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Effects of wood harvesting and utilisation policies on the carbon balance of forestry under changing climate: a Finnish case study

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ABSTRACT

We studied the effects of different wood harvesting and utilisation policies on the carbon balance and economic profitability of forestry under the current and changing climate (A1B climate scenario). Sixty-year carbon balance was calculated for two Finnish boreal case study areas, one dominated by Scots pine and the other by Norway spruce. Carbon balance included changes in the carbon pools of living forest biomass (above- and below-ground), dead organic matter and wood products, as well as carbon releases from harvesting, transporting and manufacturing. Substitution effects of using biofuel instead of fossil-fuels were also taken into account. Business-as-usual (baseline) management policy (even-aged forestry: thinning from below, harvesting timber for wood-based products from thinning and final felling) and five other management policies were applied by changing the timing and type of thinning and the utilisation of harvested trees. Net present value (NPV, 2%) and carbon balance were maximised with even-flow net income constraints. In both case study areas, postponing the thinning of young stands and using thinning from above improved carbon balance and NPV. The use of pulpwood, logging residues and stumps as biofuel also increased carbon balance. Climate warming improved carbon balance and NPV when harvests were not increased from those under the current climate.
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1. Introduction

The greenhouse gas (GHG) concentration of the atmosphere, and especially carbon dioxide is expected to increase significantly in the future. In northern Europe, the mean annual temperature is projected to increase by 3–6 °C and precipitation by 11–18% by 2100, depending on the climate scenario used for the GHG concentrations (IPCC, 2013). However, sustainable forest-based bioeconomy may play an important role in climate change mitigation in forested areas like Northern Europe.

When analysing the carbon balance of forestry, changes in the carbon pools of growing stock (living above- and below-ground forest biomass), dead organic matter (soil carbon) and wood-based products should all be taken into account, as well as the energy consumption of wood harvesting, transporting and product manufacturing (Malmsheimer et al., 2011; Verified carbon standard, 2013; Pukkala, 2014). The carbon pools of forest biomass are affected by regeneration, growth and mortality of trees (e.g. Pukkala, 2004; Kellomäki et al., 2008). The carbon pools of soil organic matter are affected by the mortality of trees, litter production, residuals of harvested trees and decomposition of organic materials (e.g. Kellomäki et al., 2008; Liski et al., 2009) whereas the carbon pools of wood products (including fuel feedstock) depend on harvested assortments, releases of harvesting, transporting and manufacturing and life cycles of products (e.g., Skog and Nicholson, 1998; Petersen and Solberg, 2005). Recycling waste paper and using wood from demolished buildings as fuel feedstock improves the carbon balance because emissions from fossil fuels are reduced (Werner et al., 2010).

The carbon balance of forestry may be improved for instance by increasing the carbon stocks of forest ecosystems and wood-based products through modifying forest management and utilisation of wood (Skog and Nicholson, 1998; Lim et al., 1999; Liua and Hana, 2009; Kilpeläinen et al., 2015). Further, using forest biomass for energy (e.g. biofuels) would reduce emissions from the use of fossil fuels (Werner et al., 2010). It is also possible to reduce carbon releases of forest industries by decreasing the capacity of energy-intensive mechanical pulping (grinding or refining) and by increasing the use of construction wood to substitute concrete and steel (Petersen and Solberg, 2005; Sathre and Gustavsson, 2009, 2012; Sathre and O'Connor, 2010; Malmsheimer et al., 2011; Börjesson et al., 2014; Haus et al., 2014).

The use of thinning from above instead of thinning from below has been shown to improve the carbon balance of forestry because it increases the share of saw logs in removed volume (e.g. Liski et al., 2001; Pukkala, 2011, 2014; Pukkala et al., 2011). Increasing the use of pulpwood and especially spruce pulpwood as fuel feedstock instead of pulping it also improves the carbon balance of Finnish forestry. Most

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spruce pulpwood goes to mechanical pulping, which consumes more energy than chemical pulping (Liski et al., 2001; Lundmark et al., 2014).

Under the foreseen climate warming, the carbon balance of forestry is expected to improve in boreal conditions due to the increased growth rate of trees (Karjalainen et al., 2003). Nonetheless, Norway spruce (*Picea abies*) may suffer from drought especially in the most southern parts of boreal zone on soils with relatively low water holding capacity (Kellomäki et al., 2008; Ge et al., 2013). Increasing temperature may also accelerate the decomposition of cutting residues and soil organic matter, increasing carbon emissions to the atmosphere (e.g. Kirschbaum, 1995; Keyser et al., 2000; Garcia-Gonzalo et al., 2007; Russell et al., 2014).

To integrate the effects of climate change in the optimised forest management, Pukkala and Kellomäki (2012) developed growth trend functions for empirical growth models, based on process-based model simulations. There have also been other attempts to integrate the impacts of climate change (e.g. changes in temperature, precipitation and atmospheric CO_2) in empirical growth and yield models (Matala et al., 2005, 2006; Crookston et al., 2010). Process-based growth models have also been used directly in optimisation studies (Hyytiäinen et al., 2004; Niinimäki et al., 2013). The effects of climate change on the decomposition of cutting residues and soil organic matter may be taken into account by using climate-sensitive decomposition models, such as the Yasso07 model (Liski et al., 2009; Tuomi et al., 2011a,2011b).

The aim of this study was to identify the effects of different wood harvesting and utilisation policies on the carbon balance and economic profitability of forestry under the current and changing climate in two Finnish boreal case study areas, of which one was dominated by Scots pine and the other by Norway spruce. We considered changes in the carbon pools of living forest biomass, dead organic matter and wood products, carbon releases of harvesting, transporting and manufacturing, and reduced carbon emissions due to the use of construction wood and forest biomass-based fuels instead of fossil-intensive materials and fuels. The calculations were done for the current climate and assuming a gradual climate change (A1B climate scenario, see Jylhä et al., 2009). Business-as-usual (baseline) management scenario was used as the starting point, defined to be even-aged forestry, applying thinning from below and harvesting timber only for wood-based products from thinning treatments and final fellings. In addition, five alternative management scenarios were applied, in which the timing and type of thinning and utilisation of forest biomass were varied. We assumed that, compared to the baseline scenario, each of the following measures would improve carbon balance: i) using spruce pulpwood as fuel feedstock; ii) postponing the thinning of young stands; iii) replacing thinning from below by thinning from above, iv) using the pulpwood of pine and broadleaf species as fuel feedstock, and v) collecting logging residues of clear-felling sites for fuel feedstock. These changes were implemented one at a time, making it possible to quantify the effect of each change separately. The effects of using pulpwood for energy production were analysed separately for spruce and other species, assuming that changing the use of spruce pulpwood would have a greater influence on carbon balance than changing the use of pulpwood from other species. Net present value and carbon balance of forestry were maximised in each scenario with even-flow net income constraint.

2. Material and methods

2.1. Simulation of treatment schedules for stands

The Monsu simulation-optimisation tool (Pukkala, 2004) was used to analyse the effects of different wood harvesting and utilisation policies on the carbon balance and economic profitability of forestry under the current and changing climate. Monsu simulated the stand development in alternative treatment schedules, calculated the carbon balance of each schedule and finally determined also the optimal combination of simulated treatment schedules. The first case study area was dominated by Scots pine (*Pinus sylvestris*) and broadleaf species (henceforth referred to as pine-dominated forest) and another by Norway spruce (spruce-dominated forest) (Table 1).

The effects of climate change were implemented in growth simulations of Monsu using the species- and site-specific growth trend functions (growth multiplier functions) built by Pukkala and Kellomäki (2012). They were based on simulations by the process-based FinnFor model (Kellomäki and Väisänen, 1997). These functions can be used for Norway spruce, Scots pine and silver birch (*Betula pendula*) for their typical growing conditions in central Finland (62°40′N, 29°38′E, 94 m asl., 1050 d.d.) when assuming that the annual mean temperature increases by 4 °C, the annual precipitation increases by 10% and the atmospheric CO_2 concentration doubles by year 2100 (see the SRES A1B climate change scenario of the CMIP3 climate projection, see IPCC, 2007; Jylhä et al., 2009). The increase in tree diameter increment, as predicted by the growth trend functions related to climate change scenario, ranged from 0.27 to 0.52% per year for different tree species (see Pukkala and Kellomäki, 2012).

In addition to the business-as-usual (baseline) management scenario with thinnings from below and harvesting timber only for wood-based products from thinnings and final fellings, five alternative management scenarios were applied, in which the timing and type of thinning and utilisation of forest biomass were varied. In each scenario, alternative treatment schedules were simulated for every stand to obtain the decision space for optimisation. The total number of treatment scenarios ranged from 2467 to 5989, depending on the scenario.

Stand development in alternative treatment schedules was simulated for three consequent 20-year periods (60 years in total) using both the current climate and gradually changing climate. The currently recommended thinning thresholds (stand basal area that activates the thinning treatment) and average diameter at breast height (dbh) required for final felling (Äijälä et al., 2014) were used to define the earliest possible time of thinning and final felling. Other treatment schedules were obtained by postponing the thinning and final felling from their earliest possible time. A no-cutting schedule was also simulated for each stand. As a result, each stand had several alternative treatment schedules for the coming 60-year period. The simulation was repeated for each management scenario (Table 2), resulting in six sets of alternative treatment schedules for each stand.

All simulated treatment schedules represented even-aged management. Clear felling followed by planting was used on mineral soils, except in Scots pine on sub-xeric and poorer sites where natural regeneration with seed trees was used instead. Thinning from below (TB) was used in three management scenarios (Table 2). The other three alternatives used thinning from above (TA). In both thinning types (TB and TA) half of the removed basal area was harvested uniformly from all diameter classes (using the same thinning intensity in every class) and the rest was harvested from the smallest (TB) or largest (TA) diameter classes.

Table 1
Characteristics of the two boreal case study areas located in eastern Finland (North Karelia).

Case study areas	Pine-dominated forest (Vaivio)	Spruce-dominated forest (Koli)
Forest area, ha	950	1117
Forest biomass (above and below ground) stock, tonnes ha $^{-1}$	88	150
▪ Scots pine (%)	48	30
▪ Norway spruce (%)	9	47
▪ *Betula* sp. (%)	43	17
▪ Others broadleaves (%)	1	6
Total carbon stock, tonnes ha $^{-1}$	191	359
▪ Trees	41	65
▪ Mineral soils	150	294

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