CLIMATE IMPACT ASSESSMENTS OF FOREST BIOENERGY AFFECTED BY DECOMPOSITION MODELLING – COMPARISON OF THE Q AND YASSO MODELS

Report to the IEA-Bioenergy Task 43 & Task 38

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Climate impact assessments of forest bioenergy affected by decomposition modelling – comparison of the Q and Yasso models

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2 Introduction

The climate benefits of forest bioenergy have been internationally debated (e.g. Manomet Center for Conservation Sciences, 2010; McKechnie *et al.*, 2010; Schulze *et al.*, 2012; Zanchi *et al.*, 2012). Bioenergy systems have often been considered neutral with regard to biogenic carbon, based on reasoning that the CO_2 released into the atmosphere in the combustion process was previously taken up from the atmosphere or will be taken up again by the next generation of growing vegetation (e.g. Chum *et al.*, 2011). However, scientists have reported that implementation of bioenergy can have positive, neutral or negative effects on biogenic carbon stocks, depending on the characteristics of the bioenergy system, soil and climate factors, vegetation cover, and land-use history in the areas where bioenergy systems are established. Some studies show that intensifying biomass removals from forests can decrease forest carbon stock and the carbon sink, which may offset the climate benefits of substituting fossil fuels with bioenergy (Haberl *et al.*, 2012; Holtsmark, 2011; McKechnie *et al.*, 2011; Schlamadinger *et al.*, 1995; Schulze *et al.*, 2012) .

In the Nordic countries the common practise is to manage the forests for timber production. A majority of the stands that make up the managed forest landscape are regularly clearcut and re-planted, primarily to provide timber raw material to the forest products industry. In Sweden, for example, the forest area available for wood supply is 19.3 of the 23.1 Mha of the productive forest land (Claesson *et al.*, 2015). In Finland the area of forestry land is 26.6 Mha, of which approximately 20 M ha is forest land and the rest poorly productive forest land, unproductive land and other forestry land (e.g roads) (Finnish Statistical yearbook of Forestry 2014).

The climate target for Sweden states that 50% of the energy supply should be supplied by renewable energy sources in 2020, and for the same target year the Finnish climate and energy strategy aims to increase renewable energy to 38% of total final consumption and to 20% in transport sector. In the Finnish strategy, wood chips are seen as the most important and cost-efficient means to increase the share of renewable energy in the production of heat and electricity (National Energy and Climate Strategy, 2013). Further, Finland aims to abandon coal in energy production and halve the usage of crude oil by end of 2020 (Prime Minister’s Office, 2015). The long term objective is to become a carbon-neutral society, both for Finland (Energy and Climate Roadmap, 2050) and Sweden. Due to the large forest area harvested each year, harvest residues represent a large available source of fuel for bioenergy in both countries.

The bioenergy produced from harvest residues has benefits compared to dedicated bioenergy harvesting; 1) forest harvest residues are residual biomass and 2) branches, tree tops and stumps can be harvested simultaneously with timber, which reduces costs. Previous studies provide varying estimates for the climate impact of utilizing different types of forest harvest residues for bioenergy in the Nordic countries (e.g. Kilpeläinen *et al.*, 2011; Zetterberg & Chen, 2015; Gustavsson *et al.*, 2015; Holtsmark, 2011; Lindholm *et al.,* 2011; Repo *et al.*, 2011; Hammar *et al.*, 2015; Guest *et al.*, 2012). The range of quantitative estimates of climate impacts of forest residue bioenergy results from: differences in approaches, metrics for climate impact assessment, time perspective, reference scenarios and models applied to estimate changes in forest carbon balance. The climate impacts have been assessed, for example by calculating greenhouse gas (GHG) balances, estimating changes in radiative forcing, or estimating the global temperature change. Some studies have applied a life cycle approach to estimate the emissions. Studies also differ in the way they account for the timing of emissions and uptake. Some studies have followed the timing of carbon emission and uptake from year to year, whereas others have calculated the average emission over a certain time period, for example a forest rotation period or 100 years. Studies focusing on the time aspects of the climate impacts of bioenergy put different emphasis on the short-term and long-term climate impacts in their conclusions, and even differ in their definitions of short- and long-term. However, most studies define short term as ca. 10 to 20 years and long-term as more than 100 years. Differences in the reference scenario also results in widely diverging conclusions about the climate impacts of bioenergy. In addition, there are differences in the GHG emission factors applied and energy conversion losses in the production of heat or electricity.

The estimation of changes in the forest carbon balance has crucial impact on the quantitative estimates for the climate impacts of forest residue bioenergy. Previous studies show that the sequestration/emissions resulting from changes in forest carbon stocks mainly determine the climate impact because the emissions from the procurement chain are small in comparison (Jäppinen *et al.*, 2014; Kilpeläinen *et al.*, 2011; Lindholm *et al.* 2010; Palosuo *et al.*, 2001; Repo *et al.*, 2012). Differences in forest carbon stocks by harvesting residues are mainly related to the pools of decomposing litter and soil organic matter and how these decay. Hence the choice of models that quantify the decomposition process, and the associated mass loss of organic matter, becomes critical for the end result. Previous climate assessments of forest bioenergy have applied different decomposition models, and they conclude that model differences may influence the conclusions (Gustafsson *et al.*, 2015; Zetterberg & Chen, 2015). However, there has been no detailed analysis of exactly how the decomposition dynamics differ between models and the reasons behind the differences.

The objective of this report was to analyze the importance of the choice of decomposition model for the estimate of the forest carbon and climate effects of extracting types of forest harvest residues, for example, stumps and branches of different diameters and using them for bioenergy. Further, differences in the model concepts and parameterizations were analyzed. The climate effect was estimated based on a life cycle analysis (LCA) using radiative forcing metrics.

We note that there is an ongoing discussion within the scientific community, concerning different approaches to assess forest carbon balances and climate effects of bioenergy systems. We emphasize that the selection of methodology approach for this study was based on the objective to compare two decomposition models. This should not be understood as an endorsement of this specific methodology as the most appropriate for assessing the climate effects of forest bioenergy. The approach chosen for this study does not consider how forest management may vary depending on the characteristics of market demand, forest structure, climate, forest industry profile, forest owners' views about emerging bioenergy markets, and the outlook for other forest product markets. Thus, it does not inform how adjustments across affected systems (including the forest, product uses, markets and processing technologies) may combine into a positive, negative, or neutral influence on the development of forest carbon stocks and GHG emissions.

2.1 Description of the decomposition models

2.1.1 The Q model

The Q soil carbon model is a process-based ecosystem model, which simulates how litter and soil organic matter is decomposed by microorganisms in the soil (Rolff & Ågren, 1999) by transforming it into different chemical compounds and partly releasing it as CO_2. The model is based on the continuous quality concept (Ågren & Bosatta, 1998), and explicitly accounts for the continuous decline in substrate quality during the decomposition process and the associated decrease in the decomposition rate. The model is cohort-based, meaning that the annual litters from different biomass compartments represent different cohorts that are modelled independently over time and the totals will amount to the sum of all cohorts at a given time.

The model parameters include litter properties that will depend on litter type (e.g. needles, fine roots, branches, stumps, coarse roots, and stems), characteristics of the microbial community and climatic conditions (average mean temperature). The model defines a unitless variable, *q,* for litter quality, which reflects the transformation of organic matter from fresh litter to more recalcitrant form over time. As parameter input the initial substrate quality, q_0, is supplied. The quality will influence the chemical accessibility of different biomass fractions to the decomposers. The microbial community is defined by a number of fixed parameters: the carbon concentration in the microbial biomass, f_C, the microbial production to assimilation ratio (carbon use efficiency), e_0 - which is independent of substrate quality - and the deterioration of quality with each decomposition cycle, η_{11} (Ågren & Bosatta, 1996). Further, the decomposer growth rate is a function of substrate quality, q_0, a parameter determining how rapidly the decomposer growth rate changes with substrate quality, β, and the parameter u_0, which changes in response to the annual mean temperature (Ågren *et al.*, 2007). The remaining fraction (g_n) of needle (or fine root) litter over time (t) is given by:

$$g_{\mathrm{n}}(t) = (1 + f_C \beta \eta_{11} u_0 q_{0\mathrm{n}}^{\beta} t)^{-(1-e_0)/(e_0 \eta_{11} \beta)}$$

For woody litter (branches, stumps, coarse roots, and stems) the Q model assumes that there is a physical limitation for the decomposers to access the woody material, which is controlled by the parameter "invasion time", t_{max}, resulting in an expanded function for remaining fraction compared to needles (Hyvönen & Ågren, 2001). The invasion time is defined as the time before the material is entirely invaded by the decomposers leading to an initial lag-phase in decomposition rate. There is a linear relationship between the invasion time and the diameter of the woody litter.

The soil carbon store previous to the simulation period (not included in this study) is simulated as a separate pool, assuming it was formed at steady state during constant litter input (Ågren & Bosatta, 1998).

2.1.2 Yasso

The dynamic litter and soil carbon model Yasso calculates the amount of soil organic carbon, changes in the amount of soil organic carbon and heterotrophic soil respiration releasing CO_2 (Järvenpää *et al.*, 2016; Liski *et al.*, 2005; Tuomi *et al.*, 2011; Tuomi *et al.*, 2009). In the Yasso model the decomposition rate of different types of soil carbon inputs depends on the chemical composition of the input types and the climate conditions (Liski *et al.*, 2005; Tuomi *et al.*, 2009). The chemical composition of different carbon input varies depending on the species and litter type. The model divides non-woody and woody litter into four chemically distinguishable fractions that decompose at their unique rates. These groups are compounds hydrolysable in acid (denoted with A), compounds soluble in water (W) or in a non-polar solvent, ethanol or dichloromethane (E), and compounds neither soluble nor hydrolysable (N). In addition, there is a humus (H) fraction consisting of more recalcitrant compounds formed of the decomposition products of the A, W, E, and N fractions. The decomposition of the fractions results in carbon fluxes between the fractions and CO_2 flux into the atmosphere. The decomposition rate of woody litter also depends on the diameter of the litter (Tuomi *et al.*, 2011).

The Yasso model was developed using the Bayesian framework. The model structure based on the Bayesian model selection theory is not predefined, and the performance of different models is compared based on their posterior probabilities given the measurements. The parameter values of the model were estimated by fitting the model simultaneously to all the data available on soil carbon cycling (n=18500) without strong prior assumptions (Järvenpää *et al.*, 2016; Tuomi *et al.*, 2009). This data set covered, firstly, most of the global climate conditions in terms of temperature, precipitation and seasonality, secondly, different ecosystem types from forests to grasslands and agricultural fields and, thirdly, a wide range of litter types, such as leaf litter, woody litter, and soil carbon measurements. In the development of the model the same parameter values were required to fit to the entire global data set so that the Yasso model would be applicable across climate conditions worldwide and to a wide variety of litter types. The Bayesian framework was used for fitting the model to the diverse data sets because it allows one to take into account the uncertainties in measurements and in the model prediction in a consistent way. An optimization algorithm and an adaptive Markov chain Monte Carlo method was used to obtain the uncertainty estimates for the parameters and model prediction, as well as useful summaries of the parameter values. The Yasso model fulfils the Occam's principle of parsimony, which means that the most simple model structure is chosen from a set of almost equally good alternatives.

The current version of the model is Yasso15 (Järvenpää *et al.*, 2016). In the development of the Yasso15 model, an even more diverse data set was used for model calibration and more emphasis was put on modelling choices and the underlying environmental processes compared to the earlier version of the model, Yasso07 (Järvenpää *et al.*, 2016; Repo *et al.* , 2016). The additional data made it possible to distinguish three groups with different temperature and precipitation dependences. In the Yasso15 model separate dependences are applied to fast-decomposing A, W and E compartments, more slowly decomposing N and very slowly decomposing humus compartment H. The Yasso15 model estimates of mass remaining have been shown to be unbiased with respect to litter type, climate conditions, time since the start of decomposition and ecosystem type (Järvenpää *et al.*, 2016).

2.2 Decomposition of woody litter in the models

2.2.1 Woody litter in Q

The fundamental microbial decomposition process in the Q model is the same for woody as non-woody litter. The litter quality, which reflects the chemical composition, is lower for woody litter than for needle litter, but the differences are minor. The quality for the woody biomass in branches, stems and stumps is assumed to be the same. The deterioration of substrate quality over time reflects the transformation of organic matter into more recalcitrant forms. In this respect there are only minor differences between woody and non-woody litter in the degradation process. Further, no processes for redistribution into the mineral soil or for mineral protection are included. The decomposition of coarse woody litter is mainly limited by the physical access to the substrate for the decomposers, which is controlled by the invasion time, i.e. the time it takes for the decomposers to invade the substrate. This leads to an initial lag-phase in decomposition after which it may proceed at a higher rate since woody material of higher quality is made available.

The previous calibration of the Q model to coarse woody litter did not include long-term decomposition data, besides measurements on the invasion rate (Harmon *et al.*, 1986). Consequently, the predicted long term mass loss of coarse woody litter is not fully validated on measurement data. The predicted quantity of the long term residue will largely depend on the theoretical assumptions in the model.

2.2.2 Woody litter in Yasso

Woody litter decomposition in the Yasso15 model depends on climatic conditions (precipitation, temperature and temperature amplitude) together with the chemical composition and the size of the woody litter (Järvenpää *et al.*, 2016). There were two preconditions of modelling woody litter decomposition in Yasso, first, the decomposition of woody litter is basically a similar biochemical process as the decomposition of non-woody litter and, second, the size of the woody litter affects the decomposition rate. To account for the effect of the litter size on the decomposition rate, three alternative types of model structures and altogether 13 different models were compared using Bayesian model selection criteria. The best fit to the measurements was on the model, in which the mass loss rate of the A, W, E and N compartments decreased with an increasing diameter of woody litter (Tuomi *et al.*, 2011).

2.3 Data used in the development of the decomposition models

2.3.1 Data used in the development of Q

The non-woody litter decomposition in the Q model was calibrated based on decomposition data from a large number of experiments where litter mass loss was studied by litter bags for > 2 years (Ågren & Bosatta, 1996; Berg *et al.*, 1991a; Berg *et al.*, 1991b; Aber *et al.*, 1984). The calibration was mainly based on data from boreal forests in the Nordic region. This included the parameterization of the fixed parameters for the microbial community (f_C, e_0, η_{11}, β) and initial quality of needles, q_0. The influence of climate conditions on the decomposition rate is through the parameter u_0 and a relationship including mean temperature found in Ågren & Bosatta (1998), also found in Ågren *et al.* (2007). Data on the decomposition of coarse woody litter that were used for the Q model are found in Hyvönen *et al.* (2000). The calibration of the parameter t_{max}, which is central in the concept of invasion rate for coarse woody litter, was based on data on colonization rates from Harmon *et al.* (1986).

Recently, a new parameterization using GLUE methodology (Generalized Likelihood Uncertainty Estimation) was made based on historic forest production data from the Swedish National Forest Inventory (1926-2002) and calibration using measured soil carbon stocks estimated from the Swedish forest soil inventory from 1993-2002 (Ortiz *et al.*, 2011). GLUE provides parameter distributions in order to include uncertainties in the simulations. This calibration largely verified the previous calibration used in this study.

2.3.2 Data used in the development of Yasso

The Yasso15 model is based on an extensive set of measurements on i) non-woody litter decomposition (n > 12 000), ii) woody litter decomposition (n > 2000), iii) soil organic carbon accumulation (n = 26) and v) soil organic carbon stock measurements (n > 4100).

The measured data on non-woody litter decomposition (Berg *et al.*, 1991a; Berg *et al.*, 1991b; Gholz *et al.*, 2000; Guendehou *et al.*, 2013; Hobbie, 2005; Trofymow, 1995) covers most of the global climate conditions in terms of temperature, precipitation and seasonality, secondly, different ecosystem types from forests to grasslands and agricultural fields and, thirdly, a wide range of litter types. The non-woody litter data consist of foliage litter of 53 species and fine root litter of four species. The decomposition of non-woody litter was followed in litterbag experiments up to 10 years. The woody litter decomposition data consists of four sets of measurements taken in boreal forests, namely Finland, Estonia and Russia (Mäkinen *et al.*, 2006; Palviainen *et al.*, 2004; Tarasov & Birdsey, 2001; Vávrová *et al.*, 2009). The measurement data of woody litter decomposition include branches and stems ranging from 0.5 to 50 cm in diameter, and the mass loss of these woody biomass components has been followed for 1–71 years since the start of decomposition.

In addition to woody and non-woody litter decomposition measurements, data sets on soil carbon stocks measurements from Finland, and a large, global steady state data set were used in the parameterization of the model (Liski *et al.*, 2005; Liski & Westman, 1995; Zinke *et al.*, 1986. More over data on accumulation of soil carbon measured along a soil chronosequence on the Finnish coast where new soil parent material is emerging from the sea after the retreat of the most recent glacial ice sheet, was used in the model development (Liski et al. 1998). These data sets contain information on the formation and slow decomposition of humus. Because of these data sets the Yasso15 model captures also the late phases of the decomposition process and humus formation.

2.4 Climate impact assessment using the two decomposition models

2.4.1 Approach to the case study

The climate impact of producing bioenergy from branches and stumps was estimated using time-related LCA. The life cycle inventory included GHG emissions from the forest fuel procurement chain, heat production and ash recycling, and changes in the forest carbon stock resulting from forest residue harvesting. The net change in forest carbon stock leading to CO_2 emissions was defined as the yearly difference between harvest (combustion) and no harvest (decomposition). The assessment was made for both stumps and branches and for single harvest events as well as for a continuous supply case modelled as the gradual implementation of forest residue extraction for bioenergy in a hypothetical forest landscape. The effect of extracting forest residues for bioenergy was compared to effects of using coal or natural gas and leaving the residues to decompose in the forest.

This study focused on the effect of the choice of decomposition model on the estimated emissions and consequent climate impact. Hence, the carbon stocks changes were modelled with two simulation models; the model Q (Rolff & Ågren, 1999; Hyvönen & Ågren, 2001; Ågren & Hyvönen, 2003; Ågren *et al.*, 2007) and the Yasso model (Järvenpää *et al.*, 2016; Liski *et al.*, 2005; Tuomi *et al.*, 2011; Tuomi *et al.*, 2009). The mass loss rate was estimated as the difference in C stock between two consecutive years. The time-frame of the assessment was limited to 100 years due to the lack of experimental data for the decomposition of coarse woody litter beyond ca 70 years. The carbon accounting was started at the time when biomass was extracted and used for energy, since this represents a suitable approach to compare the two models. The climate warming impact resulting from full life cycle emissions was estimated applying cumulative radiative forcing metrics.

2.4.2 Calculation of GHG emissions

In the simulations it was assumed that forest harvest residues were harvested from Norway spruce stands in the south of Sweden representing the hemi-boreal vegetation zone with rotation length 70 years (Ortiz *et al.* 2016). The site had typical site conditions for the region, i.e. mesic soil moisture, parent material that was sandy/silty glacial till, and field layer dominated by grass. Forest harvest residues were collected after final felling. The stump harvesting involved the removal of 70% of the stumps in each stand. For the harvesting of branches, the removal was 70% of the branches and in addition 62% of the attached needles (Hammar *et al.* 2015). This resulted in a harvested stump biomass of 59.0 Mg dry matter (DM) ha^{-1} and a harvested branch biomass of 47.9 Mg (DM) ha^{-1} (Ortiz *et al.* 2016).

The GHG emission calculation included emissions from changes in the carbon stocks and all GHG from the procurement chain, such as emissions associated with excavation, forwarding, transport and chipping of branches and stumps. The detailed description of the LCA input data can be found in Ortiz *et al.* (2016). The release of GHGs from fuel consumptions associated with the final felling was allocated to the timber and pulpwood production. The bioenergy system was assumed to produce district heat (DH) in a DH plant using flue-gas condensation, which recovers some of the latent heat lost by water vaporisation.

The change in the forest carbon stocks was simulated with the Q model, Yasso07 and Yasso15. It was assumed that forest residue harvesting did not cause any change in the forest growth. It was also assumed that, besides the residue management, forest management was the same in all cases. Therefore, the only difference in the forest carbon between the forest residue utilization and no utilization cases was that the carbon stored in the residues is emitted into the atmosphere instantly instead of gradually through decomposition, i.e. the simulated mass loss curves (Figure 1 A-B).

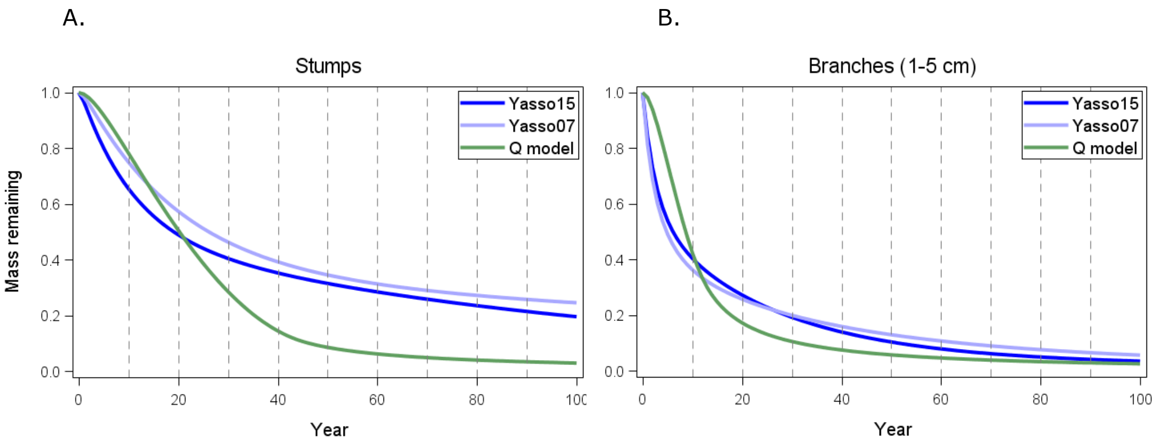

Figure 1. Mass remaining over time for stumps (A) and branches (B) based on the Q model, Yasso07 and Yasso15. The woody litter diameter was assumed to be 35 cm for stumps and an average of diameter of one to five cm for branches.

In the single harvest case, the net emission year 1 was calculated by subtracting residue decomposition emissions in year 1 from the combustion emission arising if the residues are used for bioenergy. In the subsequent years (year 2-100), annual net emissions are negative and equal to the emissions from decomposing residues (Figure 2 A-B).

A. B.

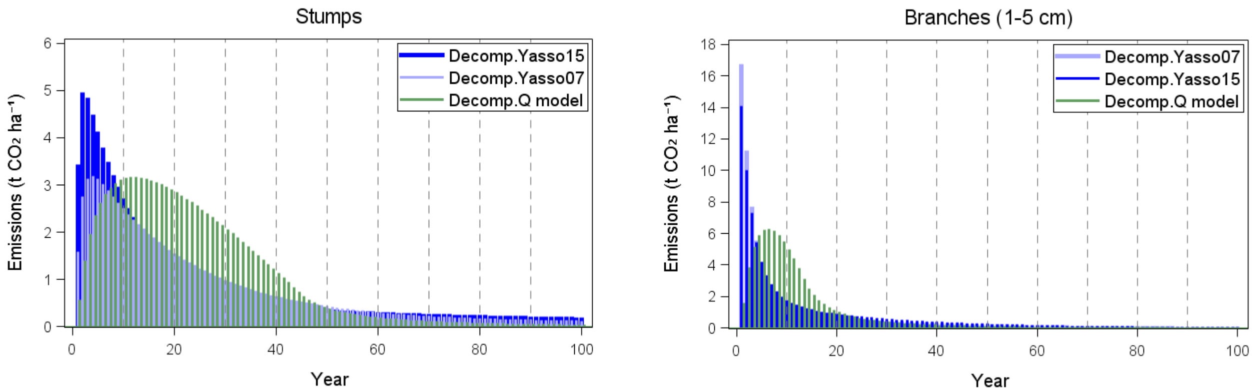

Figure 2. Emissions of CO_2 from the decomposition of stumps (A) and branches (B), based on the Q model, Yasso07 and Yasso15 calculated from mass loss rates. The woody litter diameter was assumed to be 35 cm for stumps and an average of 1-5 cm for branches.

In the continuous supply case, we simulated the case where a forest landscape was gradually taken into forest bioenergy production. The landscape consisted of 70 stands of one hectare each, i.e. there were as many stands as the number of years in the rotation (70 years). All stands were assumed to follow identical stand development (i.e. the same as in the single harvest case), but the stands varied in age according to an even age distribution. Each year, harvesting of residues was carried out on one stand/hectare in the landscape. For each year in the simulation period, the total emission from decomposing residues in the landscape was the summarized over the 70 individual stands (Figure 3, blue/green solid line). The net emissions at time t from using residues for bioenergy (Figure 3, dashed lines) were calculated as the difference between the annual combustion emission (Figure 3, black solid line) and the decomposition emissions from contributing stands until time t (Figure 3, blue/green solid lines).

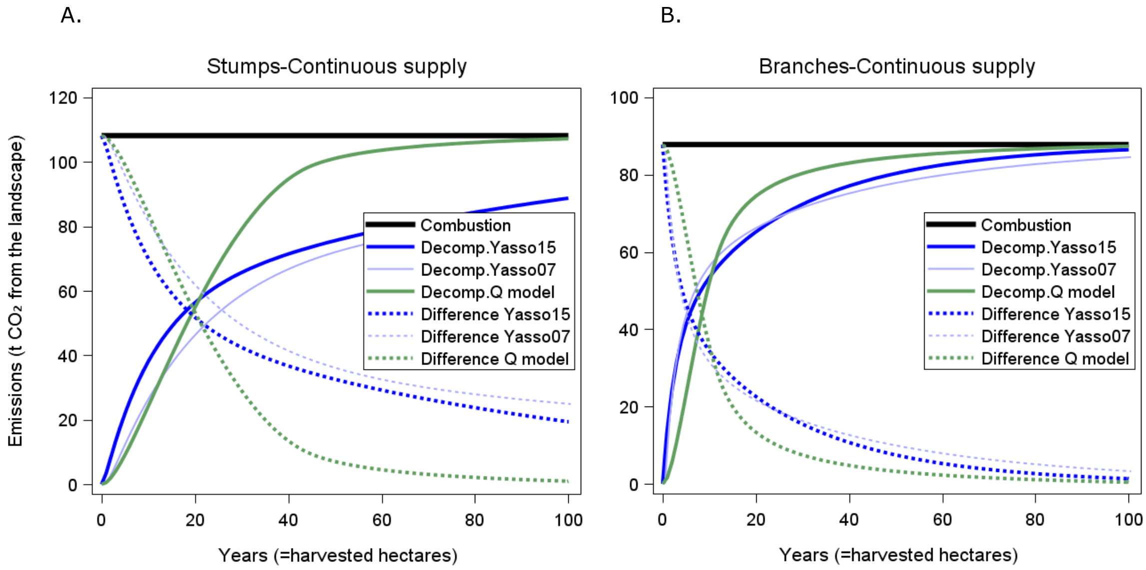

Figure 3. Annual emissions of CO_2 from biomass decomposition and combustion from a forest landscape with continuous harvesting of stumps (A) and branches (B). Starting from year 1 each year forest residues from one hectare were either combusted or left to decompose in the forest landscape. The difference between these two cases, in terms of annual CO_2 emissions, represents the net CO_2 effect of residue harvest for bioenergy. The emissions from decomposition were based on the Q model, Yasso07 and Yasso15.

The decomposition of branches with diameter of 1, 2, 3 and 5 cm and stumps with a diameter of 35 cm was simulated with both models. In the Yasso simulations the chemical composition of stumps was assumed to comprise of 1% water-soluble compounds, 1% ethanol-soluble compounds, 78% acid-hydrolysable compounds, and 28% non-soluble and non-hydrolysable residue, whereas the corresponding values for branches were 1%, 1%, 59% and 37%, and for needles 47%, 11%, 4% and 37% (Gustavsson *et al.*, 2015). The annual mean temperature in the studied area was 5.7 °C, temperature amplitude 21.5 °C, and annual precipitation 706 mm (Gustavsson *et al.*, 2015). For the Q-modelling the fixed parameters for the microbial community (f_C, e_0, η_{11}, β) were set according to Ågren *et al.* (2007) and the parameter u_0 was calculated based on the annual mean temperature (5.7 °C) using the function in Ågren *et al.* (2007). The invasion rate was calculated based on the linear relationship with the diameters of coarse woody litter, which resulted in t_{max} values of 12.4 and 44 for branches and stumps respectively.

The climate impact of bioenergy was compared with that of the two fossil fuels coal and natural gas by assuming that equal amounts of heat was produced yearly. No biogenic carbon emissions were included for the fossil systems since the net land use effect was zero (i.e. no change in forest carbon stocks when generating heat from the two fossil fuels). The effect of replacing fossil fuels with stump energy was defined as the difference between the two. The emissions for the two fossil fuels were based on emissions factors for their production, distribution and combustion. The emissions for fossil coal were 97.2 g MJ^{-1}_{fuel} (CO_2), 0.0140 g MJ^{-1}_{fuel} (N_2O), 0.563 g MJ^{-1}_{fuel} (CH_4), and for natural gas 62.3 MJ^{-1}_{fuel} (CO_2), 0.0001 g MJ^{-1}_{fuel} (N_2O), 0.276 MJ^{-1}_{fuel} (CH_4) (Ortiz *et al.* 2016). The natural gas represented a European average mix (from Western Europe, Russia and

Algeria). Values for (Polish) fossil hard coal included emissions also from the coal mine. Conversion efficiencies for stumps, natural gas and coal were set to 106% (including heat recovery), 104% (including heat recovery) and 89%, respectively (Uppenberg *et al.*, 2001). The applied heating values did not include latent heat in combustion gasses and therefore conversion efficiencies exceeding 100% were used, assuming heat recovery by flue gas condensation.

2.4.3 Climate impact assessment

The climate impact of using stumps and branches for energy was assessed by calculating the cumulative radiative forcing (CRF) reflecting the change in the radiative balance of the Earth measured in Wm^{-2} (IPCC, 2007). The radiative forcing (RF) can either be positive or negative, leading to either a warming or cooling of the global temperature. The GHGs are not equally strong climate agents and they have varying residence times before they decay in the atmosphere.

The RF of one unit pulse emission of a gas is described by its radiative efficiency which is the impact of one unit change in the atmospheric concentration of the specific gas (Myhre et al., 2013). The radiative efficiency was modelled based on initial background concentrations from Hartmann (2013). The perturbation lifetime of the gas also affects the temperature change, i.e. the atmospheric residence time before the gas decays. CH_4 and N_2O break down chemically in the atmosphere with average atmospheric lifetime 12.4 and 121 years, respectively (Myhre et al., 2013). CO_2, on the other hand, is taken up by oceans and the terrestrial biosphere, while a fraction of the emitted gas stays airborne (Joos et al., 2001; Myhre et al., 2013). The decay of CO_2 was modelled here using the Bern carbon cycle model (Joos et al., 2013), while simple decay functions were used for N_2O and CH_4 (Myhre et al., 2013).

3 RESULTS

3.1 Mass loss, mass loss rate, and emissions

The two models generally produce similar estimates of mass remaining for stumps and branches during the first ca 20 years (Figure 1). For stumps, the Q model estimate a larger remaining mass during the first 20 years and subsequently the pattern shift and the estimates for Yasso are consistently larger over longer perspectives (up to 22% larger). The models start to deviate more strongly after ca 25 years, although the gap between the models diminishes slightly again after ca 60 years. For branches, the estimated mass loss is similar for the two models although the dynamics during the first decades vary. The Q model estimates a larger remaining mass during the first ca 10 years followed by a rapid mass loss. The two models produce very similar results for branches in the long term (> 50 years). In the current version of the Yasso model, Yasso15, the decomposition rate of large sized stumps is slightly faster than in the previous version Yasso07. For branches, which have smaller diameter, the decomposition rate of Yasso15 is faster than Yasso07 only after 30 years.

Following a single harvest event, the emissions estimated by the Q model are smaller, but the emission pulse is more sustained due to the lag-phase in the decomposition (Figure 2 A-B). The higher initial emissions obtained with Yasso decline more rapidly and annual emissions are lower than in the Q model after 5-10 years. These differences between the two models are consistent for both stumps and branches. In the long term the estimated CO_2 release from decomposing stumps is higher for Yasso, although at a small absolute level, while for branches the difference between the models is minor.

The continuous supply case (gradual implementation of forest residue extraction for bioenergy in the landscape) result in different dynamics in terms of emissions from the forest compared to the single harvest case. In the case where forest residues are left in the forest, the decomposition emissions rise sharply due to the additional emissions from fresh harvest residues in newly harvested stands. The emissions increase up to a point when the there is a constant contribution from newly harvested stands, while the contribution from earlier harvest occasions becomes small (Figure 3). Emissions will level out over time, and eventually approach steady state in case the organic matter decays completely, or continue to increase slowly in case a stable decomposition remnant is formed. The initial rate at which the landscape emissions increase differs between the models and the increase is faster for Yasso than for the Q-model. The long term sustained emission level for stumps is higher when estimated by the Q model compared to Yasso (Figure 3).

3.2 Cumulative radiative forcing

Both models show that the use of stumps and branches to produce heat has a warming impact (positive CRF), compared to a situation where no heat is produced and the harvest residues are left in the forest (Figure 4, Bioenergy alternatives).

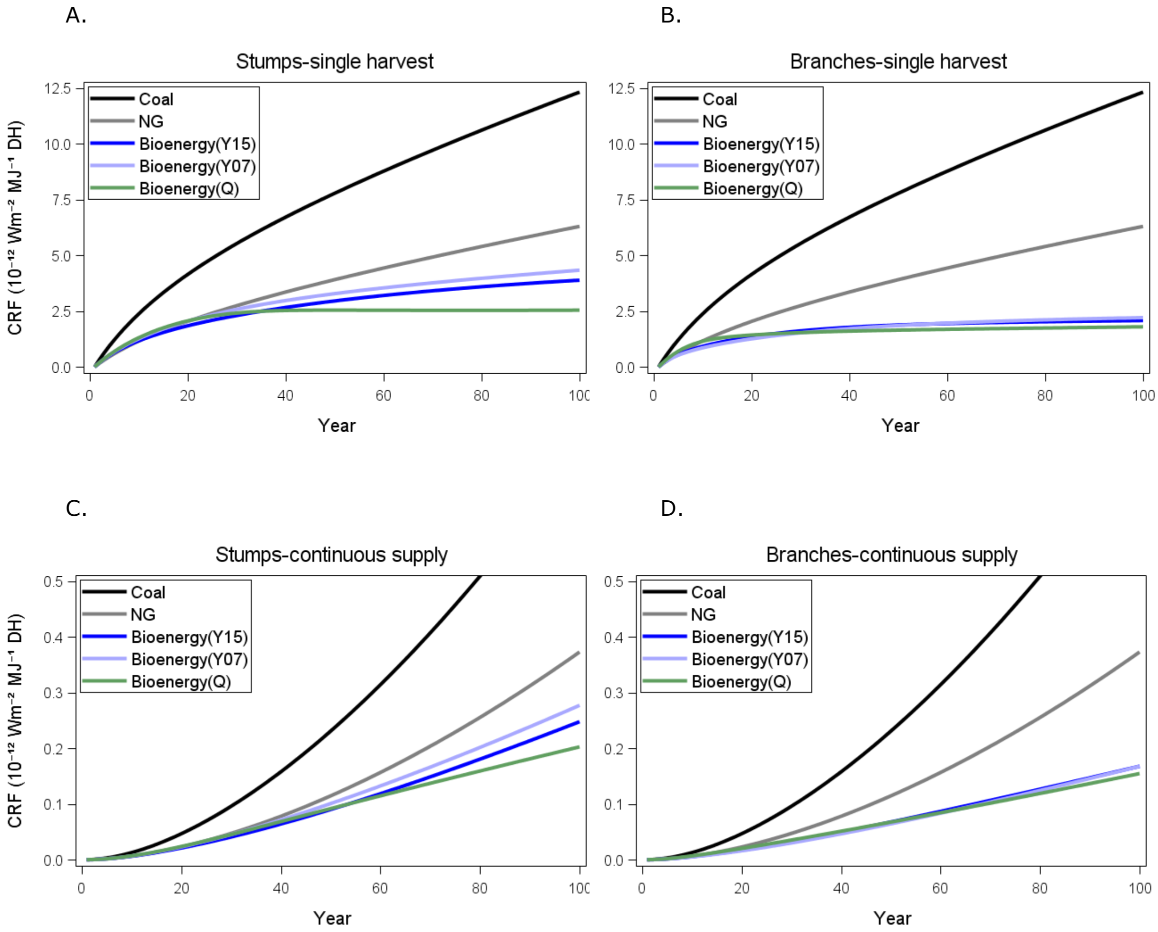

Figure 4. Cumulative radiative forcing (CRF, 10^{-12} Wm^{-2} MJ^{-1} DH) of bioenergy from single harvest of stumps (A), single harvest of branches (B), continuous supply of stumps (C) and continuous supply of branches (D) assessed with the Q model, Yasso07 and Yasso15 for decomposition modelling. The total net emissions from the continuous supply case were divided by 70 hectares to get the net emissions per hectare.

In the single harvest case, the warming impact of using branches for heat production equals the warming impact of using natural gas for heat production during the first ca 10 years (Figure 4). Beyond this initial time period, the warming impact of using natural gas is higher. The use of stumps causes similar warming impact as natural gas during the first ca. 20 years and lower warming impact thereafter (Figure 4). The difference is due to slower decomposition rate for stumps than for branches. Over longer time perspectives the CRF for the single harvest reaches a constant level, indicating a minor additional climate impact, for all cases except for stumps modelled by Yasso that increases slightly.

In the continuous supply case, i.e. gradual implementation of residue extraction for bioenergy, the warming impact equals the warming impact of using natural gas for a longer time period than in the single harvest case, i.e. ca 20 years for branches and ca 30 years for stumps for both models

(Figure 4). This is because the annual combustion emission pulse dominates during an initial time period, before it is gradually counterbalanced by the reduced ("avoided") emissions from decomposition in an increasing number of harvested stands. The dynamics of the forest carbon emissions in the continuous supply case are mainly attributed to short term decomposition. Hence, the two models produce more similar results than in the single harvest case since the models behave very similarly during the first ca 25 years (cf. above). The difference between the different bioenergy and fossil energy systems (substitution) are shown in Figure 5.

The modelled warming impact of using branches for heat production are similar (Figure 4 B and D) since the Q and Yasso models give similar estimates of CO_2 emissions from branch decomposition (Figure 2 B). The warming impact of bioenergy from stumps is found to be slightly smaller during the first 20 years and larger in the longer term when the Yasso model is used. This is because the residence time for stumps is longer when modelled with the Yasso model than with the Q model (Figure 4 A).

To summarize, in all cases there is an immediate climate benefit when branches and stumps are used for heat production instead of fossil coal. While there is a time delay before a clear climate benefit is achieved when natural gas is the alternative fuel, the accumulated avoided warming is substantial over the longer term (Figure 4 and Figure 5).

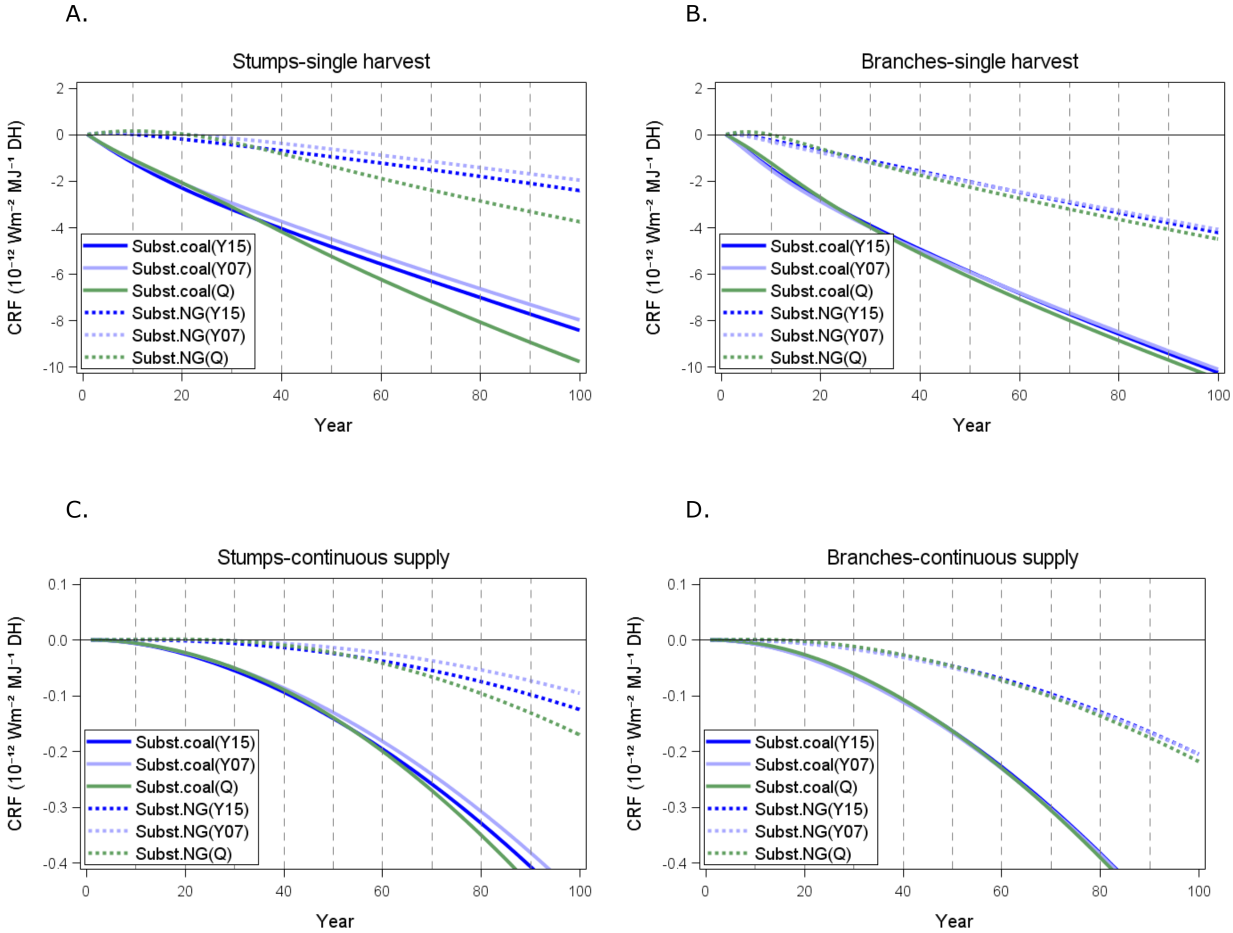

Figure 5. Cumulative radiative forcing (CRF, 10^{-12} Wm^{-2} MJ^{-1} DH) when substituting fossil alternatives for of bioenergy; single harvest of stumps (A), single harvest of branches (B), continuous supply of stumps (C) and continuous supply of branches (D) assessed with the Q model, Yasso07 and Yasso15 for decomposition modelling.

4 DISCUSSION

The Q and the Yasso models produce quite similar estimates of mass remaining for the first 10 to 20 years. After this time period the estimates differ because 1) the structures of the models are different, 2) different data sets were used in the development of the models and 3) different mathematical methods were used to determine the parameter values of the models.

The structure of the Yasso model covers three basic mechanisms of decomposition and soil organic carbon cycling. First, microbes excrete enzymes that break down the organic compounds of litter. Second, microbes use the products of this process for respiration and growth (synthesis of new organic compounds). Third, this microbial decomposition process combined with physical and chemical processes in the soil result in formation of organic compounds or organic-mineral complexes, which are more resistant to decomposition than any of the original compounds in the litter. This conceptual model was formulated into mathematical equations. When there were alternative details in the formulation to choose from, the decisions were taken objectively based on Bayesian criteria. For example, alternatives for the model formulation of woody litter decomposition (Tuomi *et al.*, 2011) were studied using this approach. The parameter values of the model were determined using Bayesian approach and Markov chain Monte Carlo method.

The Yasso model is based on measurements of 1) woody litter decomposition, 2) non-woody litter decomposition, 3) soil carbon accumulation and 4) soil carbon stocks. All these data were used simultaneously to determine the parameter values of the Yasso15 model, because this is the most efficient way of using the information in these data. The resulting fit of the model to the data was controlled to ensure that there were no systematic errors. Small systematic error had to be accepted because the model needed to fit all the various data simultaneously, but no severe errors were accepted that indicated that the formulation of the model was inadequate. As a result of this approach, all the data in the Yasso database affects the estimates of woody litter decomposition (see section Data used in the development of the decomposition models of this report**)**. However, the data on the decomposition of woody litter plus the data on soil carbon accumulation and soil carbon stocks are the most influential. The data on the decomposition of woody litter extended to 70 years after the start of decomposition. During the 100-year period analysed in this study, decomposition of woody litter depends essentially on the decomposition and formation of recalcitrant "lignin-like" and "humus" compounds. Information on these rates of these processes was obtained especially from the data on soil carbon accumulation and soil carbon stocks. The approach taken to develop the Yasso15 model is entirely transparent, as described above, and the model is based on a large and diverse global dataset. The model fits to these data without any severe systematic error (Järvenpää *et al.*, 2016). On these bases, it can be concluded that the model produces accurate estimates of woody litter decomposition.

The Q model structure covers the microbial decomposition mechanisms, the deterioration in quality of the substrate during the decomposition process and the physical limitation for the decomposers to access coarse woody litter. The transformation of the substrate into more recalcitrant compounds is implicit in the model and there is no explicit mechanism for organo-mineral complexation. The mechanisms for decomposition of coarse woody litter mainly cover the physical constraints in the current model version. The microbial degradation leading to the formation of recalcitrant compounds from coarse woody litter is not much different from other litter types, and in the long term the fraction ending up in a recalcitrant residue is similar. Hence, even for woody litter a rapid decomposition is estimated once the decomposers are not restricted by the physical dimension of the substrate anymore. The current calibration of the model was based on extensive measurements of the degradation of fine litter, while for coarse woody litter more sparse data was used and long-term data is lacking. However, a recent effort to re-calibrate the Q model was made based on data on the long term development of carbon stocks, which largely verified the original parameterization (Ortiz *et al.* 2011). The long term accumulation of soil organic matter (SOM) from coarse woody litter is uncertain, though, and the calibration is much less extensive than for Yasso.

A source of uncertainty in estimating especially the decomposition rate of stumps is related to their size. In Liski *et al.* (2014) and Smith *et al.* (2014), a method was used to characterize uprooted stump-root systems accurately in 3D, using laser-scanning and mathematical modelling. Results revealed that using the upper diameter of the harvested stumps for decomposition simulation leads to an underestimation of the actual decomposition rate. Consequently, more reliable estimates for the decomposition rate of stump-root systems can be obtained using the actual diameter distribution of stump-root systems in the simulations. The diameter distributions can be measured using the 3D method developed. The cutting diameters of stumps excavated from a final felling site in a Finnish study ranged from 21 to 37 cm (Liski *et al.*, 2014). In this report the decomposition of stumps with a diameter of 35 cm was modelled. Since the decomposition rate in both the Yasso and Q models depends on the diameter, stumps with diameters smaller than 35 cm, would decompose faster and consequently, the climate warming impact of these faster decomposing stumps would be smaller than shown in this report.

5 IMPLICATIONS FOR CLIMATE IMPACT ASSESSMENT OF BIOENERGY

The objective of this report was to investigate whether the choice of decomposition model has any major influence on the outcome when the warming impact of forest residue use for bioenergy is estimated. The report shows that the choice of the decomposition model results in different quantitative mass loss estimates. Despite this, the decomposition model choice does not lead to diverging conclusions about the warming impact of extracting forest residues for bioenergy. The conclusions from this study about the climate impact of forest bioenergy is comparable to other Nordic studies that apply the same methodology to assess the climate effects: it can be lower, similar, or higher than for fossil fuels in the short- to medium term (up to a few decades), but is consistently lower on the medium- to longer term (Hammar *et al.*, 2015; Melin *et al.*, 2010; Repo *et al.*, 2011; Sathre & Gustavsson, 2011; Savolainen *et al.*, 1994).

With all other parameters kept the same, the magnitude and timing of carbon emissions from forest residue use for bioenergy depend largely on the decomposition rate of the residues left to decay in the forest. Therefore, the better we can model the residue decomposition the more precise quantitative estimates we get of the climate impact. On the other hand, also other factors can be influential on the outcome when an LCA-type methodology is used to estimate the net climate effect of using forest residues for bioenergy. The fossil carbon displacement efficiency is probably the most important factor, which depends on (i) the conversion efficiency for the bioenergy system; and (ii) which energy system that is displaced (e.g. Gustafsson *et al.,* 2015). This was also shown in this study where significantly different results were obtained depending on whether coal or natural gas was assumed to be displaced by bioenergy use. Also other methodological choices strongly affect the outcome, e.g. the definition of a reference scenario. Further, including or excluding the substitution effect in the analysis has a crucial impact on estimates of climate impacts. Therefore it is important to define the research question and choose the correct reference scenario to answer a specific question.

6 FUTURE RESEARCH NEEDS

- The choice of models and climate impact metrics applied, reference system and studied time period affect the estimated climate impacts of forest harvest residues. Previous studies have examined some of these factors. Nevertheless, a comprehensive and transparent assessment of the sensitivity of the estimated climate impacts to changes in different factors and assumptions is still lacking. Studies comparing quantitatively the effect of different decomposition models, different reference systems, and inclusion or exclusion of substitution effects may identify factors and assumptions that lead to different conclusions about the climate impact of bioenergy from forest harvest residues.

- In order to provide reliable estimates of climate impacts of forest bioenergy in the long-term, more information on the decomposition process after 20 years is required as well as effects of increased biomass removal on productivity (Egnell 2011). Long-term experimental studies are needed to better understand the factors controlling decomposition and humification, and to provide data for model development. Further experimental investigations are needed to provide more reliable information on the size and size distribution of woody litter, especially stump-root systems.

- In addition to GHG emissions also other climate forcers, such as albedo and black carbon emissions from biomass combustion, may have important effect on the climate impact of bioenergy from forest harvest residues (for example, Betts, 2000 and Naudts *et al.*, 2016).

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