Biomass and Bioenergy 98 (2017) 291–305

Contents lists available at ScienceDirect

Biomass and Bioenergy

journal homepage: http://www.elsevier.com/locate/biombioe

Research paper

Net climate impacts and economic profitability of forest biomass production and utilization in fossil fuel and fossil-based material substitution under alternative forest management

T.K. Baul [a, b, *], A. Alam [a], H. Strandman [a], A. Kilpeläinen [a]

[a] University of Eastern Finland, Faculty of Science and Forestry, School of Forest Sciences, P.O. Box 111, FI-80101 Joensuu, Finland
[b] University of Chittagong, Institute of Forestry and Environmental Sciences, Chittagong, Bangladesh

ARTICLE INFO

Article history:
Received 9 August 2016
Received in revised form
23 December 2016
Accepted 9 February 2017

Keywords:
Carbon dioxide
Climate impact
Economic profitability
Energy biomass
Life cycle assessment
Substitution
Timber

ABSTRACT

We studied net climate impacts and economic profitability of the production and utilization of biomass from a Norway spruce (*Picea abies* L. Karst) stand under alternative forest management in Finnish boreal conditions over 60–100-year rotations. The work employed ecosystem model simulations and a life cycle assessment tool as integrated. The net climate impact of biomass referred to the difference in annual net CO_2 exchange between the biosystem and fossil system. Sawn wood, pulp, energy biomass and processing waste substituted for concrete/steel, plastic and coal/oil. In the biosystem, 'business as usual' (baseline) and alternative management (maintaining 10–30% higher or lower stocking than the baseline, and/or nitrogen fertilization, and harvesting intensity) were used. The fossil system considered baseline and unthinning as reference management and also net ecosystem CO_2 exchange as excluded. We found that using timber and energy biomass generated 32–40% higher net climate impacts compared to using only timber. Generally, harvesting of energy biomass increased the economic profitability but the net climate impacts of biomass were highest over 80–100-year rotations. Maintaining higher stocking in thinning and fertilization generally enhanced net climate impacts, but maintaining up to 20% higher stocking and both energy biomass and timber production increased both net climate impacts and economic profitability. The baseline as a reference produced higher climate benefits compared to unthinning regime. The increased production and use of sawn wood with energy biomass appeared the best option for long-term mitigation, since they enhanced both net climate impacts compared to the fossil system and economic returns.

1. Introduction

The policy of the European Union (EU) aims at achieving substantial reductions in greenhouse gas emissions to limit global temperature rise [1]. Accordingly, at least 20% of EU total energy consumption should be generated from renewables by 2020, of which 47% will be from wood and wood based biomass [2]. The use of biomass for heating and cooling is expected to constitute 80% of total renewable heating/cooling and 19% of total renewable electricity by 2020 in EU countries, as documented in the National Renewable Energy Action Plans (NREAPs) [3]. In the Nordic countries, such as Finland and Sweden, the role of forests for enabling the use of bioenergy and biomass to substitute for fossil-based materials is emphasized [4,5]. Currently, the largest share of forest biomass in these countries is used in sawing, pulping, and paper industries, not only directly for heating, cooling and power generation [6]. Around half of the biomass used in these industries is finally combusted to generate energy [7].

Substituting fossil fuels with forest bioenergy decreases carbon dioxide (CO_2) emissions and mitigates climate change (e.g. Refs. [8–12]). However, in general, the substitution benefits of biomass depend on the substituted energy and material and are highly dependent on the timing of substitution and lifespan of the biomass products [13–16]. When wood-based products (produced from pulp wood and sawlogs) are used as substitutes for fossil-based materials (e.g. concrete, steel, and plastic), carbon is staying longer in the technosystem stocks than in the case of energy biomass, the combustion of which releases carbon immediately

---

* Corresponding author. University of Eastern Finland, Faculty of Science and Forestry, School of Forest Sciences, P.O. Box 111, FI-80101 Joensuu, Finland.
E-mail address: tarit.baul@uef.fi (T.K. Baul).

http://dx.doi.org/10.1016/j.biombioe.2017.02.007

[13,17]. Thus, wood-based products will play a great role in mitigating climate change (e.g. Refs. [18,19]).

When evaluating the net climate impacts of forest biomass utilization, forest-based systems are compared with corresponding fossil systems (e.g. Ref. [20]). The net climate impacts of forest biomasses are regulated by the dynamics of carbon balances both inside and outside a forest ecosystem. Therefore, carbon emissions and sequestration in forest-based systems are also sensitive to alternative forest management and variable at temporal scales. In addition, the climate benefits are dependent on land-use options used in the fossil system (e.g. Ref. [21]). These affect the climate change mitigation potential of forest biomasses, owing to the change in CO_2 in the atmosphere due to both carbon sequestration and substitution of fossil fuels and materials [18,19,22–24].

According to current stand management practices in Finnish forestry, timber (pulp wood and sawlogs) is harvested in thinning and final felling. Energy biomass is mainly harvested from energy wood thinning (small-sized trees) and from final felling as logging residues and/or stumps and roots. Current recommendations for forest management ('business as usual') aim to produce mainly timber, due to its higher profitability compared to the production of energy biomass [25,26]. However, 'business as usual' management could be modified to improve biomass recovery and carbon sequestration in integrated timber and energy biomass production systems [8,27–29]. Maintenance of slightly higher stocking in thinnings than currently recommended may increase timber production, carbon stock in trees and soil and carbon sequestration over rotation [8,27,29–31]. Conversely, too high increase in stocking may reduce total timber production [32]. Rotation periods of forest stands up to 100 years increase carbon storage in forest ecosystems, but shorter rotations (40–60 years) increase the annual production of timber and energy biomass along with economic profitability (e.g. Refs. [33,34]). In addition, nitrogen fertilization and increased harvesting intensity may enhance timber and energy biomass yields, hence increase the economic return of the biomass production [35–37].

In this study, we aimed at investigating the net climate impact and economic profitability (net present value) of the production and utilization of biomass derived from a Norway spruce (*Picea abies* L. Karst) stand on a medium-fertile site under alternative forest management in Finnish boreal conditions over 60–100-year rotations. Net climate impacts were calculated as the difference between annual net CO_2 exchanges between the forest-based biosystem and the fossil system by using an ecosystem model (SIMA) and life-cycle assessment (LCA) tool as integrated. Wood products (pulp and sawn wood) substituted for concrete, steel, and plastic and energy biomass (logging residues, stumps) and processing waste (saw dust, bark, black liquor) substituted for coal and oil. 'Business as usual' management was used as a baseline in the biosystem and also as a reference management in the fossil system. Additionally, the fossil system was considered, with unthinning regime as a reference management and net ecosystem CO_2 exchange as excluded. In the biosystem, alternative management regimes included maintaining 10–30% higher or lower stocking compared to the baseline and/or nitrogen fertilization.

2. Materials and methods

2.1. System boundaries of the study

Net climate impact of producing and utilizing forest biomass was calculated as a difference in the net exchange of carbon dioxide (CO_2) between emissions and sequestration due to the biosystem and to the fossil system in their ecosystem and technosystem parts. The substitution impacts of biomass were calculated by comparing the wood-based products (sawn wood, pulp, energy biomass, processing waste) replacing the fossil-based materials (concrete, steel and plastic) and energy (coal and oil) in the fossil system (Fig. 1). The amounts of used energy (in energy units) and material (in tons, i.e 1 t = 10^3 kg) and the product lifespans in the fossil system followed the counterparts in the biosystem.

Fig. 1 shows the system boundaries with flows of carbon of different materials and energy in the biosystem and the fossil system regarding ecosystem, technosystem and atmosphere. In both systems, 1 ha (i.e 1 ha = 10^4 m^2) of forest land with different forest management was used. The analysis started from a stand which was to be final felled and thereafter three different rotations (60, 80 and 100 years) were used. 'Business as usual' management (BT) [25,26] was used as a baseline in the biosystem. Reference forest managements of the fossil system were 'business as usual' management with only timber production and harvesting (BT_{ref}) and unthinning of forest stand (NT_{ref}). Additionally, the fossil system was considered as the net ecosystem CO_2 exchange excluded (NEE not included). In the latter case, the net climate impacts were calculated only based on current available emission factors for fossil-based materials and energy. The effects of alternative management regimes in the biosystem were used to study the sensitivity of net climate impact to the changes in the biomass production. Alternative reference managements (land-use options) in the fossil system were used to study the sensitivity of net climate impacts to indirect effects of forest management and use of forest biomass to the use of fossil-based materials and energy.

In the biosystem, we assumed that half of the sawlogs produced sawn wood and the rest of the mass consisted of sawing residues (saw dust, bark). The sawn wood substituted concrete (50%) and steel (50%) in the fossil system. Gradual removal of CO_2 from the atmosphere into the concrete material depends on the life cycle of a building [38], and we assumed that 8% of the emissions from cement manufacturing are sequestrated back by concrete (in tons of CO_2). Sawing residues were considered to substitute for coal and oil (50/50%) in heat and electricity generation, respectively. Similarly, half of the amount of pulp wood was used for paper production and substituted plastic products in the fossil system, while the rest (black liquor from the chemical pulping process) was assumed to substitute coal and oil (50/50%) in heat and electricity generation. Energy biomass, including logging residues (top parts of the stems, branches, and needles), stumps and roots harvested in the final felling were combusted and substituted for coal and oil (50/50%) in the fossil system (Fig. 1). We assumed an energy use efficiency of 60% as in heat and power/electricity production.

2.2. Calculation of net climate impact for biomass production and utilization

The net climate impact of forest biomass production and utilization (I) was calculated by comparing the production and utilization of forest biomass in the biosystem (I_{BIO}) to the corresponding fossil system (I_{REF}) in terms of annual net CO_2 exchange (g CO_2 m^{-2} a^{-1}, i.e 1 g = 10^{-3} kg) (Equation (1)). Negative (−) net climate impacts indicate that the forest-based biosystem produces lower emissions and positive (+) net climate impacts indicate that the forest-based biosystem produces higher emissions compared to the fossil system.

$$I = I_{BIO} - I_{REF} \tag{1}$$

where I_{BIO} and I_{REF} are the net CO_2 exchanges of the biosystem and the fossil system, respectively.

The components of I_{BIO} were calculated by using the SIMA ecosystem model [39] and the life cycle assessment tool as