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Optimal forest species mixture with carbon storage and albedo effect for climate change mitigation

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2016

Matthies , B D & Valsta , L T 2016 , ' Optimal forest species mixture with carbon storage and albedo effect for climate change mitigation ' , *Ecological Economics* ,

<http://hdl.handle.net/10138/173352>

<https://doi.org/10.1016/j.ecolecon.2016.01.004>

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1. Introduction

Perturbations from forest management on the radiative energy budget form an integral part of the global climate feedback mechanisms related to land use and land use change (LULUC) (IPCC, 2007; Lukes et al., 2013). They can result in positive or negative radiative forcing dependent on the type and magnitude of the changes¹. Increases in the length of the forest stand's rotation age, a decision that varies according to economically and ecologically specific management, can be a critical component in climatic impacts of managed forests (Betts, 2000; Harmon and Marks, 2002). For boreal forests, the associated regulating and supporting ecosystem services (ES) are vital components of the global biogeochemical and biogeophysical processes related to the carbon cycle and the albedo effect² (Bonan, 2008). These ES also have the greatest effect on global annual mean temperatures (Snyder et al., 2004). Thus, boreal forests, which are a geographically extensive, covering 22% of the terrestrial surface, and an ecologically significant, representing 32% of the Earth's forested land cover, also are crucial for managing climate change impacts from LULUC (Chapin III et al., 2000; Burton et al., 2006).

At the stand level, the primary level for forest management decision-making, any positive radiative forcing from management is an environmental externality of that management. One way to internalize these externalities is to monetize the impacts of these actions so that forest management planners must account for them in economic planning (Marland et al., 2003). Internalization can be achieved through tradable permits for climatic impacts measured in carbon dioxide equivalent units (Betts, 2000; Thompson et al., 2009b). The positive or negative impacts of the albedo effect on the radiative energy budget are then converted and accounted for alongside the negative impacts of carbon sequestration and storage (Betts, 2000; Thompson et al., 2009b). Previously Thompson et al. (2009a) and Betts (2000) have used this approach, but differences and uncertainties related to the deciduous and coniferous species-specific parameters regarding the albedo effect were not covered by those studies in the context of mixed stands.

Thompson et al. (2009a) considered the differences between coniferous and deciduous species when maximizing economic rents. However, they only considered one monoculture of a given species replacing another monoculture through reforestation and not mixed forests. Lutz and Howarth (2014) have also calculated the optimal rotation age with considerations for the albedo

¹ Where positive forcing leads to increased warming and radiative forcing is the net change in global irradiance measured in $W m^{-2}$.

² Albedo effect is defined as the extent that an object reflects radiation and represented by the ratio of reflected and incident electromagnetic radiation.

effect, but considered only two types of forest, deciduous mix and coniferous mix. They focused on estimating the shadow price of albedo using an integrated assessment model for climate interactions. Therefore, neither of these previous studies has looked at mixed species ecological interactions in the context of the optimal economic rotation and the inclusion of the albedo effect. However, the increasing promotion of mixed stands in Europe and elsewhere, as a way to increase ES provisioning and forested landscape resilience, means that understanding their potential climatic impact is essential.

This study looks at both the impacts of intra-species parameter uncertainty for the albedo effect in a mixed species boreal forest stand, between silver birch (*Betula pendula* Ehrh.) and Norway spruce (*Picea Abies* Karsten), and the effect that this uncertainty has on the optimum species composition and rotation age. We incorporate the albedo effect using carbon dioxide equivalent units also following Betts (2000) within a tradable permit program similar to the European Union Emissions Trading Scheme (EU ETS) that incentivizes climate change mitigation. Finally, we also explore the trade-offs between carbon storage and the albedo effect associated with of intra-species albedo parameter uncertainty and its effect on the species mixture, the optimal rotation, and the expected revenues for the stand.

2. Boreal stands, species mixtures, and climate change

Boreal forests generally have lower rates carbon storage than those in the temperate or tropical zones. This is the result of geographically determined lower temperatures and sunlight that act to limit the growing period (Jackson et al., 2008). Despite lower productivity, boreal forests, which are seasonally covered in snow, have been shown to have an important interaction with land surface albedo (Betts, 2000; Manninen and Stenberg, 2009).

Fresh snow tends to have a high albedo, but the low overall surface albedo of mature stands shadows the snow during winter and reduces the negative forcing effect (Betts and Ball, 1997; Sharratt, 1998; Moody et al., 2007; Bonan, 2008). Therefore, bare land resulting from agricultural expansion or deforestation in this biome can have a cooling effect (Otterman et al., 1984; Thomas and Rowntree, 1992; Bonan et al., 1995). The same would apply for the regeneration stage of a managed forest stand. The cooling effect of higher albedo achieved through reduced forest cover conflicts with the aim to maximize the carbon sequestration and storage by continuing to grow stand for a longer time period. Sequestration and storage represent an alternative cooling effect through longer rotations when the average carbon stock is increased. Various authors have shown that by incorporating the albedo effect of boreal forests into global land use models, previous and

current changes in land use towards absolute reductions in forest cover over time have and could continue to produce a net negative forcing (Brovkin et al., 1999; Govindasamy et al., 2001; Bala et al., 2007; Betts et al., 2007; van Minnen et al., 2008). This indicates that prioritizing albedo impacts over those from carbon storage could have a globally negative effect on the radiative energy budget. It has been suggested that as a result of trying to balance between these two factors, boreal forests currently have a net warming effect on the global climate if reforestation for carbon storage is prioritized over management for albedo effects (Gibbard et al., 2005). Those authors highlight that the warming effects from decreasing albedo due to reforestation dominates in the century time scale, and the cooling effects of carbon storage only dominate in the decadal time scale.

The higher albedo of snow through an opened canopy coupled with the higher observed albedo of deciduous species relative to coniferous species means that the result is a higher albedo for monoculture deciduous than in a monoculture coniferous stand (Gardner and Sharp, 2010; Kuusinen et al., 2014). These differences have also been suggested to lengthen the optimal rotation of a mixed or monoculture deciduous stand relative to a monoculture coniferous stand with the same climatic management considerations (Thompson et al., 2009a). Given that the share of mixed forests in Northern Eurasia, consisting of mixed coniferous needle and deciduous broadleaf species, has been estimated as 22% this intra-species difference in climatic impacts is an important consideration (Sulla-Menashe et al., 2011). In Finland, the share of mixed conifer-broadleaf forest was 13.9% in 2009-2013 (FSYF, 2014).

Previous studies have noted a wide range of costs and benefits associated with mixed boreal stands. Chen and Klinka (2003) and Fahlvik et al. (2011) found that growth, yield, and net present value all decreased with increasing proportions of birch over the rotation. However, Lundqvist et al. (2014), in agreement with Mielikäinen (1985), Tham (1988), and Pretzsch (2009), contrastingly found that total yield in mixed stands was higher than in monocultures. Linden and Agestam (2003), Knoke et al. (2008) and others note that these differences arise from site quality differences, and that overall mixed stands have a greater volume increment (Kennel, 1965). Regarding the economic benefits, when only harvested timber returns were considered, Roessiger et al., (2013) noted that expected returns for optimized mixed forests tend to be lower than for a monoculture forests. However, Valsta (1986 and 1988) optimized dynamically the species composition of pine-birch and spruce-birch stands for economic return and reported higher returns for mixtures compared to pure stands. This discrepancy is partially explained by site quality, selected species, growth dynamics, and economic assumptions. Given the uncertainty of the evidence, the possibility

of lower returns from mixed stands should still be an important economic consideration for the forest owner.

Mixed boreal stands have also been noted to have higher levels of resilience to biotic and abiotic disturbances and increased biodiversity benefits (Bergeron and Harvey 1997; Cumming, 2001; Noss, 2001; Rothe and Binkley, 2001; Cavard et al., 2011; Dymond et al., 2014). This is especially true for resilience against storm damages. Knoke et al. (2005) found that stochastically including this ecological risk in financial modeling made mixed species stands with a 10-50% deciduous component more profitable than Norway spruce monocultures. Knoke et al. (2008) provides an extensive review of the benefits of admixing species in Germany where Norway spruce is also a widely grown species.

Compensation for the climatic externalities associated with forest management as additional rents could reduce the economic cost of shifting towards more resilient mixed forest stand structures. Incorporation of this economic impact is done by applying the forest owners' appropriate personal discount rate to the expected future returns of both timber and climatic benefits (Richards and Stokes, 2004). Discounting allows for an evaluation of the time preference associated with the environmental benefits. For climatic benefits this is known as present tons equivalent (PTE), and is consistent with economic decision-making in forestry.

It has been shown previously that including additional rents for carbon sequestration in economic optimization of forest stand rotation results in a lengthening of the optimal rotation age (e.g. van Kooten et al., 1995; Hoen and Solberg, 1997; Stainback and Alavalapati, 2002; Raymer et al., 2011; Pihlainen et al., 2014; Hoel et al., 2014). This increase, as the value of carbon benefits increases *ceteris paribus*, has been noted across all of these studies. The longer rotations allow for greater accumulation of above and below-ground carbon and potentially yield higher quality wood products (Krankina and Harmon, 2006; Thompson et al., 2009a). However, Thompson et al. (2009a) and Lutz and Howarth (2014) have showed that by including the albedo effect the optimal rotation age was shorter than for the carbon storage only option. Therefore, given the competing nature of these two climatic objectives, it is important to evaluate mixed stands and determine if they provide a diversification benefit for climatic change mitigation actions.

3. Materials and methods

3.1. Joint production model

In this study, the optimal species composition and economic rotation of a mixed stand of Norway spruce (*Picea Abies* Karsten) and silver birch (*Betula pendula* Ehrh.) given the joint

production of multiple ES and payments for ecosystem services (PES) were determined. The optimal thinnings and rotations were derived for the maximum mean annual increment (MAI) and soil expectation value (SEV)³. In addition to wood production, two additional ES are considered in the model: carbon storage and albedo. Following Matthies et al. (In Press) we propose the use of ecosystem service expectation value (ESEV) (€ ha⁻¹) in replacement of SEV to differentiate between the expectation of timber-only returns and those returns associated with a more broad evaluation of the forest ecosystem value (Eq. A.1). Thus, the joint production of ES or ESEV (π) is a function of harvest returns, h_t , regeneration costs, w , carbon rents, cr_t , albedo forcing cost, a_t , all at time t , with interest rate, r , and rotation length T (Eq. 1). For details concerning harvest returns in Eqn. (1) see Supplementary Information.

$$\max \pi = \left[\sum_{t=0}^T h_t (1+r)^{-t} - w + \sum_{t=0}^T cr_t (1+r)^{-t} - \sum_{t=0}^T a_t (1+r)^{-t} \right] \frac{1}{1-(1+r)^{-T}} \quad (1)$$

For Eq. (1), it was assumed that the three ES considered in this model could be summed up to produce the value of forest stand management. This follows the approach given in, e.g., van Kooten et al. (1995) and Thompson et al. (2009a). Three discount rates, 1, 3, and 5%, were used in this analysis for calculating ESEV. These were chosen as representative of a range of private and social discount rates in relation to climate change mitigation both by the forest manager and by society in Finland.

In calculating the timber component of ESEV, wood production was valued as the net of perpetually discounted stumpage sales returns less silvicultural costs (Eq. A.1). All other costs were considered fixed and not dependent on stand management. Since they do not affect the optimum solution, and would only affect the absolute value of the ESEV, they were not included. For stumpage values, the average real roadside stumpage prices from 2004-2013 for all Finland were used (FSYF, 2013) (Appendix B). For each harvest, the total volume harvested, V (m³ha⁻¹) and the average stem size, V/N (m³) were calculated. Logging costs were obtained by evaluating each individual harvest (thinning or final cut) as a function of total volume harvested (Eqn. A.3). Yields of sawlogs and pulpwood were obtained based on product class models in Valsta (1986, 1988). (Further details in Supplementary Information).

Payments for climate mitigation were made for sequestering and storing carbon and for reducing albedo impacts in the stand (Betts, 2000; Tonn and Marland, 2007; Bonan, 2008;

³ SEV is defined here as the value of infinite future returns from continuing the current management regime in perpetuity.

Thompson et al., 2009b; Bright et al., 2011). For climate offsets, a range of emission allowance prices from 0, 20, 40 and 100€ ton (t) CO₂⁻¹ were used. These are comparable to those that were used in Thompson et al. (2009a).

Carbon storage ESEV was based on the rents of carbon stored in forest biomass. The amount of carbon was computed using biomass expansion factors for total stem volume following Lehtonen et al. (2004). Forest growth was computed in 5-year time steps and the average amount of carbon for each time step was considered. Carbon storage (kg m⁻²) was then transformed further to carbon dioxide using eq. (A.2). An annual value of carbon storage was obtained by multiplying the carbon dioxide equivalent units by the carbon emission allowance price (EU ETS price) by the different discount rates of 1, 3, and 5%, which represents the social rent of carbon. The value for each 5-year time period was obtained through multiplication.

Albedo ESEV was determined by comparing the current forest albedo to that of bare land following Kuusinen et al. (2014). The values used in this study are adjusted from the age-derived values used in that study into ones based on volume. For albedo values, it was assumed that albedo was the highest on bare land and that there was a linear decrease over the entire stand until the growing stock reached 60 m³ha⁻¹. For analysis of the sensitivity of this assumption 100 m³ha⁻¹ was also used. Finally, albedo values were converted into radiative forcing based on the site-specific latitude for the data following Akbari et al. (2009). The albedo input parameters derived from Kuusinen et al. (2014) data were 11.865 W m⁻² for Norway spruce and 6.388 W m⁻² for silver birch. For analysis of the sensitivity of the results to the absolute differences in the intra-species albedo effect, a range of values were used. Therefore, both species were started from a 0 W m⁻² difference (meaning both have a starting albedo forcing effect of 6.388 W m⁻²) then steps of 5 W m⁻² increases in the Norway spruce albedo forcing value away from the silver birch value, which was held constant, were conducted until a maximum difference of 25 W m⁻² (or 31.388 W m⁻²) was reached. The albedo impacts were converted into carbon dioxide equivalent units following Sjølie et al. (2014).

3.2. Optimization approach

3.2.1. Mathematical model of the forest stand

Suppose the changes in the state variables, $\mathbf{x}(t) \in \mathbb{R}^m$, of the forest due to growth, renewal and mortality are given by the function $\mathbf{f}(\mathbf{x}(t)): \mathbb{R}^m \rightarrow \mathbb{R}^m$. Define the changes in the state variables by

human actions $\mathbf{u}(t) \in \mathbb{R}^n$ as $\mathbf{h}(\mathbf{u}(t)) : \mathbb{R}^n \otimes \mathbb{R}^m$. The frequently used form (e.g., Clark 1976, Johansson & Löfgren 1985) of the differential state equation is:

$$\frac{d\mathbf{x}(t)}{dt} = \mathbf{f}(\mathbf{x}(t)) - \mathbf{h}(\mathbf{u}(t)) \quad (2)$$

Note that the "harvest" function, \mathbf{h} , can be continuous over time or, typical of forestry, of impulse type. To facilitate numerical analysis, discrete time formulations are usually employed in stand management studies. Defining $\bar{\mathbf{f}} : \mathbb{R}^m \otimes \mathbb{R}^m$ as the periodic growth equation, we obtain the corresponding difference state equation:

$$\mathbf{x}(t+1) - \mathbf{x}(t) = \bar{\mathbf{f}}(\mathbf{x}(t) - \mathbf{h}(\mathbf{u}(t))) \quad (3)$$

Note that the growth function $\bar{\mathbf{f}}$ is evaluated after the stand has been harvested. Both the continuous-time and the discrete-time formulation above share one important property: future development depends only on the present state of the system. We do not need to know what has taken place before time t . This property is required for the use of dynamic programming (Bellman 1957, p. 81)

3.2.2. The optimization model

We define the value function g so that it uses the stand state before ($\mathbf{x}(t)$) and after ($\tilde{\mathbf{x}}(t)$) harvest as arguments, $g : \mathbb{R}^m \otimes \mathbb{R}^m \otimes \mathbb{R}$. Because the growth dynamics are defined by the state equations, the sequence of values of $\tilde{\mathbf{x}}(t)$ complete defines the management regime. In discrete time, the optimization problem for even-aged stand management can be stated as:

$$\max_{\tilde{\mathbf{x}}(t), T} \sum_{t=0}^{T-1} g(\mathbf{x}(t), \tilde{\mathbf{x}}(t)) \frac{(1+r)^{T-t}}{(1+r)^{T-1}} + g(\mathbf{x}(T), \mathbf{x}_0) \frac{1}{(1+r)^{T-1}} \quad (4.1)$$

$$\mathbf{s. t.} \quad \mathbf{x}(t+1) - \tilde{\mathbf{x}}(t) = \mathbf{f}(\tilde{\mathbf{x}}(t)), \quad t = 0, 1, \dots, T-1 \quad (4.2)$$

$$\tilde{\mathbf{x}}(0) = \mathbf{x}_0 \quad (4.3)$$

$$1 \leq T \leq T_{max} \quad (4.4)$$

Where:

$\tilde{\mathbf{x}}(t)$ = state vector after a treatment at time t

$g(\mathbf{x}(t), \tilde{\mathbf{x}}(t))$ = value function (revenue or cost when performing state transition from stand $\mathbf{x}(t)$ to stand $\tilde{\mathbf{x}}(t)$, $g: \mathbb{R}^m \times \mathbb{R}^m \rightarrow \mathbb{R}$)

$\mathbf{f}(\tilde{\mathbf{x}}(t))$ = state equation

T_{max} = maximum rotation

All other symbols are as stated earlier in the text. The first part of equation (4) refers to the period of thinnings and other silvicultural operations in the stand. \mathbf{x}_0 is the initial stand condition which is also established after the final harvest. The return function g and the "growth" function \mathbf{f} do not have time t as an argument. Tree or stand age can be defined a state variable if the functions are time/age dependent. For dynamic programming, the corresponding discrete-time forward recursion equation becomes:

$$R(\mathbf{x}_{t+1}) = \max_{\{\mathbf{x}_t\}} [\bar{g}(\mathbf{x}_{t+1}, \mathbf{x}_t) + R(\mathbf{x}_t)] \quad (5)$$

$t = 1, \dots, T$

Where \bar{g} is the discounted return associated with state transition from stand \mathbf{x}_t to stand \mathbf{x}_{t+1} , $\{\mathbf{x}_t\}$ is the set of stands that can lead to stand \mathbf{x}_{t+1} after growth and a possible thinning, and $R: \mathbb{R}^m \rightarrow \mathbb{R}$. Stand age can be linked to subscript t so that an additional time variable can be avoided.

The time step in the formulation affects the accuracy of the optimum solution. For forest stands, the annual cycle of growth requires a step length of at least one year. However, the time step used in the state equation is the most reasonable one for optimization, as well. Then, the computations for optimization are in line with the prediction capability of the state equation. In our case, the time step is five years.

The empirical state equation is based on three state variables: stand volume (total stem volume) [$\text{m}^3 \text{ ha}^{-1}$], V_t , percent birch of stand volume [%], B_t , and the number of trees, N_t [ha^{-1}]. These form the state vector $\mathbf{x}_t^T \equiv [V_t, B_t, N_t]$.

Finally, with the joint production approach, the dynamic programming recursion equation becomes:

$$R(\mathbf{x}_{t+1}) = \max_{\{\mathbf{x}_t\}} [H(\mathbf{x}_{t+1}, \mathbf{x}_t) + C(\mathbf{x}_{t+1}, \mathbf{x}_t) + A(\mathbf{x}_{t+1}, \mathbf{x}_t) + R(\mathbf{x}_t)] \quad (6)$$

$$t = 1, \dots, T$$

The recursion equation value now includes the ecosystem service values of timber, carbon storage, and albedo.

4. Results

4.1. Albedo parameter uncertainty and species mix

By varying the absolute difference in radiative forcing from albedo between Norway spruce and silver birch, it was possible to determine the optimum percentage of birch in a mixed stand over the whole rotation of the stand. This was done for different discount rates, climate offset prices, and points of albedo saturation in the stand and shown in Fig. 1. The results are for an albedo saturation point of $60\text{m}^3\text{ha}^{-1}$. When climate offsets were excluded, then the average percentage of birch over the rotation was constant across all points of increasing difference in intra-species albedo forcing. The average percentage of birch was approximately 20% depending on the discount rate. This represents the optimal percent of birch without climate benefits included, and shows that there is a financial benefit associated with the inclusion of birch that is unrelated to the internalized climatic benefits.

At a discount rate of 1%, the changes in the average percentage of birch were small. However, as the discount rate increased from 1 to 3% and then 3 to 5% the benefits of birch became increasingly more important as the intra-species difference in albedo forcing increased from 0 to 25W m^{-2} . The effect is more important at higher climate offset prices and discount rates. A 98% pure birch stand was reached at a forcing difference of 25W m^{-2} , climate offset price of 40€ ton CO_2^{-1} , and discount rate of 5%.

Corresponding details regarding the rotation ages and ESEVs for the optimal rotations in Fig. 1 are found in Table 1 and 2 respectively. All of the corresponding results for Fig 1, and Tables 1 and 2 for the albedo saturation point of $100\text{ m}^3\text{ha}^{-1}$ are available in the Supplementary Information. A carbon only case is given in both tables for comparison against the carbon and albedo combined case. In Table 1 the optimal rotation age stays the same for both the carbon only and carbon and albedo combined cases for all climate offset prices and discount rates. However, in Table 2 the exclusion of the albedo effect in estimating the ESEV resulted in an overpayment for the climatic benefits of management.

Fig. 1. Average percent of silver birch over the entire rotation for increasing climate offset prices (€ ton CO₂⁻¹) and increasing differences in albedo forcing (W m⁻²) between Norway spruce and silver birch. Where a) is the value at a discount rate of 1%, b) at 3%, and c) at 5%.

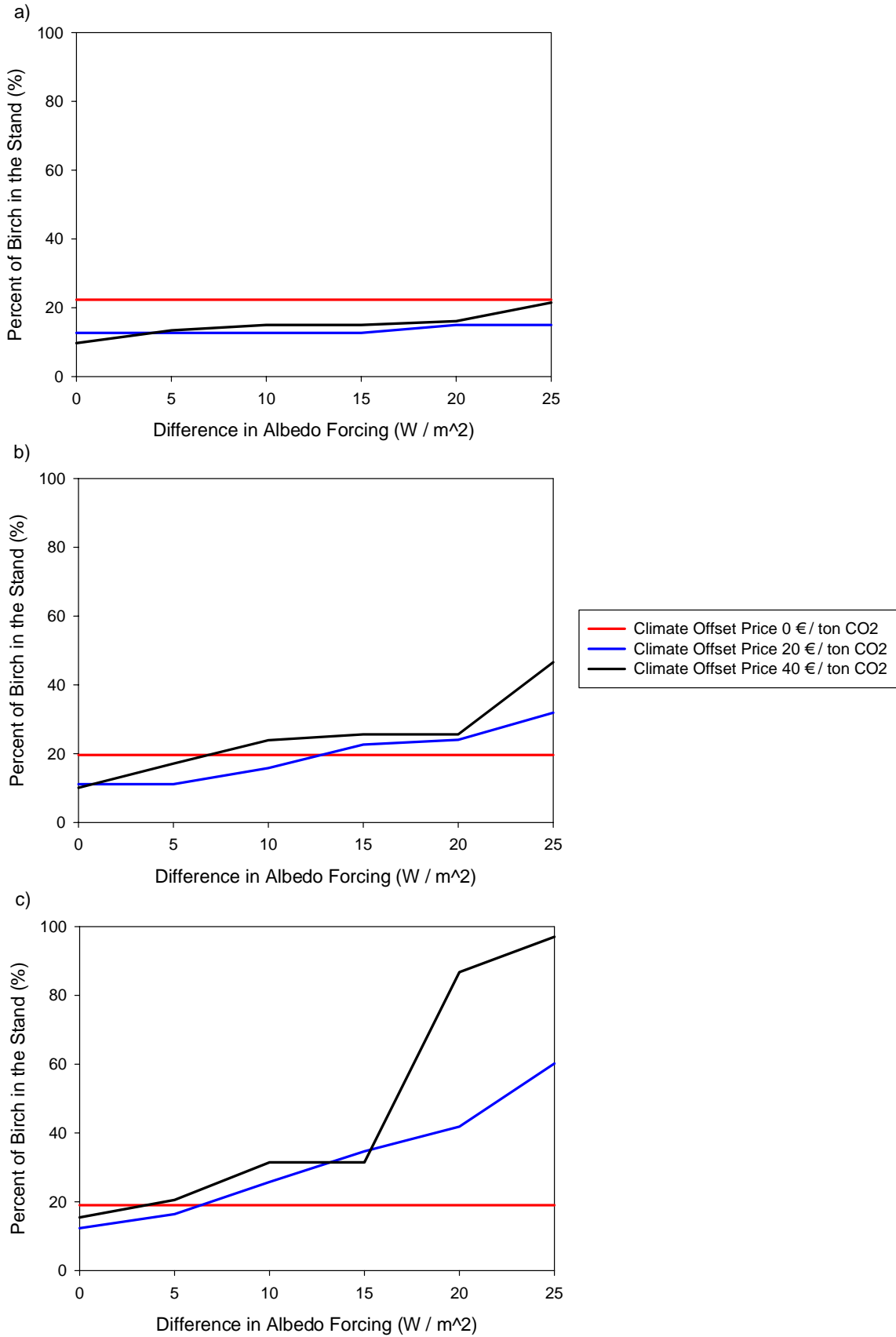


Table 1. Optimal rotation ages at varying climate offset prices (€ ton CO₂⁻¹) and differences in albedo forcing (W m⁻²) for mixed Norway spruce and silver birch stands. Carbon Only refers to the optimal rotation with albedo excluded.

Climate Offset Price (€ tCO ₂ ⁻¹)	Difference in Albedo Forcing	Albedo and Carbon			Carbon Only		
		Discount Rate (%)					
		1	3	5	1	3	5
0	0 - 25	90	85	70	90	85	70
20	0	95	85	75	95	90	75
	5	95	85	75	-	-	-
	10	95	85	75	-	-	-
	15	95	85	75	-	-	-
	20	95	85	75	-	-	-
40	25	95	85	90	-	-	-
	0	95	90	95	95	90	95
	5	95	90	90	-	-	-
	10	95	85	90	-	-	-
	15	95	85	90	-	-	-
	20	95	85	100	-	-	-
	25	95	85	100	-	-	-

When albedo effects and carbon storage are both included at a discount rate of 1% and climate offset prices were either 20 and 40 € ton CO₂⁻¹, then the optimal rotation age was constant for all increases in the difference in intra-species albedo effect. At the same discount rate, the optimal rotation was shorter by 5 years when climate impacts were excluded. An increase in the discount rate to 3% resulted in a 5-10 year decrease in the optimal rotation across all climate offset prices and changes in species-specific albedo impacts. When the discount rate was increased further to 5%, then optimal rotation was shorter than the optimal rotations for a 3% discount rate only when climate benefits were excluded and when the intra-species differences in radiative forcing from albedo were low (Table 1). However, the optimal rotation increased with increasing intra-species difference in albedo and with increasing climate offset prices. With the higher climate offset price of 40 € ton CO₂⁻¹, increasing interest rate did not shorten the optimum rotation, contrary to the case of timber only management.

As the absolute difference in albedo effect increased between silver birch and Norway spruce, the ESEV at the optimal rotation ages declined at all discount rates and climate offset prices (Table 2). This decline within each offset price level and discount rate, resulted in negative values at a discount rate of 5% and climate offset price of 20 € ton CO₂⁻¹. In Table 3, a sample set of data regarding the outputs for an optimal management regime is also given. The data is regarding the case for a climate offset price of 20€ ton CO₂⁻¹, a discount rate of 3%, and at a difference in albedo forcing of 5W m⁻². It corresponds to the outputs in Table 2 for the same input parameters.

Table 2. Ecosystem expectation values (ESEV) (€ ha^{-1}) at varying climate offset prices (€ ton CO_2^{-1}) and differences in albedo forcing (W m^{-2}) for mixed Norway spruce and silver birch stands. Carbon Only refers to the optimal rotation with albedo excluded.

Climate Offset Price (€ tCO_2^{-1})	Difference in Albedo Forcing	Albedo and Carbon			Carbon Only		
		Discount Rate (%)					
		1	3	5	1	3	5
0	0 - 25	47467	5234	365	47467	5234	365
20	0	50422	6559	968	51313	7164	1352
	5	49787	6127	700	-	-	-
	10	49151	5741	463	-	-	-
	15	48515	5338	223	-	-	-
	20	48054	4983	(4)	-	-	-
40	25	47433	4589	(136)	-	-	-
	0	53514	8097	1933	55295	9317	2760
	5	52452	7250	1373	-	-	-
	10	51133	6456	896	-	-	-
	15	49892	5645	896	-	-	-
	20	48548	4922	427	-	-	-
	25	47372	4421	397	-	-	-

Table 3. Stand summary statistics for a sample management regime at an offset price of 20€ ton CO_2^{-1} , a 5W m^{-2} difference in albedo forcing, and 3% discount rate. Percent of Birch refers to the percent at that age.

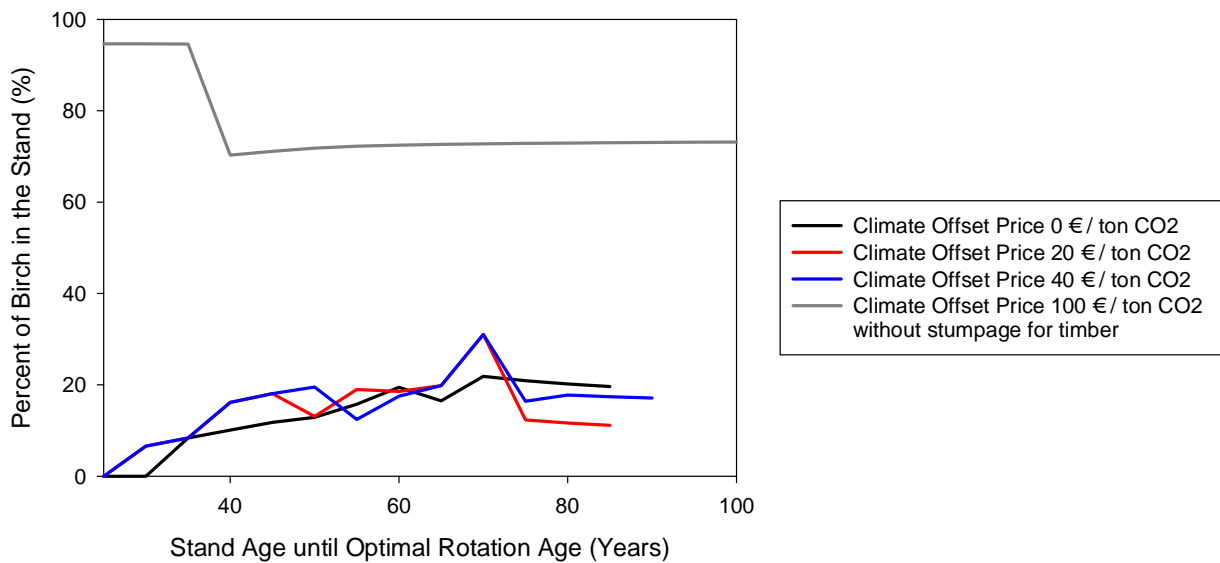
Age (Years)	Volume (m^3ha^{-1})	Percent of Birch (%)	Number of Trees	Volume per Tree ($\text{m}^3\text{ha}^{-1}\text{stem}^{-1}$)
85	208.67	1.09	219	0.95
80	258.10	0.90	318	0.81
75	342.70	0.72	489	0.70
70	323.79	5.57	522	0.62
65	320.21	14.93	596	0.54
60	273.09	13.88	596	0.46
55	225.00	12.75	596	0.38
50	238.61	11.57	796	0.30
45	186.74	10.21	796	0.23
40	137.34	8.82	796	0.17
35	91.52	7.44	796	0.12
30	71.19	6.20	1108	0.06
25	52.00	5.00	1800	0.03

4.2. Considerations for climate only management

Fig. 2 shows the development of the percentage of birch in the stand over the entire rotation from age 25 until final harvest, when the species-specific differences in the albedo effect were based on the empirical results noted in Section 3.2. The upper range of the impact from increasing the climate offset prices is demonstrated by applying an offset price of 100€ ha^{-1} , which represents stands where only payment for carbon storage and albedo effect-based rents are considered and timber production is no longer economically optimal. The percentage of birch at that price had a minimum threshold of 70% that was noted at all ages over the rotation. For lower offset prices ranging from 0 to 40€ ton CO_2^{-1} , birch, as a percentage of the stand structure, was relatively similar among the stands at all ages over the rotation. The curves for the applied range of offset

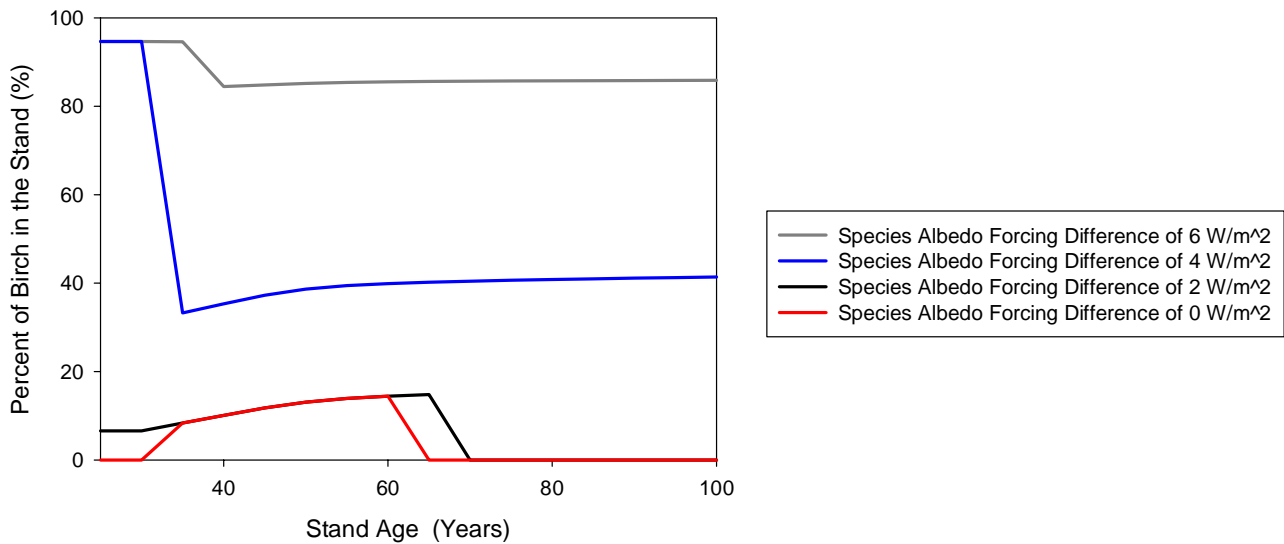
prices fluctuate as proportions of birch in the stand relative to spruce, which shifts due to growth, thinnings, and mortality of each species over time. This demonstrates that at lower climate offset prices the ESEV was still dominated by rents from commodity production.

Fig. 2. Percent of silver birch in the stand over the rotation until the optimal rotation is reached for increasing climate offset prices (€ ton CO_2^{-1}) at an albedo difference $5.477\text{m}^3\text{ha}^{-1}$ for spruce over birch, discount rate of 3%, and consideration for offsets at a price of $100\text{€ ton CO}_2^{-1}$ with no timber stumpage (i.e. climate only). Albedo difference between species is based on empirical results from Kuusinen et al. (2014)



Increasing the offset prices to incentivize a climate only management regime also increased the sensitivity of the results to changes in the absolute difference in species-specific radiative forcing values (Fig. 3). Small changes of 2W m^{-2} created large shifts in the percentage of birch in the stand over the optimal rotation. These results demonstrate that uncertainty associated with the estimation of the absolute difference in the intra-species albedo could have an important impact on the diversification benefit of birch. This is especially true when managing exclusively for climate benefits and at high levels of offset prices. If the species difference is 2W m^{-2} less, then the decrease in the optimal percentage of birch is $<40\%$ over the entire rotation relative to $>80\%$ for a 6W m^{-2} intra-species difference. In comparing these results to the reported empirically-based albedo forcing values noted earlier, where the intra-species difference is 5.477W m^{-2} , the effect would be similar to a 6W m^{-2} difference in Fig. 3. In comparison to Fig.1, it is important to note that in Fig. 3 rents from commodity production are no longer included due to the dominance of rents from climate mitigation. Additionally, the maximum price for climate offsets in Fig. 1 was 40€ ton CO_2^{-1} and in Fig. 1 the maximum value is $100\text{€ ton CO}_2^{-1}$.

Fig. 3. Percent of the silver birch in the stand until 100 years at decreasing levels in the difference in albedo forcing ($W m^{-2}$) between Norway spruce and silver birch at a climate offset price of $100 \text{ € ton CO}_2^{-1}$ and an albedo saturation point of $60(m^3 ha^{-1})$ and discount rate of 3%.



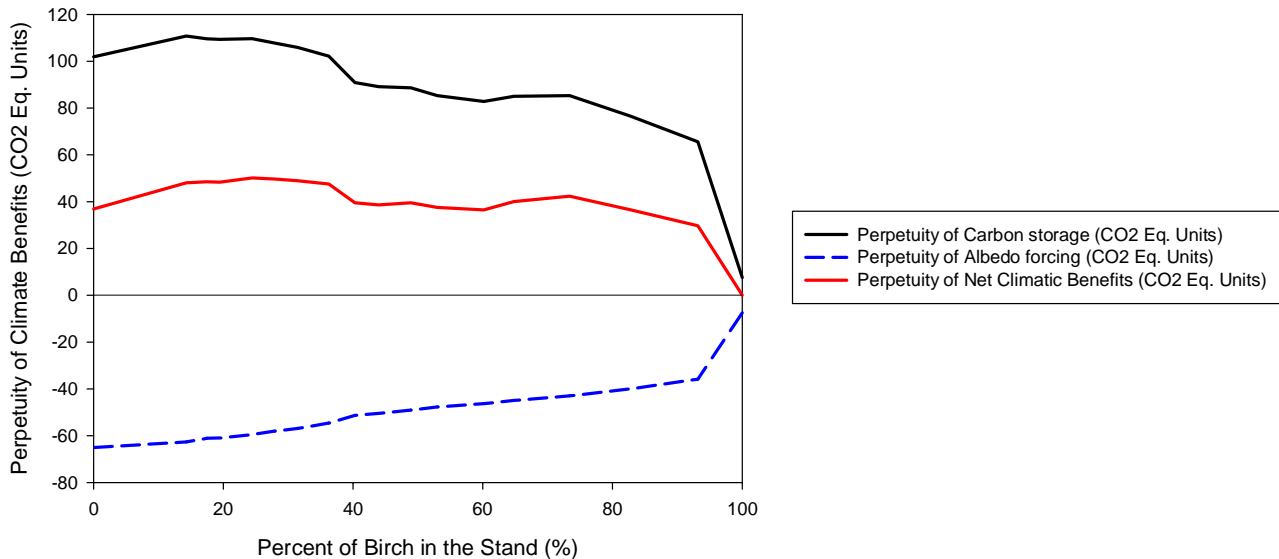
4.3. Trade-offs between climatic benefits and species mix

The ESEV values represent the present value of a perpetual periodic series of ecosystem service rents from the three categories outlined in Eq. (1) (Klemperer, 2003). In Fig. 4, the present value of discounting the periodic perpetuities of environmental benefits and costs, both separately and as a net of the carbon storage and albedo effects, are shown for increasing percentages of silver birch within the stand. In this figure, the percentages of birch correspond to the average percent over the rotation. The parameter values for the species-specific radiative forcing from the albedo effect used in in Fig. 4 were those reported in Section 3.2.

The trade-off curve between increased species mixture and discounted environmental effects demonstrates a diversification benefit that is present for mixed forest structures over the alternative single-species Norway spruce and silver birch stands. The optimal mixture for maximizing this net environmental benefit between albedo and carbon storage effects was found to be at 24% silver birch and 76% Norway spruce. Fig. 4 compares with Fig. 1b, given their comparable underlying assumptions, where the range of birch percentage in the stand was between 10 and 30% over the increasing difference in species-specific albedo forcing values.

Fig. 4. Perpetuity of climate benefits of carbon storage and albedo forcing, separate and net, at increasing average percentage of silver birch over the whole optimal rotation from

monoculture Norway spruce stand to monoculture silver birch stand. Climate benefits are reported as the discounted perpetuity of carbon dioxide equivalent units of carbon storage and radiative forcing from albedo, at a 3% discount rate, stand albedo saturation point of $60 \text{ m}^3 \text{ ha}^{-1}$, and a baseline climate offset price of $20 \text{ € ton CO}_2^{-1}$.



In Table 3, the rents from the periodic perpetuities of each ecosystem service noted in Eq. (1) are shown corresponding to their respective service, timber commodity production, carbon storage, and albedo effect, and as the aggregated sum. The results shown here are based on the results reported in Fig. 2. Increasing the percentage of silver birch in the stand relative to Norway spruce increased the costs associated with the albedo effect, but reduced the benefits associated with timber production and carbon storage. This trade-off is visible in the Total ESEV that is achieved at each level of birch percent. The highest ESEV value achieved was 6056 € ha^{-1} . This result can be compared to those for the corresponding optimal rotation in Table 2 based on the same assumptions, which had a birch percentage of 15% and ESEV of 6127 € ha^{-1} when the difference in albedo forcing between species was 5 W m^{-2} . For the empirically-based results reported in Table 3 the intra-species difference was 5.477 W m^{-2} . The difference between these two cases is the larger intra-species parameter difference for the results in Table 3, which creates an increase in the negative rents from the albedo effect and results in a 71 € ha^{-1} reduction in ESEV. Additionally, in Table 3 as the percentage of birch increases the rotation ages decrease from 85 to 80, but then increase again to 85 once the birch percentage exceeds 70%.

Table 3. Ecosystem service rents that form the objective function in Equation 1 organized by ecosystem service and percentage of silver birch in the stand. Values are taken from the results reported in Fig. 2 and correspond to different average birch values for the whole rotation. Climate benefits are reported using a 3% discount rate, an intra-species albedo parameter difference of 5.477 W m^{-2} and a baseline climate offset price of $20 \text{ € ton CO}_2^{-1}$.

Silver birch in the stand (%)	Rotation Age	Ecosystem Service Expectation Values (ESEV)			
		Timber ESEV	Carbon ESEV	Albedo ESEV	Total ESEV
0	85	5015	2038	(1301)	5752
17	85	5085	2192	(1222)	6055
24	85	5095	2216	(1254)	6056
36	85	4717	2044	(1093)	5669
44	80	4756	1783	(1010)	5529
53	80	4298	1706	(954)	5050
65	80	3911	1700	(899)	4712
74	85	3299	1707	(860)	4145
83	85	3005	1531	(800)	3736
93	85	2593	1312	(717)	3188

5. Discussion and Conclusions

5.1. Parameter impacts on species mixture

The red lines in Fig. 1a-c note the baseline value for species mixture in the economically optimal thinnings and rotation for all discount rates. This represents the economic diversification benefit of birch relative to a single-species silver birch or Norway spruce stand. The baseline percentage is about 20% birch of forest area at all discount rates. However, the species composition is not fixed over the rotation and the economically optimal management utilizes the more rapid early growth of birch and then gives way to spruce later in the rotation. Thompson (1991) found that the financially optimal tree species mixture for moderately risk-averse forest managers was 73% coniferous and 27% deciduous. Knoke et al. (2005) have noted a range of 10-50% for European beech and Norway spruce stands. These and other studies support the finding that a financially optimal baseline exists for deciduous species in a coniferous dominated stand in boreal and temperate forests.

Including carbon storage benefits and the cost of albedo impacts changed the proportions of each species in the optimal stand management relative to these commodity only stands. In the case where the intra-species albedo parameters are the same for both birch and spruce, then the higher prices for commodity production from spruce reduces the optimal percentage of birch in the stand. However, it has been shown previously that birch has a lower albedo than spruce, and the empirical results used in this study based on Kuusinen et al. (2014) correspond to an optimal species mixture of around 20% (as an average over the rotation). This result corresponds to the optimal species mix with only commodity production, and may indicate the strong role that commodity production and stumpage prices still have in determining the optimal rotation in a mixed stand, with the baseline levels of climatic parameter values.

Thompson et al. (2009) also noted that the higher albedo effect of deciduous species in monocultures lengthens the optimal rotation relative to coniferous monocultures, and that it moves the rotation closer to the carbon only rotation. In this study, there was no difference between the carbon only and carbon and albedo rotation ages except at high intra-species albedo parameter differences. This demonstrates the potential environmental and economic diversification benefits of mixed stands regarding management for climate change impacts when externalities are internalized.

Including environmental externalities of forest management in the aggregated rents from forest management means that increased albedo impacts become a climatic cost. By including these effects in the climatic incentives for forest management, the species with the lowest albedo costs relative to benefits of storage and timber production are favored. Therefore, increasing the albedo effect from spruce relative to that from birch also increased the relative costs between the two species. This relative increase in costs favored birch, and resulted in an increase in the optimal percentage of birch in the stand. However, this is a simplistic interpretation of the intra-species dynamics. Further evaluation of the results shows, in comparing the $100\text{m}^3\text{ha}^{-1}$ saturation point to the $60\text{m}^3\text{ha}^{-1}$ saturation point, the $60\text{m}^3\text{ha}^{-1}$ saturation point had a higher birch percent at the time of final harvest over the range of intra-species albedo parameter estimates at a discount rate of 3%⁴. However, at the 5% discount rate the $100\text{m}^3\text{ha}^{-1}$ saturation point has higher optimal birch percent for the same parameter estimates. This result corresponds to the exponential nature of discount rates, which consider the impact of time preferences on decision-making. This exponential nature dictates that decreasing time preference by the decision-maker is associated with an increasing discount rate to reflect their utility function. As the discount rate increases then present value of returns decreases, and the ESEV is adjusted downward. Higher rates correspond to lower consideration for future generations when the discount rate is the social discount rate. The longer time taken for reaching the saturation point of $100\text{m}^3\text{ha}^{-1}$ coupled with the higher discount rate lead to an even larger emphasis on the reduced costs associated with birch over spruce at high intra-species albedo effect differences. When the saturation point was adjusted downwards, then the reduced costs associated with birch were more important at lower discount rates. In addition to this effect, the discount rate also corresponded to the productivity differences between the two species.

Each species' ecological growth characteristics, which differ according to mixed stand dynamics and species-specific factors, interact with the price of the ES for each species. These two factors combine with the discount rate to give the discounted returns for each species. In this study,

⁴ Results for $100\text{m}^3\text{ha}^{-1}$ saturation point are found in the Supplementary Information.

silver birch has a higher growth rate than that of Norway spruce during the early period of stand development. Therefore, the increased discount rate favors the faster growing and shorter rotation associated with birch in the optimization. This also helps to explain why the climate only management regime resulted in a higher proportion of birch relative to spruce. Therefore, the choice of discount rate is a key variable for deciding whether to promote deciduous or coniferous trees based on their climatic benefits. The underlying interactions between growth rate and time preferences coupled with parameter uncertainty for the climatic benefits and costs may make various species appear more or less optimal.

This climate friendliness effect is due to the trade-off between the carbon storage and albedo forcing that occurs between the two tree species. When the albedo parameter value for spruce exceeded the threshold of 5W m^{-2} more than that for birch, then a relatively greater trade-off between carbon storage and the albedo effect was found for spruce than for birch. As a result, the increasingly negative impact of the increased albedo effect favored a shift to birch. This draws the distinction that the albedo benefits are found mostly in the birch, but the carbon storage benefits are more closely associated with growing spruce. Given that prices for commodity production and climate offsets are held constant as the albedo parameters were allowed to diverge, this acted to magnify the albedo effect on the species composition of the economically optimal stand structure. This effect combined with the higher growth rate of birch and increasing discount rates, meant that it was increasingly favorable to shift to silver birch over Norway spruce. Additionally, it explains the highly sensitive results in Fig. 4, where a small decrease in the W m^{-2} difference between species resulted in a large shift away from birch towards spruce. The decrease in the trade-off between carbon storage and the albedo effect for spruce favored an increase in the proportion of spruce.

These results contribute to a growing body of literature that, taken together, indicates the importance of including all of the climatic environmental externalities associated with forest management in the estimation of tradable permits for climatic impacts. This not only includes albedo effect along with carbon storage, but also volatile organic compounds (VOCs), aerosols, and additionality of management relative to a baseline case. Nevertheless, uncertainties and risks associated with these methods clearly remain. Overestimating the benefits of deciduous species relative to coniferous ones may perversely incentivize management with limited climatic benefit. Also, parameter estimation and the choice of input variables can clearly have an important effect on the optimal results.

Further, if offsets are based on a market mechanism similar to the EU ETS, then there are further risks associated with the fluctuations in market price of offsets needs to also be accounted for. The ability to mitigate this risk through diversification may not be possible for forest owners, and could present an obstacle to policy acceptance. A rapid increase in prices may act as an incentive for not harvesting and extending the life of the stand past an ecologically appropriate period of time. This could reduce the supply of harvested wood for the forest industry and distort forest products markets. It could also have important ecological implications if the existing stand consists of a species with a shorter ecological rotation, such as silver birch. Similarly a collapse in offset prices could devalue the intended compensation. This would expose forest owners to the downside risks of mixed species management, which include lower returns for economically sub-optimal species distributions.

This study also builds on the previous work in promoting the idea that the benefits associated with mixed stands extend well beyond only intrinsic values and biodiversity. Mixed stands can also promote environmental and economic benefits, which are important in mitigating the effects of climate change. In mixed stands, the trade-offs between ecosystem services provided by a given species are multiplied to include not only the same trade-offs for many species, but also the trade-offs between species. Species mixtures can act to reduce the trade-offs when multiple objectives are considered co-currently within the optimization, but this requires strong parameter certainty. As forest management increasingly focuses on providing the widest array of and the maximum achievement of ecosystem services over the landscape, it is ever more important to evaluate how these services interact with each other and how incentives to increase service provisioning act to promote or detract from those trade-offs.

Acknowledgements

This research was possible with funding from the Helsinki University Center for the Environment (HENVI) “Forest and Climate Change” grant.

Appendix A

$$ESEV = \frac{\left[C_0 + \left[\sum_{t=1}^T \frac{R_t}{(1+r)^t} - \sum_{t=1}^T \frac{C_t}{(1+r)^t} \right] \right]}{(1+r)^{T-1}} \quad (A.1)$$

For discounting the perpetuity of a given stand management regime let C_0 = costs occurred at the year 0, R_t = all revenues from all ecosystem service rents occurring at time t , C_t = all costs occurring at time t , t = time when revenue or cost occurs, T = is the time period of perpetual future rotations after the initial standing timber is harvested, and r = real discount rate.

$$CO_2 = 0.5 * CS \left(\frac{44}{12} \right) \quad (A.2)$$

For calculating the equivalent CO₂ content where *CS* is the carbon storage.

$$PC = -11.025 + 2.3953 * \ln(V) \quad (A.3)$$

For calculating the logging cost correction to stumpage price where *PC* is the price correction, €m⁻³ and *V* is total stem volume harvested, m³ ha⁻¹.

Appendix B

Table B1. Real stumpage and cost input values^a

Stumpage Category	Price
Spruce Logs above bark (€m ⁻³)	58.81
Birch Logs above bark (€m ⁻³)	46.69
Spruce Pulp above bark (€m ⁻³)	22.29
Birch Pulp above bark (€m ⁻³)	15.79
Cost Item	Cost
Regeneration (€ha ⁻¹)	1200.00

a. All prices and costs are based on real averages over 2004-2013 using data from Finnish Yearbook of Forestry (2013) price and cost data and Statistics Finland (2013) Consumer Price Index data.

Appendix C. Supplementary Information

Supplementary information for this article can be found at XX.

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