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Research paper

Effects of intensive forest management on net climate impact of energy biomass utilisation from final felling of Norway spruce

Antti Kilpeläinen*, Ashraful Alam, Piritta Torssonen, Hanna Ruusuvuori, Seppo Kellomäki, Heli Peltola

University of Eastern Finland, School of Forest Sciences, P.O. Box 111, 80101 Joensuu, Finland

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ABSTRACT

The main objective of this work was to study the effects of intensive forest management on net climate impact of energy biomass (logging residues and/or stumps and coarse roots) utilisation from final felling of Norway spruce (*Picea abies* L. Karst) grown on medium-fertile site under boreal conditions in Finland. We employed forest ecosystem model simulations and a life cycle assessment (LCA) tool to calculate net CO_2 exchange for utilising biomass in biosystem and coal in fossil system. In the biosystem, baseline management (business as usual, BT) and management with maintaining 30% higher stocking in thinning than in the BT regime were used. In addition, nitrogen fertilisation and improved planting material both alone and as combined were used to enhance growth in order to assess effects of intensive management on net climate impact. Carbon neutrality of biomass utilisation under alternative management was compared with the utilisation of coal. We found that the carbon neutrality of biomass utilisation varied between 0.5 and 3.4 (i.e. from partial to full neutrality), depending on the management applied. Under intensified management, CO_2 emissions associated with energy biomass utilisation could be offset by forest ecosystem carbon sequestration over the following 20 years. Under the BT regime, such compensation could not be fully achieved over the rotation, but the utilisation of biomass produced less emissions per unit of energy than the use of coal. From a climate change mitigation point of view, the intensive management of Norway spruce could increase the climate benefits of energy biomass utilisation.

1. Introduction

Substitution of fossil energy and materials with renewable forest-based biomass may help to slow down both the rise in atmospheric carbon dioxide (CO_2) concentrations and the subsequent increase in radiative forcing and climate warming [1]. However, the temporal scale of carbon emissions into the atmosphere from biomass products can vary from immediate release (i.e. combustion of energy biomass) to decades or centuries (e.g. wood products with long life cycles), which affects any emission decrease associated with such mitigation measures. In biomass (logging residues: needles, branches, roots and stumps) combustion, the amount of CO_2 released into the atmosphere may be higher than for fossil fuel per unit of energy because of lower energy content (and higher moisture content) of biomass. This can temporarily increase the amount of carbon in the atmosphere at the start of using energy biomass compared to fossil fuels. However, over a longer period, the net climate impacts associated with the utilisation of energy biomass can be altered by a balance between carbon uptake and emissions related to functioning and management of forest ecosystem.

In Nordic countries such as Finland and Sweden, main part of biomass harvested directly for energy purposes consists of logging residues (i.e. needles, branches, roots and stumps) derived from final fellings. The use of such biomass for energy reduces the radiative forcing in comparison to that of fossil fuels (e.g. Refs. [2–3]), but the CO_2 benefits associated with logging residues and stumps are apparent within 10–25 years [4]. Mitigation efficiency is also affected by the type of energy biomass and fossil fuel to be substituted. For example, the climate benefit achieved in using energy biomass is smaller if substituting for natural gas than for coal. Thus, when evaluating the CO_2 emission and climate change mitigation potentials of forest-based biomass utilisation,

* Corresponding author.
E-mail address: antti.kilpelainen@uef.fi (A. Kilpeläinen).

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time-dependent fluxes of carbon uptake and emissions, as well as the residence time of carbon in the atmosphere, play a key role [5–9].

The climate change mitigation potential of forestry is affected by both the sequestration of atmospheric carbon and its storage in trees and soil, and the substitution of fossil energy and fossil-based materials with energy biomass and timber. In the short term, carbon sequestration, as well as biomass production and utilisation potential, could be increased in boreal forests by maintaining a higher stocking over rotation than currently recommended for timber production [10]. The use of nitrogen fertilization, will also enhance forest growth in northern Europe (e.g. Ref. [11–15]). This also allows shortening of rotation length and increases economic profitability of forest biomass production [2,16–19]. The effect of nitrogen fertilization on carbon sequestration of forests depends on both the dose of the nitrogen addition and the site fertility (e.g. Refs. [20,10]). In the longer term, carbon sequestration and biomass production could be increased by site-specific tree species choice and using improved seedlings with increased growth rate in planting ([16,21]). From the viewpoint of a forest owner, the economic profitability of forestry is determined especially by saw wood production. This favours the use of a rather long rotation length (i.e. 60–120 years) in boreal conditions.

The main objective of this work was to study the effects of intensive forest management on net climate impact of energy biomass (logging residues and/or stumps and coarse roots) utilisation from final felling of Norway spruce (*Picea abies* L. Karst) on medium-fertile site under boreal conditions in Finland. We employed forest ecosystem model simulations and a life cycle assessment (LCA) tool to calculate net CO_2 exchange for utilising energy biomass in biosystem and coal in fossil system. In the analysis, carbon neutrality of energy biomass utilisation under alternative management regimes was compared with the utilisation of coal. In the biosystem, baseline forest management (business as usual, BT) and management with maintaining 30% higher stocking in thinning over rotation than in the BT were used. In addition, nitrogen fertilisation and improved planting material both alone and as combined were used to enhance growth in order to assess effects of intensive management on net climate impact.

2. Materials and methods

2.1. Outlines for the calculation of net climate impact

Net climate impact refers to the difference in net carbon dioxide (CO_2) exchange between the biosystem and fossil system, regarding the combustion and ecosystem net CO_2 exchange (NEE) (Fig. 1). In the analysis, biosystem refers to an energy system, which uses only forest energy biomass, while fossil system refers to an energy system using only coal in heating. Energy biomass (logging residues includes top of stem, branches, 70% of needles, stumps and coarse roots) in the biosystem was replacing fossil fuel (coal) in the fossil system at the beginning (first year) of the study period (Fig. 1). When fossil energy is utilised, logging residues are left on site to decay, emitting carbon gradually to the atmosphere. In the biosystem, carbon is cycled through the atmosphere/biosphere; in the fossil system, carbon is removed from geological storage and emitted into the atmosphere when combusted as energy.

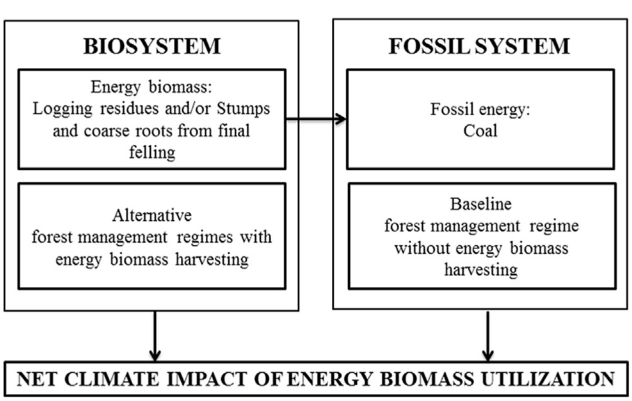

Fig. 1. Schematic figure of the system boundaries of the study.

When comparing these two systems, the quantity of energy was assumed equal at the beginning of the study period in both systems and was based on the harvested amount of energy biomass from the final felling. After the combustion of energy biomass in biosystem or coal in fossil system at the beginning of the study period, the net CO_2 exchanges were analysed annually for both systems over the stand rotation. The net climate impact considered only the impact of energy biomass utilisation, excluding substitution benefits associated with saw logs and pulpwood used for wood-based material. Different harvest intensities were used for energy biomass, i.e. logging residues were harvested with or without stumps and coarse roots (Fig. 1).

In the fossil system, baseline (business as usual, BT) forest management used in Finland was utilized as a reference regime (see Refs. [22,23]). In the biosystem, alternative management regimes deviating from baseline management were used to study the sensitivity of net ecosystem CO_2 exchange (NEE) to intensified forest management regimes. Energy content used for energy biomass (dry biomass) was 11.6 GJ Mg^{-1} [24,25], and the CO_2 mass emission factor used for coal was 93.3 kg GJ^{-1} [26].

2.2. Calculation of climate impacts for alternative management regimes

The well validated forest ecosystem model SIMA [10,27–30], was used in the present study to simulate carbon sequestration and forest biomass production in pure Norway spruce (*P. abies* L. Karst) stands on medium fertile sites (MT, *Myrtillys* type) in central Finland (62°39′ N, 29°37′ E). Carbon sequestration (in trees and soil) and forest biomass production (timber, energy biomass) of stands were controlled by the environmental conditions (temperature sum, availability of light, soil water and nitrogen, and atmospheric CO_2 concentrations) and forest management. In the simulations, organic matter in litter and dead trees ended up in the soil, where they decayed, releasing CO_2 and nitrogen. In decomposition, carbon emissions originated from new litter and old litter and humus on the site. The initial soil organic matter (SOM) was 67 Mg per hectare (i.e 1 ha = 10^4 m^2) for the site, represented the mean values obtained from the Finnish National Forest Inventory plots [29]. New litter and humus represented the SOM originated during the simulations. The dynamics of available nitrogen is determined by the amount of nitrogen released and immobilized in the decomposition of soil organic matter. Annual nitrogen deposition was set at 10.0 kg ha^{-1} [31]. The decomposition rate parameters for the litter and humus of Norway spruce are shown in Ref. [32].

In the model, management included planting (with desired spacing), use of better growing seedlings, thinning, nitrogen fertilisation and final felling. The timing, intensity and frequency of thinning over each rotation were determined based on given thresholds for a basal area (the cross-sectional area of the stems of all trees in a stand) as a function of dominant stand height. In thinnings, only timber (saw logs and pulp wood) was harvested, and in final felling, timber and energy biomass (branches, needles,