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Time-dependent global warming impact of tree stump bioenergy in Sweden ☆

Carina A. Ortiz [a], Torun Hammar [b], Serina Ahlgren [b], Per-Anders Hansson [b], Johan Stendahl [c,*]

[a] *Statistics Sweden, Regions and Environment Department, Box 24300, Stockholm SE-104 51, Sweden*
[b] *Department of Energy and Technology, Swedish University of Agricultural Sciences (SLU), Uppsala SE-750 07, Sweden*
[c] *Department of Soil and Environment, Swedish University of Agricultural Sciences (SLU), Uppsala SE-750 07, Sweden*

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ABSTRACT

Tree stump harvesting could significantly increase the amount of bioenergy feedstock that forestry can supply to substitute for fossil alternatives. However, the climate mitigation potential of using stumps for bioenergy has been debated due to their often long residence time in the forest caused by slow decomposition. This study evaluated the climate effect over time of utilising stumps for bioenergy using ecosystem forest carbon modelling and time-dependent LCA methodology, including uncertainties in soil carbon changes. Different climate impact metrics were used (global mean temperature change, global warming potential and cumulative radiative forcing) and evaluations were made for single harvest as well as continuous supply over a landscape. Stump harvesting scenarios for spruce forests across Sweden were simulated and the forest net carbon balance was estimated as the difference compared with a reference scenario where the stumps were left to decompose in the forest.

The results showed that using stump residues from commercial forestry in Sweden gives a climate benefit when they substitute for fossil fuel, even in a shorter perspective of around two decades. The temperature impact from using stumps for bioenergy at the stand level peaked after 10–15 years and then declined steadily to ~15% of the maximum level during the following 4–5 decades. The remaining long-term climate impact was small compared to using fossil fuel. An immediate climate benefit was achieved when replacing fossil coal, whereas the parity time, i.e. the time to reach climate benefit was 12–16 years (±2 years) when replacing natural gas, depending on geographical location. For continuous supply of stump bioenergy over a landscape, the corresponding parity time was 22–28 years. There was a higher impact on global climate for northern Sweden, although the absolute difference was small. Sensitivity analysis indicated a moderate additional climate warming effect from the soil disturbance caused by stump harvesting.

1. Introduction

In order to reduce the climate impact by limiting greenhouse gas (GHG) emissions, increased use of non-fossil energy sources is an important solution that needs to be assessed to gain a better understanding and to support policy making. Stumps are an underutilised resource for bioenergy in Sweden and other countries where commercial forestry is predominant, resulting in a large residue-based forest fuel potential. In Sweden, stump harvesting is currently limited to ~0.1% of the total final felling area (~0.19 M ha yr^{-1}) (Official Statistics of Sweden, 2014), while the area that can be stump-harvested sustainably accounting for environmental and technical constraints amounts to ~10% (de Jong et al., 2012). Increasing the harvesting to 10% of the stumps from all final fellings in Sweden would contribute to 5 TW h (de Jong et al., 2012), which can be compared to the current 115 TW h of bio-based energy production, which in turn constitutes 23% of the total energy production in Sweden (Anon., 2014). Thus, there is considerable potential to increase stump harvesting in order to increase the amount of bio-based energy further and substitute for fossil fuels.

The benefits of forest bioenergy to the climate have been debated (Manomet Center for Conservation Sciences, 2010; McKechnie et al., 2010; Schulze et al., 2012; Zanchi et al., 2012) and studies investigating this issue have differed in assumptions,

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* Corresponding author.

E-mail addresses: Carina.Ortiz@scb.se (C.A. Ortiz), Torun.Hammar@slu.se (T. Hammar), Serina.Ahlgren@slu.se (S. Ahlgren), Per-Anders.Hansson@slu.se (P.-A. Hansson), Johan.Stendahl@slu.se (J. Stendahl).

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regional scope and conclusions (Lamers and Junginger, 2013). As regards stump bioenergy, some studies conclude that it is beneficial from a climatic point of view compared to fossil fuels (Melin et al., 2010; Zetterberg and Chen, 2015), while others report a contribution to the climate impact that persists for centuries (Repo et al., 2012; Mäkipää et al., 2015). However, it is claimed that active forest management can compensate for losses in carbon (C) stock following forest fuel harvesting. For example, Alam et al. (2013) and (Repo et al., 2012, 2015) found that adequate forest management, such as a choice of thinning regime, increases carbon sequestration in the forest ecosystem, leading to more positive climate benefits.

Stump harvesting can lead to various environmental impacts such as: increased soil erosion, increased compaction, increased aeration, depletion of soil nutrients, decreased forest productivity, loss of valuable habitat for fungi, bryophytes and insects, and increased soil temperature and water content (Walmsley and Godbold, 2010). It is still unclear to what extent and for how long these effects persist. One important concern about stump harvesting, that may influence the climate efficiency of stump bioenergy, is the effect on the turnover of soil organic matter through soil disturbance (Walmsley and Godbold, 2010). Changes in the physical environment and the redistribution of organic matter are believed to accelerate decomposition. However, field studies of average emissions across stump harvested plots have observed no significant effects on carbon dioxide flux from the soil after disturbance (Strömgren and Mjöfors, 2012; Strömgren et al., 2012), although they found a slight change in physical conditions leading to an increase in soil temperature of 1–2 °C.

The impact on atmospheric temperature of bioenergy produced from forest fuel will vary over time due to: (1) carbon emissions from the branches and/or stumps, had they been left in the forest to decompose (counterfactual emissions), (2) the decay/fate of GHGs released into the atmosphere and (3) the time lag in the warming effect due to the inertia of the atmosphere. This makes it critical to consider time in assessments of the climate impact of these energy systems. For stump bioenergy it is particularly important to consider time aspects, due to their slow decomposition rate compared with branches and tops. This slower decomposition rate may lead to a postponed climate benefit because the organic material – had it been left in situ – would have remained in the forest for a longer period, emitting CO_2 to the atmosphere at a later stage. This also implies a smaller climate impact in warmer climates where decomposition rate is faster, while the opposite will be the case in colder climates. Sweden is a long country with large variations in climate between north and south, and thus large differences in productivity and decomposition between regions can be expected (Hammar et al., 2015).

When assessing the climate impact of forest bioenergy systems, based on e.g. stumps, the whole system of stump harvesting, procurement, conversion to energy and possible replacement of fossil fuel needs to be analysed (Lamers and Junginger, 2013). The timing of GHG sinks and emissions should be analysed in a life cycle assessment (LCA) framework (McKechnie et al., 2010; Helin et al., 2013), where the uptake and emissions in the forest is quantified, preferably using ecosystem models (Helin et al., 2013). Further, an appropriate reference system to which the energy scenario is compared needs to be defined (Helin et al., 2013). The LCA methodology is standardised (ISO 14040/44) and has been widely used for evaluating bioenergy systems and for considering the GHG emissions released (ISO, 2006a, 2006b; Cherubini, 2010). Commonly, the global warming potential (GWP) metric is used to assess the climate impact. However, this metric does not consider the timing of the emissions since it measures the relative effect between one GHG and CO_2 during a fixed timeframe.

To include biogenic CO_2 fluxes, several climate metrics have been developed, e.g. the concept of 'ton-year' which has been applied to assess global warming due to land use changes and forestry by accounting for forest carbon development (Fearnside et al., 2000; Moura Costa and Wilson, 2000). Other studies have presented metrics to include CO_2 emissions from biomass combustion, e.g. the GWP_{bio} (Cherubini et al., 2011). Further, LCA approaches have applied dynamic characterisation factors for assessing climate impact of biofuels and forest carbon changes (Levasseur et al., 2010, 2012). The time-dependent climate metric absolute global temperature change potential (AGTP) was used in this study (Myhre et al., 2013), which have previously been used in LCAs that have included SOC changes (Ericsson et al., 2013; Porsö and Hansson, 2014; Hammar et al., 2015).

Choice of ecosystem model can play an important role in estimates of climate impact, due to differences in model concepts and calibration, making the decomposition dynamics vary between models (Palosuo et al., 2012; Gustavsson et al., 2015). One way of dealing with this is to include uncertainty in ecosystem modelling by accounting for parameter variation in the models to cover the full range of decomposition rates. No previous study has reported climate impact assessments for stump bioenergy that include soil carbon change uncertainties.

The aim of this study was to assess the climate impact of harvesting forest stump residues for bioenergy production, to replace the fossil fuels coal and natural gas in a district heating (DH) system. Ecosystem models (Heureka and Q model) and a time-dependent LCA method were used to evaluate the climate impact from using stumps as bioenergy from spruce stands in three climate regions in Sweden. In the assessment the forest net carbon balance was estimated as the difference compared with a reference scenario where the stumps were left to decompose in the forest. An additional aim was to evaluate the uncertainties in the carbon balances arising from the ecosystem modelling and the impact of these uncertainties on the climate impact.

2. Material and methods

2.1. System description

Three scenarios were defined based on forest stands in different vegetation zones of Sweden (South, Central and North) with different site productivity rates (Table 1, Fig. 1). These locations represent a climate gradient that affects both biomass productivity and carbon turnover in the soil. In all three stands, Norway spruce (*Picea abies* (L.) Karst.) was studied.

The forest management considered was conventional Swedish forestry with the primary focus on timber and pulpwood. The release of GHGs from energy use prior to and during final felling

Table 1
Descriptions of the scenarios (South, Central, North) compared in the analysis.

Scenario	South	Central	North
Location	Jönköping	Dalarna	Västerbotten
Vegetation zone	Hemiboreal	Southern boreal	Northern boreal
Latitude	60° N	61° N	64° N
Productivity (H100)[a] (m)	32	24	20
Understorey	Herbs, mosses	Bilberry, mosses	Bilberry, mosses
Rotation interval (yr)	70	90	120
Thinning age (s) (yr)	25, 35, 45	30, 50	65

[a] H100 is the maximum tree height at age 100.