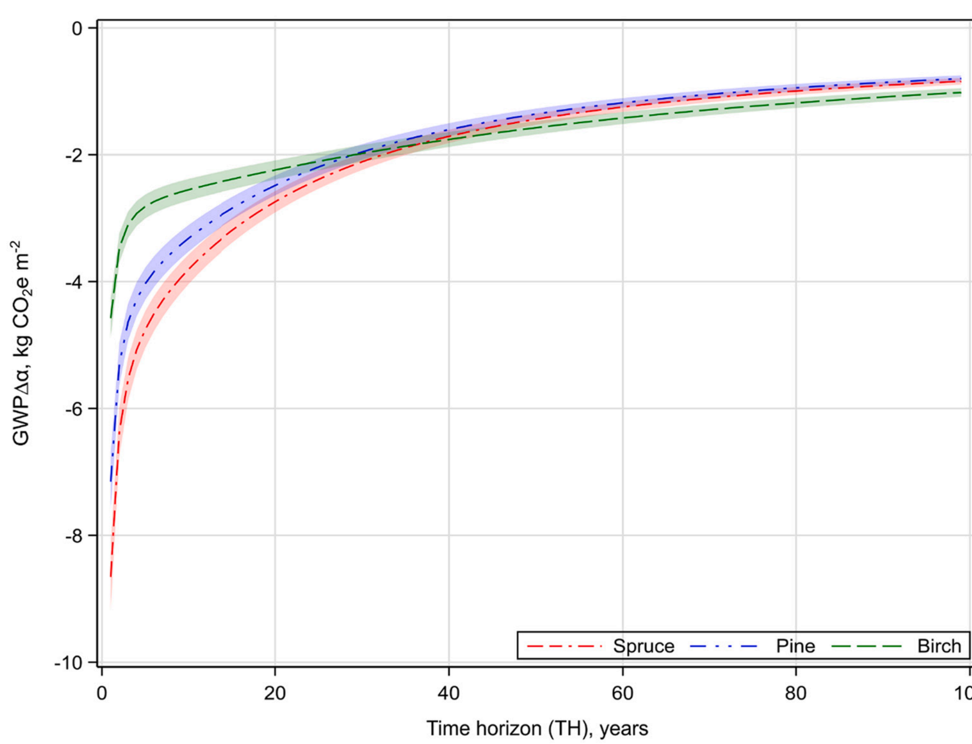

Fig. 2. Station mean $GWP_{\Delta\alpha}(TH)$, kg CO_2e m^{-2}, with a 95% confidence interval. $N = 217$.

4.2. The effects on optimal rotation age

In the previous section we saw that the carbon effect seems to be larger than the albedo effect for a newly established stand. From eq. [3] we can infer that the optimal rotation length will therefore increase as a function of payment for carbon sequestration and albedo. How large the increase in harvest age will be, depends on the payment, interest rate and the curvature properties of the production function, i.e. the site index.

Before we turn to the combined effect of the two forcers, we look at the isolated effect of albedo. Payment for the cooling effects from albedo will lower of the optimal harvest age in line with the literature presented above and the theoretical framework.

The effect was estimated by optimizing the two net present value functions presented above; eq. [1] for the case of $GWP_{\Delta\alpha}(100)$ and eq. [4] for $GWP_{\alpha}(t)$. The estimations were done for each climate station's mean albedo effect and for all site indexes. The albedo effect is independent of site index. Since there are only small differences in albedo effects, there are small differences in optimal rotation length – only maximum a couple of years. All figures below are averages across stations. SAS were used to estimate optimal rotation age.

The two different payments schemes yield similar and generally modest results (see Fig. 3). For poor sites there is a sizable effect at high levels of the forcing payment, especially for the scheme based on yearly forcing.

All curves in the figure above have a kink when the optimal rotation age passes the inflection point of the underlying timber production function (Fig. 6). The functions are not symmetric around maximum current annual increment (CAI) but changes more rapidly for stand ages below than above the inflection. This skewness decreases with increasing site index. For G23 CAI is close to symmetric in the relevant stand age range, thus the effect is hardly visible. Also, $GWP_{\alpha}(t)$ is falling with increasing stand age. This means that the effect in terms of shortening the rotation length increases with increasing forcing price. This we can infer from eq. [6].

If we now turn to the combined effect of albedo effect based on $GWP_{\Delta\alpha}(100)$ and CO_2 sequestration, the optimal rotation length assuming bare land is shown in Fig. 4. From the figure we see that the effect on optimal harvest age increase as site index reduces. Since the albedo effect is assumed to not depend on site index, this means that CO_2 sequestration economically is more important than timber sales in low compared to highly productive forests. This difference reduces as interest rate increases.

In all cases, at some point it becomes more profitable to earn income from carbon sequestration only, i.e. optimal rotation length tend to infinity. In the model this is driven by the non-decreasing production function and sigmoid shape. In practice, the stands will not be as stable as assumed over 500 years or more. The results should therefore be taken to mean that the rotation period should be as long as possible.

The increase in harvest age increase with the interest rate. A study in Norway concluded that the forest owners harvest their forests as if they use a discount rate in the range 2.5–3.7% p.a. (Nyrud, 2004). From the point of society, the Ministry of Finance has set the discount rates for use in social cost-benefit analyses to 4.0% for the first 40 years of the time horizon, 3.0% for the years 40–75 and 2.0% p.a. thereafter (Finansdepartementet, 2014). Within this discount rate range, we see from the figure that with the current quota price in the EU emission trading system (EU ETS) – fluctuating around 80 € ton^{-1} CO_2e so far this year – it is more profitable to provide climate service in terms of sequestration than timber products.

Since the sequestration effect is dominating over the albedo effect, the total effect will be largest for bare ground and reduce with increasing stand age at scheme implementation. This is shown in Fig. 5 for 3% p.a. real interest rate. The reason for this is that the forest owner is only liable for the carbon sequestered after the implementation of the scheme. Hence, the older the stand is when the scheme starts, the lower is the carbon amount sequestered. This holds for both types of albedo payment.

The figure above is for the current rotation. Once harvested we are back to the situation in Fig. 4 (or the upper leftmost panel). In Norway, about 57% of the forest is older than 60 years old (Svensson et al., 2021). The optimal rotation length of these stands are only to a limited degree affected by forcing payment. This also means that in short to medium term, i.e. some decades, the effect on timber supply is limited. This conclusion coincide with one of the main conclusion of Lintunen et al. (2022): current stands are not affected much while newly established stand will have long rotation length.

It should also be mentioned that forest provides a wide range of ecosystem services in addition to the ones analyzed here. The value of non-timber services may be much larger than the timber value, e.g. recreation opportunities (Costanza et al., 2014; de Groot et al., 2012). Some of the other services are negatively affected by clear cutting, and thus, prolonged rotations will increase social welfare.

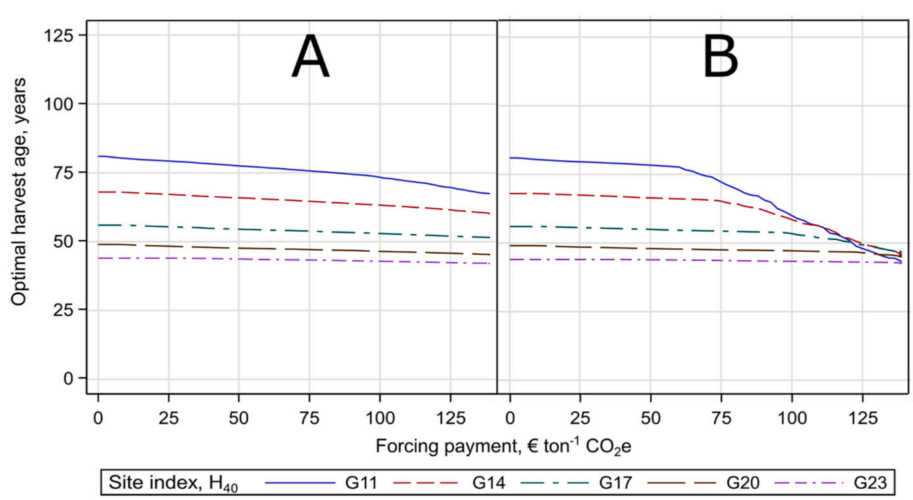

Fig. 3. Optimal rotation period for spruce when only the albedo effect is included and the discount rate is 3% p.a. Panel A (to the left) shows the results when the albedo is calculated as a one-time effect at harvest, $GWP_{\Delta\alpha}(100)$, while panel B shows the results when the albedo payment is based on continuous (yearly) forcing, $GWP_{\alpha}(t)$.

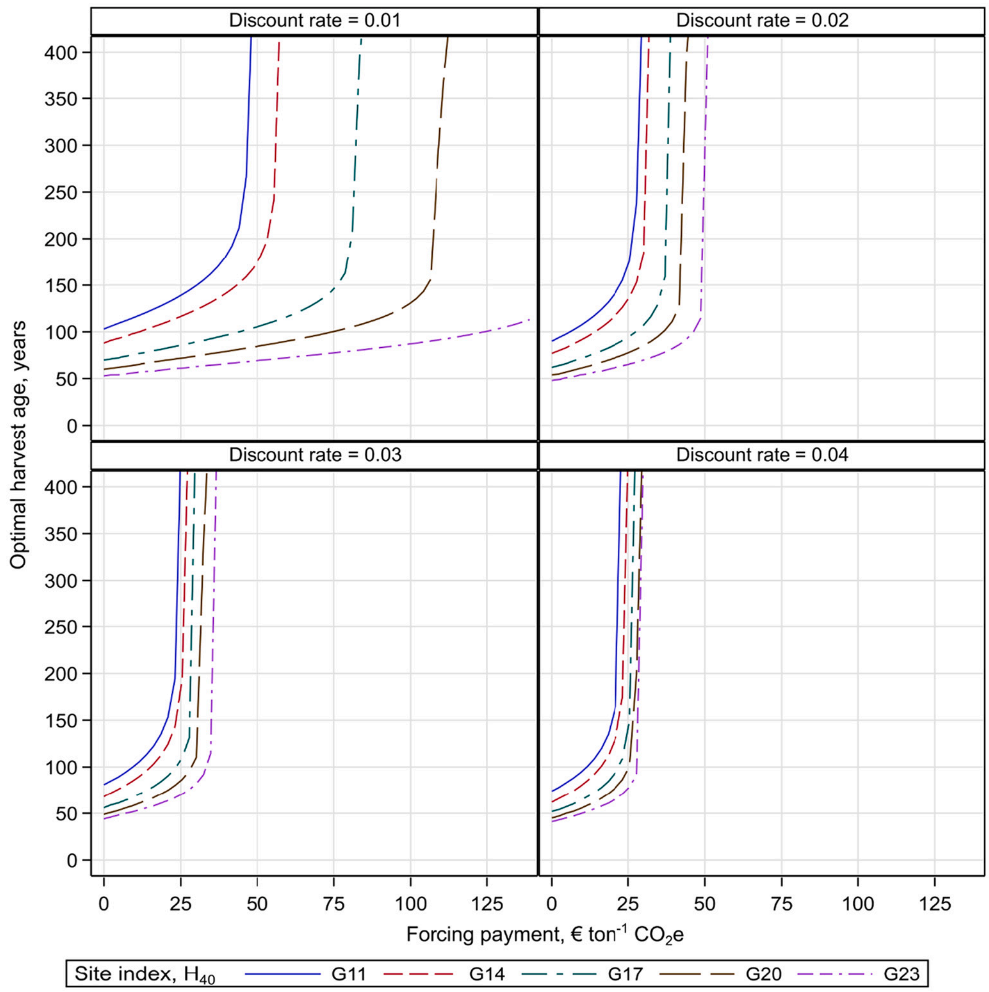

Fig. 4. Optimal rotation period for spruce as a function of forcing payment (albedo + CO_2 sequestration), site index and discount rate for bare ground. The payment for the albedo effect is calculated as a one-time effect at the time of harvest ($GWP_{\Delta\alpha}(100)$).

4.3. Uncertainties

The model used to derive the results above is a simplification of reality. It is therefore important to discuss to what extent the assumptions affect the outcomes of the model. It is assumed that the timber price is constant over time and invariant to the forcing payment. There is a falling trend in the long-term real timber prices. In the Faustmann framework, this would lead to longer rotation period. On the other hand, when/if the price on GHG emissions increase, it is reasonable to believe that timber prices also will increase. Pohjola et al. (2018) lend some support to this speculation. Timber products can substitute carbon intensive products such as metals and transportation fuels, and wood can be the carbon source in industrial processes (e.g. reduction agent in smelting). This will shorten the rotation period.

In the calculations, the albedo is assumed to not vary with site index or standing stock. It is reasonable to believe that the albedo is larger for stands with low productivity since biomass and tree density is lower. The effect of harvest would be lower, and thus the effect on optimal rotation less if payed as the one-time payment (based on $GWP_{\Delta\alpha}(TH)$).

Climate change may change the albedo. Snow is the driving force for the albedo effect alongside insolation. It is especially the spring conditions (March–May) that are important. The insolation is significant, and with snow covering the ground, the albedo effect is large. Both the albedo and insolation may be affected by climate change. Higher temperatures generally mean less snow, but at higher elevations, the temperature may still be sufficiently low. Most parts of Norway will see more precipitation according to the projections. It seems, however, likely that the albedo effect will be reduced over time since the number of days with snow cover will be reduced (Hanssen-Bauer et al., 2017). This will have little influence on the optimal rotation length.

5. Policy implications and conclusions

When devising policy schemes policymakers must balance precision and (transaction) costs. A “perfect” system where actual forest growth, changes in soil carbon, albedo and so forth are monitored, will have high precision, but will incur large costs. This is clearly not feasible. Information is not for free and this must be taken into account.

EU regulations are complex and detailed. For example, under the renewable directive (Directive (EU) 2018/2001, 2018) biofuel has to deliver a certain climate gas emission reduction in order to count against the fulfillment of policy targets and/or to be eligible for support. The calculation procedure is described in the directive, along with default values for the different parts. The actors must use the procedure as described but may choose to use own and documented values instead of the default values. This will reduce the transaction costs of the regulation. A similar procedure could be used for CO_2 and albedo.

A large share of the forest owners in Norway has a forestry management plan with an overview of the resource situation (e.g. area, site index, age, standing stock) in her/his forest along with recommended operations (silviculture, thinnings and final fellings). This could be a starting point when combined with a simple model as presented above.

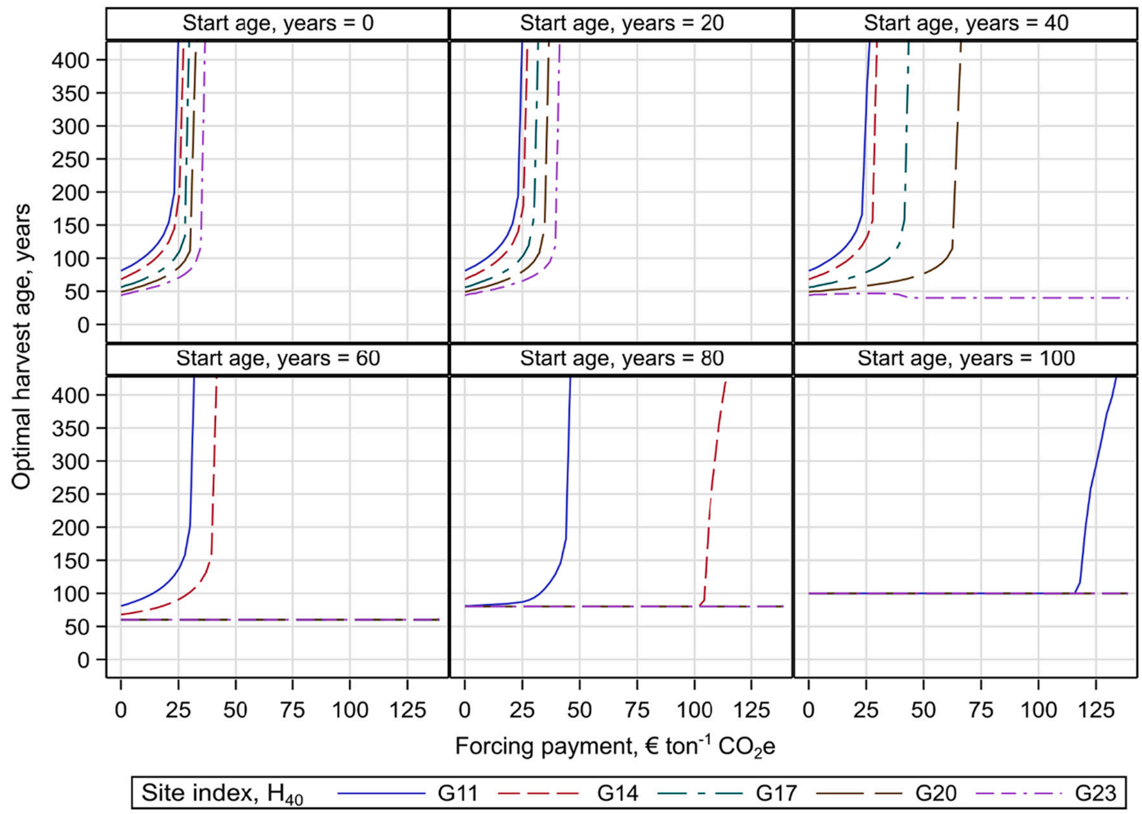

Fig. 5. Optimal rotation period for spruce as a function of forcing payment (albedo + CO_2 sequestration), site index and stand age at time of scheme implementation. The payment for the albedo effect is calculated as a one-time effect at the time of harvest ($GWP_{\Delta\alpha}(100)$). Rate of return is 3% p.a.

The results above show that albedo effect is low, and to reduce the complexity of the scheme, it can be dropped from the scheme.

How the forest owners will react to a forcing payment scheme, is an empirical question, and for now also a hypothetical one. The model above assumes risk neutrality, full information and that the owner maximizes the net present value. Since the effect on the rotation length are so large – i.e. a large prolonging of the harvest age – it is reasonable to believe that the main result also holds under also other behavioral assumptions.

The main conclusion is that if the forcing payment is linked to the EU ETS – currently about 80 € ton^{-1} CO_2 equivalents – and with current stumpage value, it will be more profitable to use forest for carbon storage than commercial timber production if stands are young. For stands close to maturity, forcing payment will have little effect.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

This work was supported by the Research Council of Norway through FME Bio4Fuels – Norwegian Centre for Sustainable Bio-based Fuels and Energy (257622) and Climate Smart Forestry Norway (302701). Comments and suggestions from two anonymous referees have greatly improved the article.

Appendix A. Appendix

Forest growth functions

Timber production functions are estimated on the basis of standard production tables for Norway spruce (Braastad, 1975) with no thinnings. A functional form with an asymptote is used (the Gompertz function):

$$h_{SI}(t) = a_{SI}e^{-b_{SI}e^{-c_{SI}t}}$$

Where $h_{SI}(t)$ is standing stock (m^3 ha^{-1}), SI is site index (H_{40}, dominant height (m), at breast height age 40 years), t is stand age, and a_{SI}, b_{SI} and c_{SI} are parameters to be estimated. The data from the yield tables are plotted along with the estimated curves are shown in Fig. 6, while the parameters are shown in Table 4.

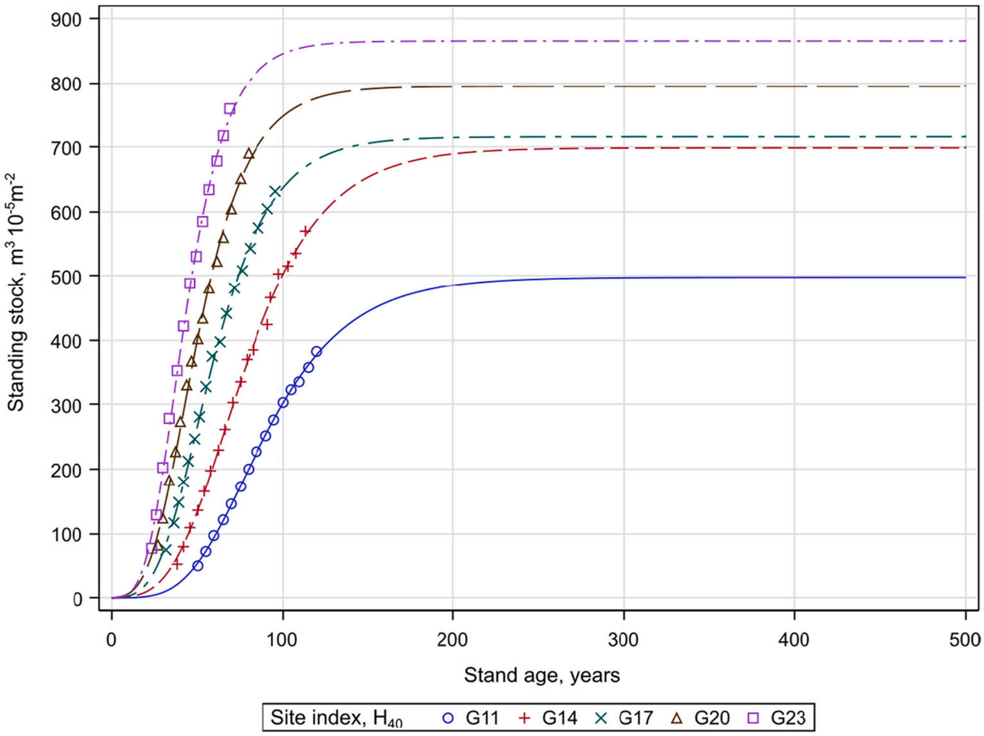

Fig. 6. Estimated timber production functions for Norway spruce. Markers show data from the production tables (Braastad, 1975), while lines are the estimated production functions.

Table 4
Parameter estimates (standard errors in parenthesis) and root mean squared error for forest production functions. All parameters are significant different from zero at 1% level.

Site index, H_{40}	a	b	c	RMSE
G11	498.08 (12.406)	9.89 (0.553)	0.03 (0.001)	3.30
G14	698.70 (21.581)	8.18 (0.564)	0.03 (0.002)	8.13
G17	715.83 (11.188)	8.22 (0.398)	0.04 (0.001)	5.95
G20	794.09 (22.098)	7.66 (0.591)	0.05 (0.002)	10.03
G23	864.92 (17.618)	8.68 (0.561)	0.06 (0.002)	8.51

Meta-analysis – National GWP map

The estimated albedo effects at the weather stations are generalized in the following way in order to calculate the effects at aggregate level:

$$GWP_{\Delta\alpha,i,s} = \beta_{0,s} + \beta_{1,s}X_i + \beta_{2,s}Y_i + \beta_{3,s}Z_i + e_{i,s}$$

Where $GWP_{\Delta\alpha,i,s}$ is the estimated albedo effect (kg CO_2e/m^2) for weather stations i and tree species s, X_i is the longitude (UTM33 Easting), Y_i is the latitude (UTM33 Northing), Z_i is the elevation (m.a.s.l), $\beta_{0,s}$-$\beta_{3,s}$ are parameters to be estimated, and $e_{i,s}$ is residual error. The functions are estimated using OLS: proc. reg in SAS (SAS Institute Inc, 2011). The parater estimates are given in Table 5 and the fit for spurce is illustrated in Fig. 7.

The estimations are basde on the station mean estimates, i.e. the mean of the Monte Carlo simulations at station level.

Table 5
Parameter estimates and simple fit statistics.

Species	β_0	β_1 (long)	β_2 (lat)	β_3 (alt)	r^2	RMSE	Coeff. var.
Spruce	−4.04E+00	−1.54E-06	5.41E-07	−1.36E-03	0.86	0.014	−17.1
Pine	−3.96E+00	−1.51E-06	5.34E-07	−1.33E-03	0.86	0.014	−17.7
Birch	−5.49E+00	−2.08E-06	7.52E-07	−1.78E-03	0.87	0.018	−18.2

Although the coefficient of variation is sizable, the fit must be said to be good. The plot in Fig. 7 does not reveal any systematic bias.

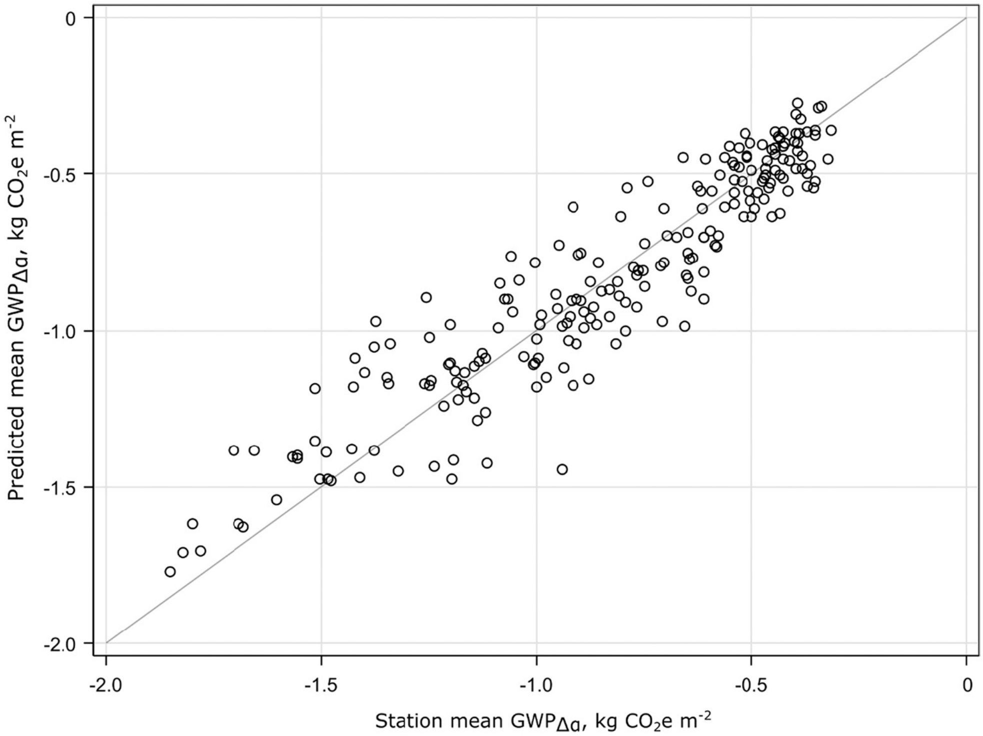

Fig. 7. Station mean $GWP_{\Delta\alpha}$ and predicted mean $GWP_{\Delta\alpha}$.The solid line is the 1:1 line.

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