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Effects of management on biomass production in Norway spruce stands and carbon balance of bioenergy use

Piritta Pyörälä *, Seppo Kellomäki, Heli Peltola

University of Eastern Finland, Joensuu Campus, FI-80101 Joensuu, Finland

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A B S T R A C T

In this study, we analyzed the effects of management on the production of timber and energy biomass, and ecosystem carbon balance in Norway spruce (*Picea abies*) stands, with impacts on carbon neutrality of the use of biomass in energy production. In simulations, we employed the ecosystem model and life cycle analyses tool with varying management scenarios (thinning, nitrogen fertilization and rotation length) on medium fertile and fertile sites in central Finland. We found that the annual mean timber production could be increased by using longer rotation lengths of 60–80 years. This was opposite to energy biomass production, which was increased the most by using shorter rotations of 30–50 years. On the other hand, both of them could be increased by applying nitrogen fertilization and by maintaining higher stocking over the rotation compared to the current Finnish baseline management. This positively affected both the carbon storage and carbon balance in forestry, as well as the energy carbon balance which takes into account both carbon balance for forestry and the CO_2 emissions from the burning of energy biomass. It also decreased the CO_2 emissions per unit of energy by approx. 30% compared to baseline management, regardless of site fertility type. Similarly, the carbon neutrality of the bioenergy system could be increased in this way compared to the use of coal instead. To conclude, based on proper management it will be possible to increase simultaneously the production of timber and energy biomass, and carbon stock in the forest ecosystem and to improve the forest ecosystem carbon balance so that in the long-term the CO_2 uptake will exceed concurrent emissions.

1. Introduction

The target of the European Union is to reduce its greenhouse gas emissions and increase the share of renewable energy by 20% until 2020 in order to decrease the use of fossil fuels, and thus mitigate climate change. In Finland, the target is to produce, by 2020, up to 38% of consumed energy based on the use of renewable sources, such as forest biomass. In this respect, the role of forest biomass is crucial, because currently about 80% of Finnish renewable energy production is based on wood (Finnish Statistical Yearbook of Forestry, 2011). By the year 2020, the Finnish target is to use forest chips from 8 up to 13.5 million $m^3\ a^{-1}$, when the current use of forest chips is about 6.9 million $m^3\ a^{-1}$ (Finnish Statistical Yearbook of Forestry, 2011). Currently, about 60% of energy biomass, including the top part of stems, branches, stumps and coarse roots, is harvested from final felling related to timber harvest (i.e. pulpwood and saw logs). This makes the harvest and logistics of energy biomass cost-effective. The rest of it consists of small sized trees, which are harvested mainly by tending of seedling stands and energy wood thinning with relatively high harvesting costs. The technical harvesting potential of forest chips is about 16 million $m^3\ a^{-1}$ (Helynen et al., 2007).

The current Finnish forest management guidelines emphasize timber production, because its profitability for forest owners is much higher than that of energy biomass, especially with no subsidies for energy biomass. However, there is a need to increase integrated production of timber and energy biomass over rotation in order to meet the targets given for forest based bioenergy. Currently, wide spacing in planting and thinning will enhance the growth of trees with earlier achievement of dimensions of timber than if narrow spacing is preferred. This implies a lower stocking and reduced potential growth of biomass in tree stands, and the consequent reduction in accumulation of carbon in trees and soil compared to stands with narrow spacing and higher stocking regardless of rotation length. On the other hand, the forest growth in Finland is limited on sites with lower fertility by the scarce supply of nitrogen, which makes the tree growth very responsive to nitrogen fertilizing (Tamm, 1991). The fertilization may also be needed to compensate for the loss of nutrients removed in energy biomass harvesting.

* Corresponding author. Address: Faculty of Science and Forestry, School of Forest Sciences, University of Eastern Finland, Joensuu Campus, FI-80101 Joensuu, Finland. Tel.: +358 0294451111; fax: +358 132513634.

E-mail addresses: piritta.pyorala@uef.fi (P. Pyörälä), seppo.kellomaki@uef.fi (S. Kellomäki), heli.peltola@uef.fi (H. Peltola).

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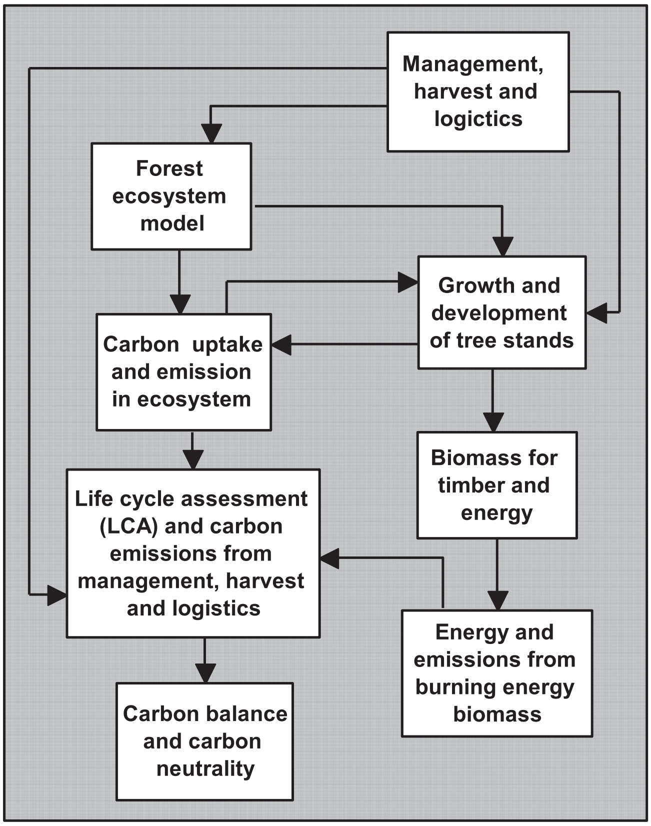

Fig. 1. Outlines of model based analyses by the forest ecosystem model (SIMA) and the life cycle assessment (LCA) tool.

The growth of trees and harvesting of forest biomass and concurrent changes in carbon stock in trees and soil over a rotation affect the ecosystem carbon balance, i.e. the balance between CO_2 uptake in trees growth and decomposition in the soil. Similarly they affect the potential to use forests in mitigating climate change. Recently regenerated stands and old stands lose carbon due to larger CO_2 emissions from soil in regard to uptake in growth. The opposite is true in young stands of pole stage and stands of intermediate age, where the carbon uptake in growth exceeds that emitted from soil (e.g. Liski et al., 2001). On the other hand, the use of forest biomass as a substitute for fossil fuels in energy production and the wood-based products affect the potential of forests in mitigating climate change. Therefore, there is a clear need to modify the current management recommendations (i.e. spacing, thinning, and nitrogen fertilization and rotation length). In this way, it can be increased simultaneously the carbon sequestration in the forest ecosystem and provided in a sustainable way timber and energy biomass for different purposes (Eriksson et al., 2007; Routa et al., 2011a,b,c). Higher stocking through the rotation than that currently recommended may be needed to increase the carbon stock and carbon uptake in the forest ecosystem, as well as production of timber and energy biomass (Alam et al., 2011).

The energy based on forest biomass is carbon neutral in the long term (IPCC, 2000; Schlamadinger et al., 1995), if only the direct CO_2 emissions are considered. In the short term, CO_2 and other greenhouse gases (GHG) are emitted in management, harvesting and logistic operations related to supply and use of forest biomass in energy production. Therefore, the carbon neutrality of renewable biomass has been questioned due to large indirect emissions of CO_2 and other GHG in different phases of the biomass supply (e.g. Melillo et al., 2009; Melin et al., 2010; Repo et al., 2011; Searchinger et al., 2008). In assessing the carbon neutrality of forest biomass in energy production, there is a clear need to consider all the direct and indirect emissions from management and logistic operations used in supplying biomass for energy plants. This makes it also possible to estimate how much CO_2 and other GHG are emitted per energy unit in comparison to the use of fossil fuels such as coal.

In the boreal conditions, forestry is characterized by a long production cycle from regeneration to final harvest. Traditionally, long-term experiments have been used in developing management practises. However, the simulations by forest ecosystem models offer an option to study the sensitivity of growth and dynamics of forests to management (e.g. choice of tree species/genotypes and spacing, thinning and fertilization and rotation length) under varying environmental conditions. Based on model simulations, life cycle assessment (LCA) can concurrently be used to study the sensitivity of CO_2 balance to management, considering the material and energy requirements and emissions to the air, water and soil over the whole life cycle (Kilpeläinen et al., 2011). Similarly, benefits and drawbacks for the use of forest biomass for energy production can be estimated, including its carbon neutrality.

In the above context, the aim of this study was to study how the management affects the production of timber and energy biomass, and carbon balance in the forest ecosystem dominated by Norway spruce (*Picea abies*). The study utilized a forest ecosystem model together with the life cycle assessment (LCA) tool to analyze the impacts of management on carbon neutrality of the use of biomass in energy production. More specifically, we studied the effects of management in terms of thinning, nitrogen fertilization and rotation length on: (i) the production of timber and energy biomass, and carbon sequestration in forest ecosystem, and (ii) the CO_2 emissions over the biomass supply chain when using forest biomass in energy production to replace the use of fossil fuels like coal. Based on this, we evaluated also the potentials provided by forest management in reducing the CO_2 emissions per energy unit based on the use of forest biomass in energy production. Compared to the previous studies, for example, by Routa et al. (2011a,b,c), we evaluated first time simultaneously the effects of management on biomass production in Norway spruce stands and carbon neutrality of bioenergy use in energy production. In this context, we will also study how the maintaining of higher stocking over a rotation affects the biomass production potential and CO_2 emissions from the combustion of energy biomass, using also shorter rotation lengths (with a range from 30 to 80 years) compared to the previous studies.

2. Material and methods

2.1. Outlines of the ecosystem model

A gap-type forest ecosystem model SIMA was used to simulate the growth and dynamics of tree stands as affected by environmental (climate and site) conditions and management (see Kellomäki et al., 2005, 2008) (Fig. 1). In the model, the growth of a tree is calculated based on diameter growth, which is the product of potential diameter growth in optimal conditions and prevailing climatic and site conditions (i.e. temperature sum, within-stand light, soil moisture and nitrogen availability and atmospheric CO_2). The death of the trees is determined by the competition between trees for growth resources with the consequent reduction in the growth, which determines the risk for a tree to die at a given year. Litter and dead trees end up on the soil to be decomposed, with the release of nitrogen in the long run. The dynamics of available nitrogen for trees is determined by the amount of nitrogen released and immobilized in the decomposition of the soil organic matter.