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Analysis

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

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ABSTRACT

Accounting for carbon storage and the albedo effect through Payments for Ecosystem Services (PES) or mandatory offset permits aims to internalize the environmental externalities of forest management. This can shift the economically optimal rotation age, and incorporate rents for a wider range of ecosystem service offerings. A mixed stand economic optimization model was used to determine the optimal stand mixture and inter-species climate regulation trade-offs. Mixed forest dynamics between deciduous silver birch (*Betula pendula* Roth.) and coniferous Norway spruce (*Picea abies* Karst.) were evaluated. The sensitivity of our results to the absolute species-specific differences in albedo parameter values was also conducted. Results indicated that a synergistic climate regulation trade-off between the two species exists. The optimal rotation for the combined carbon storage and albedo effect was equivalent to that of the carbon storage only case. Differences in absolute albedo impacts were most sensitive at high discount rates, for 'climate only' management, and over increasing offset prices. These results demonstrate the importance of parameter certainty in the promotion of PES in forestry. They also show that mixed stands can promote more efficient trade-offs between forest ecosystem service offerings and provide a basis for diversifying between ecosystem functions.

## 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) (i.e. Bonan et al., 1995; Bonan, 2008; Brovkin et al., 1999; Penman et al., 2003; Lukes et al., 2013). They can result in positive or negative radiative forcing dependent on the type and magnitude of the changes.[1] 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 service (ES) offerings are vital components of the global biogeochemical and biogeophysical processes related to the carbon cycle and the albedo effect[2] (i.e. Bonan, 2008; Canadell and Raupach, 2008; Anderson et al., 2011; CICES, 2013). 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 (i.e. Chapin et al., 2000; Burton et al., 2006; Anderson et al., 2011).

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 a Payments for Ecosystem Services (PES) scheme or mandatory offsetting for climatic impacts that are measured in carbon dioxide equivalent units (i.e. Betts, 2000; Thompson et al., 2009b; Bright et al., 2011; Matthies et al., 2015, 2016). 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. To differentiate PES from mandatory offsetting, Wunder (2005, 2015) define PES as voluntary transactions with at least one buyer and one ES provider who meet the conditionality principle (i.e., service provider secures service provisioning of a well-defined ES). Thompson et al. (2009b) note that accounting in carbon dioxide equivalent units also helps to more holistically ensure the additionality of climatic benefits above what would have occurred without management intervention (Cathcart and Delaney, 2006).

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[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.

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The carbon dioxide equivalent units approach has been used by Thompson et al. (2009a); Betts (2000) and others in evaluating the most efficient and effective forest management for climate mitigation. Thompson et al. (2009a) considered the differences between coniferous and deciduous species when maximizing economic rents from climate regulation (e.g., albedo effect and carbon storage) ES and traditional provisioning ES (e.g., sawlogs and pulpwood). Still, they only considered one monoculture of a given species replacing another monoculture through reforestation and not mixed forests. Lutz and Howarth (2014, 2015) have also calculated the optimal rotation age with considerations for the albedo effect and different albedo pricing methods, 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 and comparing that model to other approaches. Therefore, the impact of species-specific albedo parameter differences on optimal economic rotation for mixed deciduous and coniferous stand management has not been covered by any previous studies.

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. Betts and Ball (1997) have noted that, due to the numerous factors that underlie differences in forest albedo, species mixtures can result in differing stand albedo values. Kuusinen (2014) noted that temporal and spatial variation in the albedo effect for mixed stands is a result of differences in species composition, snow cover, and stand and understory structure. This study looks at the impacts of inter-species parameter differences for the albedo effect in a mixed silver birch (*Betula pendula* Roth.) and Norway spruce (*Picea abies* Karsten) boreal forest stand. We incorporate the albedo effect within a tradable permits scheme using carbon dioxide equivalent units following Betts (2000). The scheme is similar to the New Zealand Emissions Trading Scheme (NZ ETS) that uses the international carbon offset price from the European Union Emissions Trading Scheme (EU ETS) to determine forest owner compensation and incentivize climate change mitigation (Jiang et al., 2009). Due to differences in the species-specific albedo parameter estimates between studies, we consider the sensitivity of absolute differences in mixed stands (Kuusinen, 2014). By varying input parameters, the following results were calculated: (1) the optimum rotation ages and species mixtures, (2) the economic returns, and (3) the trade-offs between carbon storage and the albedo effect.

## 2. Climate Change Interactions and Species Mixtures in Boreal Stands

Boreal forests are important stores of carbon, but generally have lower marginal rates carbon sequestration than those in the temperate or tropical zones (Anderson et al., 2011). This is the result of geographically determined lower temperature and sunlight levels 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 (e.g., Betts, 2000; Manninen and Stenberg, 2009; Bright et al., 2011).

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 the stand for a longer time period. When the average carbon stock is increased, then sequestration and storage represent an alternative cooling effect through longer rotations. Various authors have shown that by incorporating the albedo effect of boreal forests into global land use models, previous and current LULUC 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 in boreal forestry 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 effect 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.

In the boreal forest, higher albedo from snow through an opened canopy and deciduous species relative to coniferous species results in a higher albedo for monoculture deciduous than monoculture coniferous stands (Eugster et al., 2000; Gardener and Sharp, 2010; Bright and Kvalevåg, 2013; Lukes et al., 2013; Kuusinen et al., 2014). These differences have also been suggested to lengthen the optimal economic rotation of a mixed or monoculture deciduous stand relative to a monoculture coniferous stand with the same climatic management considerations (Thompson et al., 2009a). The share of mixed forests in Northern Eurasia, consisting of mixed coniferous needle and deciduous broadleaf species, has been estimated as 22% (Sulla-Menashe et al., 2011). In Finland, the share of mixed conifer-broadleaf forest was 13.9% in 2009–2013 (FSYF, 2014). Therefore, this inter-species difference in climatic impacts is an important consideration for guiding climate-oriented forest management decisions.

In addition to climatic benefits, previous studies have noted a wide range of other costs and benefits associated with mixed boreal stands. Chen and Klinka (2003) and Fahlvik et al. (2011) found that growth, yield, and expected economic returns 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), found that total yield in mixed stands was actually 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 be lower than for a monoculture forests. Valsta (1986, 1988) dynamically optimized 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. Bright et al. (2011) also note that evidence (e.g., Lieffers and Beck, 1994; MacDonald, 1995; Burton et al., 2006) suggests that there are economic benefits from allowing for initial deciduous succession through natural regeneration in the boreal forest management. Given the wide variation 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. Mixed forestry also provides regulating and supporting ES that sustain biological diversity (e.g., Fries et al., 1997; Wallrup et al., 2006; Felton et al., 2010). 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.