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Domestic heating from forest logging residues: environmental risks and benefits

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ABSTRACT

The European Union (EU) relies largely on bioenergy to achieve its climate and energy targets for 2020 and beyond. Special focus is placed on utilization of biomass residues, which are considered to cause low environmental impacts.

We used the dataset from the latest European Commission document on the sustainability of solid and gaseous biomass (SWD2014 259), complementing those results by: i) designing three pathways for domestic-heat production using forest logging residues, with different combustion technologies; ii) expanding the analysis to include forest carbon stock development with and without bioenergy; iii) using absolute climate metrics to assess the surface temperature response by the end of the century to a bioenergy and a reference fossil system; iv) including multiple climate forcers (well-mixed GHG, near term climate forcers and surface albedo change); iv) quantifying life cycle impacts on acidification, particulate matter emissions and photochemical ozone formation; v) reviewing potential risks for forest ecosystem degradation due to increased removal of residues.

Supply-chain GHG savings of the three pathways analysed ranged between 80% and 96% compared to a natural gas system, above the 70% threshold suggested by the EU. However, the climate impact of bioenergy should be assessed by considering also the non-bioenergy uses of the biomass and by including all climate forcers.

We calculate the Surface Temperature Response to bioenergy and fossil systems by means of Absolute Global surface Temperature Potential (AGTP) metric. Domestic heating from logging residues is generally beneficial to mitigate the surface temperature increase by 2100 compared to the use of natural gas and other fossil sources. As long as residues with a decay rate in the forest higher than $2.7\%{*}\mathrm{yr}^{-1}$ are considered as feedstock, investing now in the mobilization of residues for heat production can reduce the temperature increase by 2100 compared to all the fossil sources analysed, both in case of bioenergy as a systemic change or in case of bioenergy as a transitory option.

Furthermore, several environmental risks are associated with the removal and use of forest logging residues for bioenergy. These issues concern mostly local air pollution, biodiversity loss and, mainly for stumps removal, physical damage to forest soils.

Forest logging residues are not free of environmental risks. Actions promoting their use should consider: (i) that climate change mitigation depends mainly on the decay rate of biomass under natural decomposition and time and rate of technology deployment, (ii) whether management guidelines aimed at protecting long-term forest productivity are in place and (iii) whether proper actions for the management of adverse effects on local air pollution are in place.

Abbreviations: AGTP, Absolute Global surface Temperature change Potential; AS, Advanced Stove; DH, District Heating; EC, European Commission; EU, European Union; GHG, Greenhouse Gases; GWP, Global Warming Potential; id, idem; (I)LUC, (Indirect) Land Use Change; LCA, Life Cycle Assessment; NMVOC, Non Methanic Volatile Organic Carbon; NG, Natural Gas; NTCF, Near-Term Climate Forcers; PS, Pellet Stove; STR, Surface Temperature Response; SM, Supplementary Material; SOC, Soil Organic Carbon; WMGHG, Well-Mixed Greenhouse Gases; JRC, Joint Research Centre.

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1. Introduction

The European Union (EU) promotes bioenergy as one of the main renewable, low-carbon sources to achieve its ambitious climate and energy targets for 2020 and beyond (EC, 2014a; EU, 2009a). Among bioenergy feedstocks, residues, including logging residues from forestry operations, are strongly supported under European legislation. Biofuels from residues are subject to multiple counting towards the renewable transport targets and are assigned zero greenhouse gas (GHG) emissions up to the point of collection (EU, 2009a). Furthermore, they are considered to cause low environmental impacts and very low Indirect Land Use Change (ILUC) emissions (EC, 2012).

Currently, no mandatory sustainability criteria at European level have been formulated for solid biomass used for power and heat production. However, the European Commission (EC) provided recommendations to Member States to develop criteria similar to the ones designed for liquid biofuels (EC, 2010). A recent document from the EC presented the state of play of bioenergy in the EU (EC, 2014b) and introduced updated typical and default GHG emissions values for a large selection of bioenergy pathways. A companion document (JRC, 2014) detailed the datasets and assumptions used to calculate those values.

The simplified life cycle methodology, applied in (EC, 2014b), accounts for the GHG emissions (CO_2, CH_4 and N_2O) related to the production of power or heat from biomass caused by: the combustion of fossil fuels, the combustion of biomass (only non-CO_2 GHG), cultivated soils, and direct Land Use Change (LUC). We define the system boundaries and the results obtained with this methodology as “supply chains” (Figs. 1 and 2). The EC methodology suggests that bioenergy should deliver GHG savings of at least 70% with respect to a defined fossil fuel system. The scope of such criterion is to compare the supply-chain GHG emissions of various bioenergy pathways on a common basis (GHG savings) to identify and exclude the pathways that perform worst on this relative scale.

Several Life Cycle Assessments (LCA) of wood pellets produced from various biomass feedstocks have generally reported high GHG savings when compared to an arbitrary reference fossil system (Caserini et al., 2010; Giuntoli et al., 2013; Magelli et al., 2009; Tsalidis et al., 2014).

However, many recent studies have demonstrated that the assumption of immediate carbon neutrality for forest biomass is not correct; the timing of carbon release and absorption as well as the inclusion of all the relevant carbon pools is essential to identify the climate performances of bioenergy (Agostini et al., 2013; Cowie et al., 2013; Helin et al., 2012; Matthews et al., 2014; McKechnie et al., 2011).

Other studies went beyond the carbon-only accounting to highlight that other climate forcers such as surface albedo change should be included in the analysis (Cherubini et al., 2012; Holtsmark, 2014). Further, it was pointed out that the quantification of the climate impact of bioenergy is also influenced by the specific climate metrics used (Cherubini et al., 2012). Cherubini et al. (2014) highlighted that biogenic-CO_2 may be assimilated to short-lived GHG and that its impact on peak temperature is determined by rates of emission rather than by cumulative emissions.

However, the way to account for the climate impact of bioenergy in policy is still debated in the scientific and policy community (Schulze et al., 2012; Bright et al., 2012; Haberl et al., 2013).

Finally, concerns over the impact of an increased removal of logging residues on forest ecosystems were raised and guidelines and mitigation measures have been proposed (IEA, 2014; Lamers et al., 2013; Fritsche et al., 2014; Sikkema et al., 2014).

We present a LCA that links together these various aspects of the environmental footprint of bioenergy in a case study related to domestic heating production from forest logging residues. The dataset presented in the JRC report (2014) is the starting point of our LCA but we complement those results by: i) defining three pathways with different end-use technologies; ii) expanding the system boundaries to include forest carbon stock development with and without removal of residues for bioenergy; iii) using instantaneous and cumulative absolute climate metrics (Absolute Global surface Temperature change Potential (AGTP)) to assess the response of the planet surface temperature to the production of heating by bioenergy and by the reference fossil system, evaluated at the year 2100; iv) including not only CO_2, CH_4, N_2O (Well Mixed GHG (WMGHG)) but also Near Term Climate Forcers (NTCF) and surface albedo change; v) quantifying life-cycle impacts on acidification, particulate matter emissions and photochemical ozone formation; vi) reviewing potential risks for forest ecosystems due to increased removal of residues.

We envision that this comprehensive assessment will help policymakers and local authorities to carry out their own assessment of possible risks and trade-offs when using logging residues for bioenergy, so that only the best pathways are promoted and the potential environmental risks are properly monitored and mitigated.

2. Materials and methods

2.1. Goal and scope definition

The LCA used is of the attributional comparative type, it analyses the environmental performance of three systems producing thermal energy for domestic use with forestry logging residues as biomass fuel. The term logging residues refers, in this context, to the crown mass (tops and branches with leaves, also called slash) and stumps (Helmisaari et al., 2014), produced as a result of commercial logging operations for the production of industrial wood (sawlogs and pulpwood). We did not include logs from any thinning operation.

We study three pathways: loose residues burned in a log-stove; a district heating plant utilizing forest chips and a domestic stove fuelled with wood pellets (see Fig. 1). The analysis is divided into two stages. In a first stage we focus on the supply chain impacts of the three bioenergy systems and we compare them to a fossil reference supply chain system using natural gas (NG) (Fig. 2). This approach is the one applied in European legislation for GHG emissions (e.g. typical and default GHG emissions values in EU (2009a)).

In the second stage we go beyond the EU methodology limitations and we expand the system boundaries to include the forest system. This approach reveals additional information on the land-use impacts of bioenergy as compared to the non-bioenergy system. We quantify the implications on the forest carbon balance and we review other possible risks and benefits posed to the ecosystem by an increased removal of logging residues.

The functional unit considered is 1 MJ of useful thermal energy; this includes losses due to start-up and shutdown, partial loads, thermal inertia and losses in the heat distribution system (Obernberger and Thek, 2010).

The environmental impact categories evaluated are: global warming, acidification, particulate matter and photochemical ozone formation. The physico-chemical properties of the wood are summarized in Table S1. We use the characterization models at midpoint recommended by the ILCD (2012) (Table S2). The characterization factors used are detailed in Tables S3–S4. The model used to calculate the response of global surface temperature to the

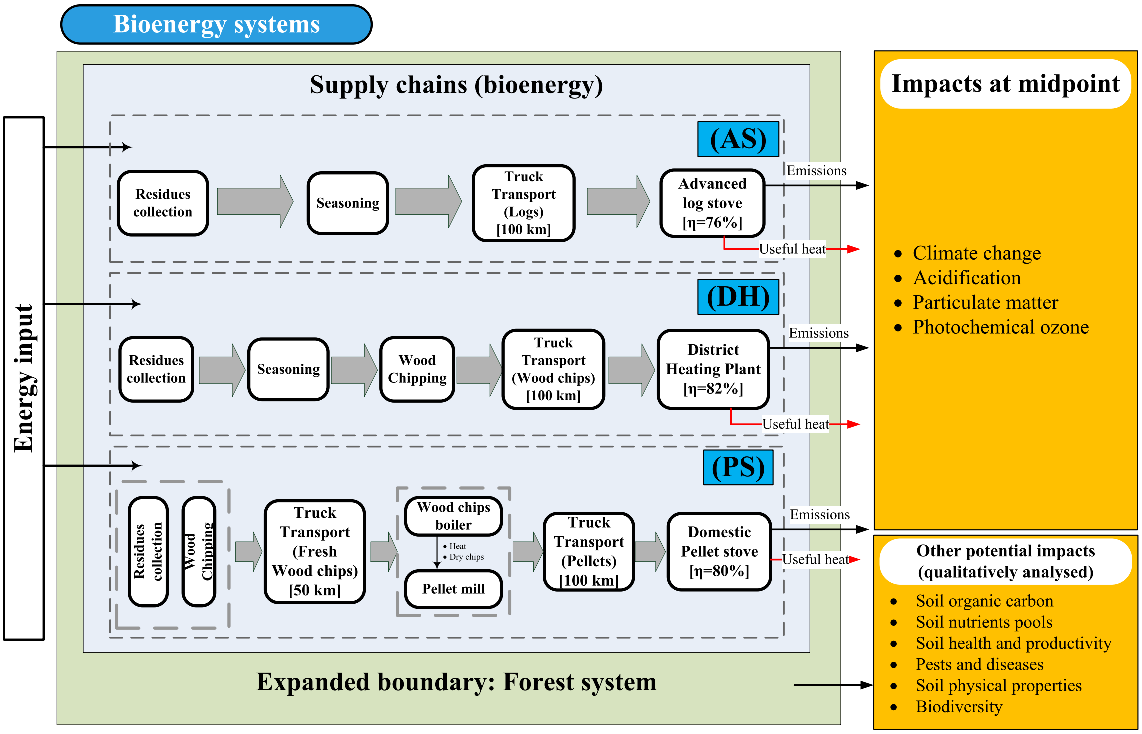

Fig. 1. System boundaries for the bioenergy systems, including supply chains and expanded boundary including the forest system. Environmental impacts quantified at midpoint and other impacts analysed qualitatively are also shown. AS = Advanced Stove; DH = District Heating; PS = Pellet Stove.

emission profiles from the systems is detailed in the Supplementary Material (SM). Infrastructures are not included. The geographical scope of the paper is the EU-28 countries. The software used is Gabi 6.3 from PE International. No allocation of emissions from timber logging operations is considered.

2.2. Life Cycle Inventory (LCI)

All the datasets related to collection and processing of the logging residues are the same as the ones presented in JRC (2014) (see SM).

We modify a few assumptions compared to the JRC report. Firstly, the conversion efficiency and pollutants' emissions associated to the final conversion of the biomass fuel to thermal energy are now based on published data (Table 1) as opposed to the standard conversion efficiency applied in the JRC report. Secondly, transport distances for the biomass fuels have been reduced to reflect more realistic conditions (100 km) compared to the fixed distance of 500 km considered in the JRC report. Thirdly, updated GWP(100) factors are used in this work for CO_2, CH_4 and N_2O (see Table S3), as compared to the GWP(100) values from the 4th IPCC Assessment Report used in the JRC report. Finally, the data for fossil fuel supply and combustion emissions represent average European conditions (PE, 2014) as compared to the values in the JRC report.

For illustrative purposes, we have chosen to compare the environmental impacts of the bioenergy pathways to the ones caused by a natural gas condensing domestic boiler with an annual thermal efficiency of 90%. The processes for the reference system are taken from the PE Professional database (2014). We have studied also the surface temperature change of two additional fossil

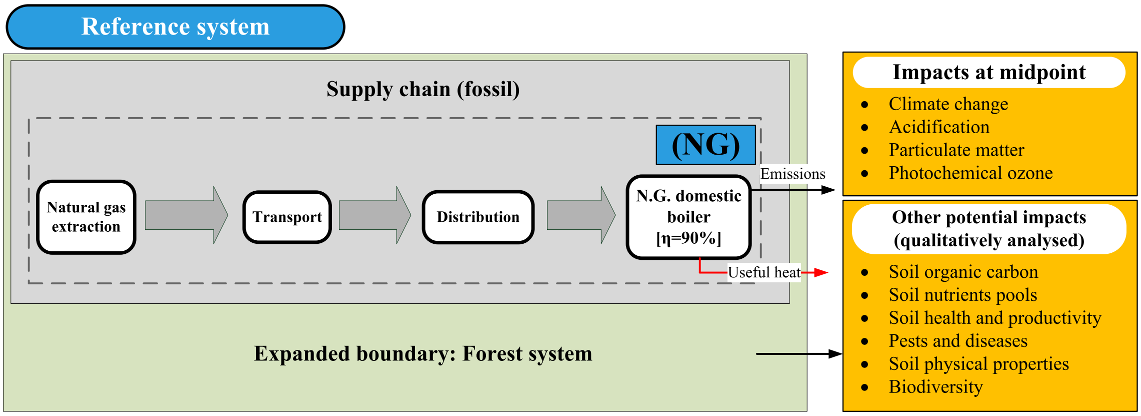

Fig. 2. System boundary for the reference fossil system and forest system. Environmental impacts quantified at midpoint and other impacts analysed qualitatively are also shown. NG = Natural Gas boiler.

Table 1
Emission factors considered for the combustion technologies studied: Advanced log Stove (8 kW_{th}); wood chips-fired District Heating plant (5 MW_{th}); Pellet-fired domestic Stove (8 kW_{th}). Values are derived from the sources reported in the table. All values are reported in mass of pollutant per GJ of fuel input.

Parameter	Unit	Advanced stove (AS)	District heating plant (DH)	Pellet stove (PS)	Sources (AS; DH; PS)
Thermal efficiency	%	76	82[a]	80	(Ozgen et al., 2014; Obernberger and Thek, 2010; id.)
Electricity	$MJ\ MJ^{-1}{}_{in}$	0	0.02	0.015	(-; Ecoinvent, 2010; GEMIS, 2014)
CO	$g\ GJ^{-1}{}_{in}$	5000	50	150	(Ozgen et al., 2014; Pola, 2012; Pretto, 2012; Lamberg et al., 2013)
NOx	$g\ GJ^{-1}{}_{in}$	110	150	100	(Ozgen et al., 2014; Pola, 2012; Pretto, 2012; Lamberg et al., 2013)
SO_2	$g\ GJ^{-1}{}_{in}$	11	11	11	(EEA, 2013; id.; id.)
CH_4	$g\ GJ^{-1}{}_{in}$	4.9	4.9	3.0	(JRC, 2014)
NMVOC	$g\ GJ^{-1}{}_{in}$	350	10	5.0	(Ozgen et al., 2014; Pola, 2012; Pretto, 2012; Lamberg et al., 2013)
N_2O	$g\ GJ^{-1}{}_{in}$	1.0	1.0	0.6	(JRC, 2014)
Total Solid Particles (TSP)	$g\ GJ^{-1}{}_{in}$	200	11	31	(Ozgen et al., 2014; Pola, 2012; Pretto, 2012; EEA, 2013)
PM2.5	$g\ GJ^{-1}{}_{in}$	190	11	29	(Ozgen et al., 2014; Pola, 2012; Pretto, 2012; EEA, 2013)

[a] The thermal efficiency value includes not only the combustion efficiency but also the thermal losses due to heat distribution at the end user site.

references: coal and light fuel oil. The emissions from these systems are also from PE (2014) and a thermal efficiency of 90% is used. We use these values as a simple comparison without any other assumption on actual replacement.

When comparing the bioenergy system with the reference system, it is important to keep in mind the counterfactual development of the forest system in the absence of biomass removal for bioenergy.

For the case of residues from logging operations, in most circumstances if these materials were not used for energy production, they would be left on the forest floor and this is also our assumption for the residues in the reference system. It is crucial to consider the development of the carbon pool constituted by the residues to have an appropriate picture of the timing of the biogenic carbon cycle and the actual contribution of the bioenergy pathways to climate change.

We assumed that wood left in the forest would decompose following an exponential decay (as shown in Eq. S1); the kinetics of decomposition varies depending on the wood type, wood size and climate conditions (Pilli et al., 2013). A baseline decay rate for branches with diameter between 10 and 30 mm, was defined for average conditions in boreal and temperate regions, equal to 11.5% $^*yr^{-1}$ (see Table S9). Furthermore, we investigate the sensitivity of the surface temperature response to a range of possible decay values spanning between 40%$^*yr^{-1}$ (e.g. fast decaying leaves and needles) and 2%$^*yr^{-1}$ (e.g. slow-decaying coarse dead wood). Other models exist (Ågren et al., 2007; Repo et al., 2012) that evaluate the decay of forest residues based on more accurate functions of wood composition and local climate conditions. However, simple exponential decay models have been often successfully used to fit experimental data (Melin et al., 2009; Shorohova et al., 2012).

By condensing all possible variables (climatic conditions, wood type, wood size and also modelling variations) into a single parameter, the decay rate, our approach can then be applied independently from all the specific conditions that generated such decay rate.

All the carbon is considered to be released as CO_2 by the unharvested residues because the conditions in forest soils are generally aerobic (Anderson et al., 2010). A more detailed spatial analysis of the carbon cycle could be obtained with specific geographic and climatic data (Pilli et al., 2013; Repo et al., 2014), but the general approach of our results make them valid for a wide range of conditions as long as the decay rate is known.

2.3. Climate metrics

The 'GHG savings' indicator is the result of a comparative, attributional LCA and it is used in several EU legislative documents (EU, 2009a, 2009b) to assess the climate change mitigation effects of bioenergy as compared to fossil fuels. Although this approach has merits of simplicity and clarity, essential for regulatory purposes, it should not be interpreted as a direct and accurate measure of the climate mitigation effects of a policy because indirect and scale effects are ignored (Plevin et al., 2013).

Furthermore, when transient emission profiles are present, such as the change in forest floor carbon pool considered in this study, the use of simplified, normalized metrics is problematic. In fact, depending on the time horizon chosen for annualization of the carbon stock change, the result of the analysis changes significantly (see Fig. S2). For these reasons, we assess the climate impact of the systems calculating the Surface Temperature Response (STR) to the systems by 2100. We base our analysis on the Absolute Global surface Temperature change Potential (AGTP) metric. Because of the uncertainties associated to the climate metric and to the input values, our goal is not to quantify the magnitude of absolute temperature responses but rather to assess the climate impacts of the various systems relative to each other. A description of the model, equations and parameters used, based on the work of Myhre et al. (2013), Aamas et al. (2013) and Cherubini et al. (2013), can be found in the SM. The case has been made that temperature response metrics may be more suitable than the widely accepted Global Warming Potential to represent the contribution of bioenergy to long-term temperature-based targets for climate change (Cherubini et al., 2014). These metrics allow for the consideration of specific emission profiles which are not simply constant in time. We consider two cases representative of possible energy system developments in the future (Fig. S1): Case 1) a continuous production of 1 MJ_{heat} each year. This case would represent a systemic change in which bioenergy becomes permanently part of the energy mix. Case 2) a sustained production of 1 MJ_{heat} for 20 years, considered the lifetime of the heating systems, after which the forest residues continue to be produced and to decompose on the forest floor. This case considers bioenergy as a transitional solution towards an energy mix based on other renewable resources. We present the Surface Temperature Responses calculated as an endpoint (SRT(i)) and as an integrated (SRT(c)) metric. The latter can be assimilated to the Absolute Global Warming Potential metric (Peters et al., 2011).

3. Results

3.1. Supply-chain GHG emissions and GHG savings

The supply-chain GHG emissions are summarized in Fig. 3. We found GHG savings above 90% for the logs(AS) and chips(DH) pathways; 80% for the pellets(PS). The main contributor to this

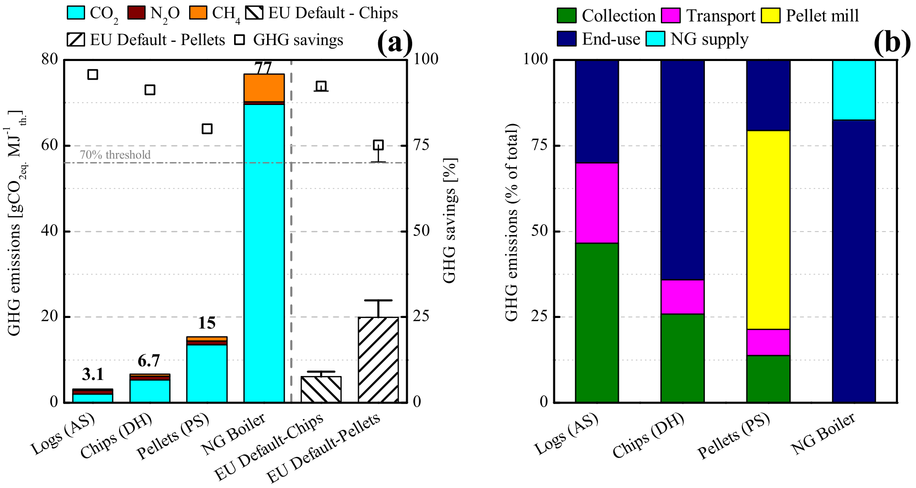

Fig. 3. Supply chain GHG emissions for bioenergy and natural gas (NG) boiler: only WMGHG and no emissions from changes in forest carbon stock are considered. Evaluation is based on GWP(100) with climate feedback as indicated in Myhre et al. (2013). (a) GHG emissions for the wood pathways and fossil system per MJ of useful heat. The bars are stacked based on the contributing gases. The total value is written on top of the bars. The square symbols represent GHG savings of bioenergy compared to the natural gas boiler (right y-axis). Striped bars represent the typical and default (error bar) GHG emission values given in JRC (2014) and the associated GHG savings. These values were calculated with GWP(100) from IPCC 4AR. (b) GHG emissions from the wood pathways and fossil system, contribution of the different processes expressed as percentage of the total impact value.

impact in the pellets(PS) pathway is fossil CO_2 associated with the electricity consumed in the pellet mill (52% of total emissions). The contribution from transport is relatively small for chips(DH) and pellets(PS) pathways, 10% and 7.6% of the total, respectively. However, because of the very low emissions associated to the logs(AS) pathway, transport emissions contribute 22.5% of the impact.

Emissions of N_2O are responsible for 27%, 13%, 6% of the total impact for the logs(AS), chips(DH) and pellets(PS) pathways, respectively. Most of the emissions are due to the direct and indirect emissions from biomass combustion. Emissions of methane, both biogenic and fossil, have a minor influence, amounting to 9%, 8% and 7% for the logs(AS), chips(DH) and pellets(PS) pathways.

The total amount of non-CO_2 GHG emissions from the end-use of biomass, including direct and indirect emissions from combustion and from electricity consumption, equals 30% of the total for the logs(AS) pathway, 18% for the chips(DH) pathway and 5% for the pellet(PS) pathway.

For comparison, the typical GHG emission values defined in the JRC report (2014) are 6.0 $gCO_{2\ eq.}/MJ_{th.}$ for wood chips and 20 $gCO_{2\ eq.}/MJ_{th.}$ for pellets. The default values, which can be directly used by operators in EU legislation, are higher because increased of a conservative factor (EC, 2014b).

The results presented in this section follow the general assumption, also commonly employed in legislation (EC, 2014b), that emissions of biogenic-CO_2 from biomass combustion can be considered equal to zero.

3.2. *Forest carbon emissions and surface temperature response*

If the residues were not collected and combusted, they would still decompose on the forest floor. For this reason, the difference between the carbon that would be retained in the forest in absence of using residues for bioenergy and the carbon that is emitted by combusting them reaches a steady state in time (Fig. S1—Case 1). Possible long-term effects on soil organic carbon and fertility are not quantified here, but they are analysed in Section 3.4.

Fig. 4 illustrates the results for case 2, i.e. 20 years of production, for both the instantaneous and cumulative surface temperature response considering branches as feedstock. The total impact is also shown as disaggregated contributions by the various climate forcers. The cooling impact of NTCF (aerosols and ozone precursors) and surface albedo change contributes to mitigate only about 10% of the temperature increase due to WMGHG by 2100. The instantaneous net temperature response to biogenic CO_2 tends to zero in the long term (ca. 50 years) because the forest floor residues would decompose in both the bioenergy and non-bioenergy systems.

The total cumulative surface temperature response (Fig. 4b) of a system fuelled with natural gas becomes larger than the one of the bioenergy system, fuelled with branches, after about 30 years and the potential saving in temperature increase by the end of the century amounts to about 60%.

Fig. 5 illustrates the STR(i) for Case 1 and 2, including a range of responses associated with different decay rates. All considerations refer to the year 2100. The final impact on global temperature for a sustained production (Fig. 5a) is lower, compared to NG, for bioenergy pathways with decay rates above 2.7%*yr^{-1}. When other fossil sources are considered, the impact of fuel oil is basically equal to a bioenergy system using residues with a decay rate of 2%*yr^{-1}. Coal causes a higher temperature increase than any bioenergy system considered. Decay rates smaller than 3%*yr^{-1} can be associated to very slow-decaying wood residues such as dead stems (Pilli et al., 2013) or stumps in northern boreal conditions where decay rates as slow as 1.7%*yr^{-1} were measured (Shorohova et al., 2012). The response of the coal system shows a net cooling impact for about 10 years after the start of the analysis. This is due mainly to the emissions of SO_2 (and partially of NOx) from the coal system (see Fig. S4). Concerning this phenomenon, Kaufmann et al. (2011) found that the hiatus in global surface temperature increase in the decade 1998–2008, despite rising greenhouse gas concentrations, could be statistically explained with the large-scale deployment of coal plants in China and the subsequent surge in SO_2 emissions. Kaufmann et al. (2011) reported that as a result, the net anthropogenic forcing has risen slower than in previous decades. Large uncertainties are associated with the definition of proper metrics for short-lived gases (Myhre et al., 2013), however, despite this short-term effect, the long-term impact of fossil–CO_2 makes coal the worst system for the climate change impact category among the ones analysed, even considering a temporary production (Fig. 5b).

When a system is considered to produce heat for only 20-years (Fig. 5b), all the bioenergy options have a smaller impact in 2100 than any fossil source considered, although with different trajectories. Branches begin to deliver mitigation compared to NG after 20 years, but slow-decaying residues become better than NG only

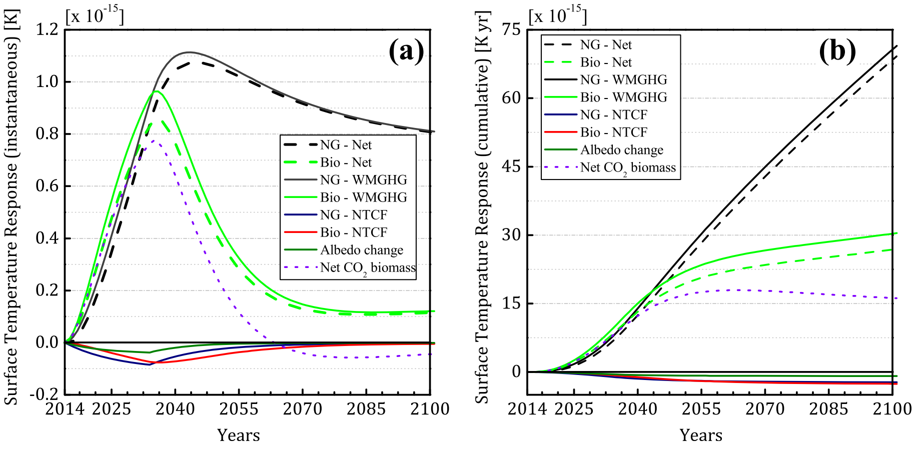

Fig. 4. Surface Temperature Response instantaneous (a) and cumulative (b) for NG and pellets(PS) pathway for a system producing 1 $MJ_{th.}$ per year for 20 years (Case 2), utilizing branches as feedstock. Dashed lines (NG-Net and Bio-Net) represent the net impact of all forcers while the solid lines illustrate the contributions to the impact from WMGHG, NTCF and surface albedo change (for bioenergy). The dotted line represents the net contribution of biogenic CO_2 between direct biomass combustion and forest floor decomposition.

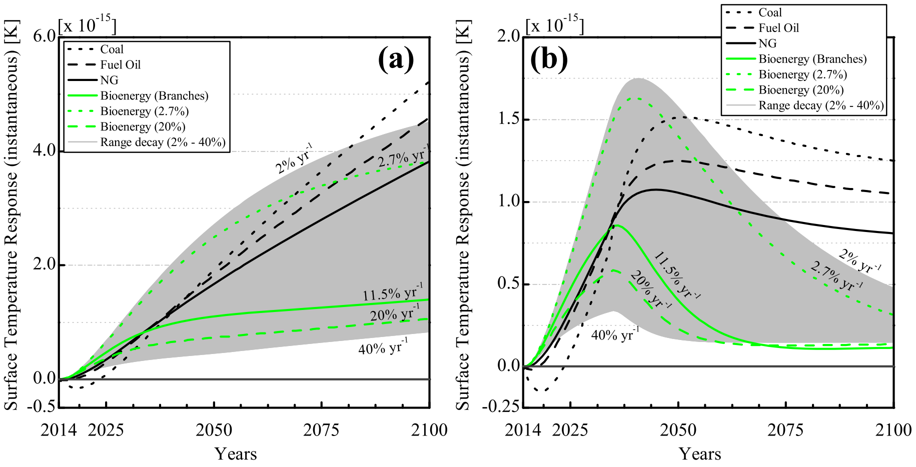

Fig. 5. Surface Temperature Response (instantaneous) to a sustained emission profile for fossil systems (NG, fuel oil and coal) and pellets(PS) pathway. (a) STR(i) for a system with emission profiles relative to the production of 1 MJth. per year (Case 1); (b) STR(i) for a system operating for 20 years (Case 2). The grey-filled area represents the range of responses when different decay rates for the biomass feedstock are considered. The solid-green curve represents the baseline case of branches (11.5%*yr^{-1}), the dashed-green curve represents fast decaying residues (e.g. leaves and needles) and the dotted-green curve represents a "critical" decay rate for which the STR(i) at year 2100 is equal between bioenergy and NG system. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

after more than 50–60 years. Further, these feedstocks reach a temperature response peak which is about 52–63% higher than the peak from NG system. Consequently, the time and rate of implementation and deployment of bioenergy systems may determine whether such a system can actually contribute to limit the temperature anomaly at the end of the century.

3.3. *Other environmental impacts*

3.3.1. *Acidification*

Fig. 6a–b show that the bioenergy systems score worse than the fossil system. The impact of the wood pathways is between 1.5 and 2.5 times higher than that of the NG boiler. Direct emissions from biomass combustion account for about 94%, 86% and 48% of the total impact for the logs(AS), chips(DH) and pellets(PS) pathways, respectively. For the pellets(PS) pathway, 40% of the impact is associated with the pellet mill, due to the emissions from chips combustion for drying purposes (21%) and to the emissions of NOx and SO_2 from the fossil electricity from the grid (19%).

3.3.2. *Particulate matter/Respiratory inorganics*

Impacts from the wood pathways are also higher than the NG reference system (Fig. 6c–d). Especially for the logs(AS) pathway the total particulate matter impact is even 5 and 14 times higher than the chips(DH) and pellets(PS) pathways, respectively. For the logs(AS) 98% of the impact is due to PM2.5 emissions from the stove. Also for the chips(DH), the direct emissions of PM2.5 account for 72% of the total impact. The direct emissions of PM2.5 from the pellet stove and the boiler in the pellet mill have a major impact in the pellets(PS) pathway, accounting for 83% of the total impact. The impact of NG is due almost completely to secondary particulates: emissions of NOx are dominant from combustion while emissions of SO_2 are associated with the supply-chain processes.

3.3.3. *Photochemical ozone formation*

The impact from the bioenergy pathways on photochemical ozone formation is more than 2.5 times the one caused by the NG boiler (Fig. 6e–f). The logs(AS) causes an impact which is more than 4 times the one of the other bioenergy options.

Emissions of NOx are the main responsible for this impact and they account for about 90% of the total impact for the pellets(PS) and chips(DH) pathways. The rest of the impact is due to the emissions of: NMVOC (7%); CO and SO_2. For the logs(AS) the main responsible are the emissions of NMVOC (51%), together with CO (33%) and NOx (16%). The impact due to NOx emissions from direct

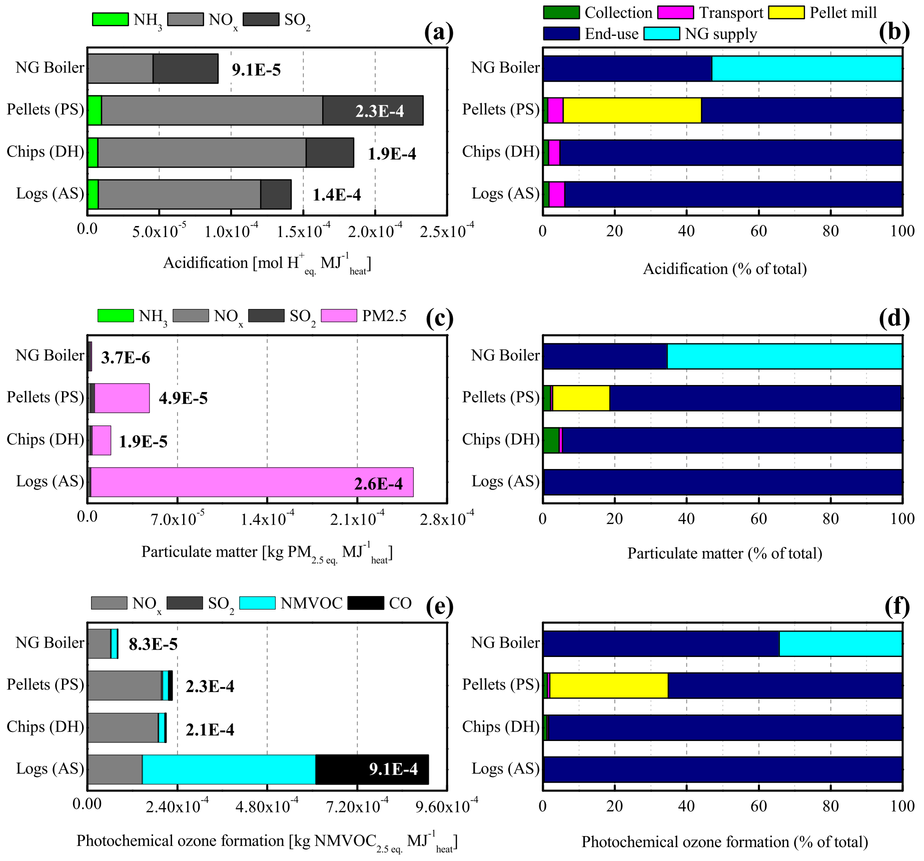

Fig. 6. (a) Acidification potential (AP) for the wood pathways in their base case and reference system, bars are stacked based on the contribution of the most relevant species. The first two bars on the left represent values of emissions per MJ of fuel at plant gate. (b) AP contribution (% of total) of the different processes. (c) Particulate matter/Respiratory inorganics (PM) for the wood pathways in their base case and reference system. (d) PM contribution (% of total) of the different processes. (e) Photochemical ozone formation potential (POFP) for the wood pathways in their base case and reference system. (f) POFP contribution (% of total) of the different processes.

combustion account for 87% of total impact for the chips(DH) pathway and for 79% for the pellets(PS) pathway.

3.4. Other bioenergy-induced environmental risks

Beside the environmental impacts quantified in section 3.3, increased removal of logging residues from the forest ecosystem poses other potential risks. We reviewed recent studies and identified a series of potential impacts relating to: Soil Organic Carbon (SOC) accumulation; soil health and productivity; soil nutrients pools; soil physical characteristics, and biodiversity. The results are summarized in Table 2. Empirical studies in the literature have shown that many of the negative impacts can be mitigated or avoided by applying a set of practices in forest management. Some of these measures are also listed in Table 2.

4. Discussions

4.1. Supply-chain GHG emissions and GHG savings

The supply-chain GHG emissions calculated are consistent with the typical and default values defined in European legislation, even if a different LCA methodology and more realistic assumptions over conversion efficiencies, transport distances and end-use processes are considered. However, both the EU default values (JRC, 2014) and our results may underestimate total GHG emissions because the possible production of methane during storage of chips and pellets is not included. Values in the range of 16–40 $gCO_{2eq.}/MJ_{woodchips}$ have been proposed (Jäppinen et al., 2014), but additional data need to be collected.

In its design, the Directive 2009/28/EC, and the documents connected to it, evaluates the supply-chains GHG emissions of various bioenergy pathways and compares them to each other on a common basis (GHG emission savings with respect to a fossil fuel comparator) to promote the pathways that perform best on this relative scale and to exclude the pathways with the worst technologies. In this respect, the three bioenergy pathways using forest logging residues comply with the 70% GHG savings threshold suggested and perform better than other bioenergy pathways (see e.g. Boulamanti et al., 2013; JRC, 2014).

4.2. Climate impact: system boundaries expansion and surface temperature response

Carbon is at the core of current EU climate policies that mostly measure the effectiveness of climate mitigations actions into GHG emissions and savings. However, other climate forcers may contribute to the impact of bioenergy on climate change. Surface albedo change for some biomass feedstocks, such as stemwood logs sourced from clear-cut of boreal forests, has been shown to compensate or strongly mitigate the impact of reducing forest carbon stocks, especially in snow-covered lands (Cherubini et al., 2012; Holtsmark, 2014). However, our analysis indicates that surface albedo change, aerosols and ozone precursors' emissions play a limited role in the three bioenergy pathways analysed when compared with the magnitude of impact due to WMGHG (Fig. 4).

Table 2
Literature review of potential environmental risks and benefits associated with the increased removal of forest logging residues from the forest ecosystem. Mitigation measures proposed in literature are also reported for each category. Impacts are categorized as: risks ("-"), benefits ("+") or no difference between removal and reference use (" = ").

Impact category	Potential risks/benefits	Mitigation measures
Soil organic carbon	= A reduction of SOC associated with whole-tree harvesting was predicted by various modelling studies (Wall, 2012). However, meta-analyses of field studies have not substantiated such results. Only a small percentage of the experimental data analysed indicated a decrease in SOC when removing logging residues (Johnson and Curtis, 2001; Nave et al., 2010; Wall, 2012). However, the actual effects on SOC may become evident in the very long-term. = Stump removal is responsible for soil disruption at depths reaching 1 m (Moffat et al., 2011). This could favour soil mixing and mineralisation.	
Nutrients pool[a]	- More than half of total tree N stock is contained in logging residues for spruce and pine. Of this amount, about half is contained in needles and it is released faster than the N in branches. Thus, removing residues may impact mostly the quantity of available N rather than total N soil stock (Tuomasjukka et al., 2014).However, N depletion is considered more critical in areas of low atmospheric deposition and in low-fertility soils (Wall, 2012). - Experimental results consistently indicate decreases in calcium, potassium, magnesium and phosphorus when residues are removed (Wall, 2012). - Increase of the acidity of soil is also recorded (Wall, 2012). - Therefore, soils with low fertility and smaller nutrient pools are more subject to suffer from the removal of residues and nutrients (Fritsche et al., 2014). - Stumps contain a small fraction of macronutrients, but coarse roots are responsible for significant inputs of nitrogen and potassium to the soil (Moffat et al., 2011).	• Leaving foliage and needles,as well as bark, on the forest floor could largely mitigate the losses of nutrients and growth losses associated with the removal of logging residues (Egnell, 2011; Lattimore et al., 2009; Tuomasjukka et al., 2014). • Mitigation of soil acidification via liming could be considered, but negative effects on tree growth have been reported when applying lime on forest soils (Saarsalmi et al., 2011). • Re-application of combustion ashes could also return some macronutrients to the soil, but the eventual positive effects of ash application on tree growth are still uncertain. Data even suggests decreased growth when ashes are recirculated on nitrogen-poor soils (IEA, 2014). • Nitrogen is almost completely lost during combustion, so it is not present in ashes and will need to be supplied via synthetic or organic fertilisers. Experimental data have shown increased growth rates in fertilised forests, but guidelines in some countries still advise against synthetic forest fertilisation (Fritsche et al., 2014; Stupak et al., 2007). • Avoid extraction on rocky, dry and poor soils (Lamers et al., 2013; Wall, 2012)
Soil health and productivity	= Many studies have shown results that are not statistically different when comparing trees grown on sites where residues are either collected or left on floor. + Some studies have shown smaller diameters for trees grown in areas where residues were regularly removed. This has been linked to the initial soil nutrients capital and the relative fraction of nitrogen removed with the residues (Holub et al., 2013; IEA, 2014; Thiffault et al., 2011).	• Measures to compensate for nutrients losses may actually have negative consequences on forest growth (see above). These measures should thus be assessed on a case-by-case basis by developing site-specific nutrient management regimes (Lamers et al., 2013). • A combination of ash recirculation and urea supply has shown increased volume production of almost 45% compared to the control study (Saarsalmi et al., 2012). • Negative impacts of residues accumulation have also been reported. An abundant bed of residues may delay the stand establishment by as long as one year (Hakkila, 2004) and excessive, long-term accumulation of residues on the forest floor could limit productivity (Grigal, 2000).
Pests and diseases	+ Removal of stumps and coarse roots has been shown to be an effective method to prevent the spread of diseases caused by fungal pathogens such as root rot (Cleary et al., 2013; Moffat et al., 2011).	
Soil physical properties	- Increased risk of surface erosion is due to the exposure of mineral soil, which provides routes for accelerated water movement (e.g. roads and skid trails), and the removal of natural debris jams. - The increased use of machinery to collect residues (Hakkila, 2004) can cause soil compaction leading to a decrease in soil aeration, water infiltration and root growth (Fritsche et al., 2014; Moffat et al., 2011). = Mild compaction has been shown to have no significant negative effects on tree growth (Holub et al., 2013). + Residues removal could also have a positive effect, such as earlier warming of soil in the spring, and consequently earlier and greater root growth (Devine and Harrington, 2007).	• Avoid stump removal on steep slopes, and on rocky and dry soils (Lamers et al., 2013; Lattimore et al., 2009) • Harvest in winter and when soil moisture is low (Lamers et al., 2013; Lattimore et al., 2009) • Use of low-impact machinery and on soils with good-bearing capacity (IEA, 2014; Lamers et al., 2013)
Biodiversity	- Increased harvest of forest residues causes the removal of niche habitats for saproxylic organisms (i.e. dead and downed wood) with a potential cascading effect on the whole ecosystem. - Reported experimental data also indicate a significant reduction in abundance and diversity of bird species when dead wood is removed from the forest. A possible correlating factor is the decrease of invertebrates and insects in areas where forest residues are extracted (Riffell et al., 2011; Victorsson and Jonsell, 2013). - Piles of branches and tops can become traps for eggs and larvae when they are removed from the forest and combusted (IEA, 2014). - Another important issue is linked with forest simplification and the possible introduction of new invasive species in heavily harvested stands (Fritsche et al., 2014).	• Fine woody debris like tops and branches from conifers stands are less likely to be host to red-listed wood-living species, as opposed to coarser dead wood. To minimize impacts on biodiversity, fine woody debris should be removed mainly from conifers stands while much stringent removal rates should be allowed for coarse woody residues, such as stumps, and for residues in general from deciduous stands (IEA, 2014). • Hetrogenerity of dead wood is important for biodiversity. Müller and Bütler (2010) found that dead wood quantity has a positive correlation with dead wood diversity. Minimum threshold values for maintainement of dead wood could thus be defined on a local basis, but more research is needed (Tuomasjukka et al., 2014). • Special care should be placed on areas where biodiversity is still rich (Tuomasjukka et al., 2014) • Create and maintain adequate buffer zones (Lattimore et al., 2009).

[a] Many empirical tests apply a complete removal of residues to amplify the magnitude of the results. These results could thus be considered as the upper limit of potential impacts.

Therefore, in the case of forest logging residues, analyses that focus solely on WMGHG, and CO_2 in particular, can deliver results which are accurate enough for many applications.

Another important parameter is the decay rate of the forest residues and, generally, what happens to the wood left in the forest. Decay rates depend on forest characteristics, wood type and on climate conditions. Also, the decay rates may change in time due to climate change. Our study provides general results in function of specific decay rates, irrespective of these factors.

Furthermore, the model of exponential decay used may underestimate the long-term temperature change caused by bioenergy because it does not foresee any sequestration in the soil organic carbon pool. Other models predict that a fraction of the initial carbon is incorporated into the more stable SOC (Repo et al., 2012). On the other hand, wildfires could speed up the rate of carbon released from the forest floor but their influence is difficult to model because of their stochastic nature, the difficult evaluation of the extent of carbon losses during natural fires and the possible role of climate change in exacerbating forest fires frequency and regimes (Liu et al., 2010).

In situations where the reference use of residues is combustion on-site, the missed accumulation of carbon stock in the forest should not be attributed to bioenergy because this would happen in both the reference and the bioenergy systems. Bioenergy has then immediately lower impact on surface temperature than fossil systems.

Market-mediated effects are not considered here because the logging residues studied are unlikely to have any other major industrial use if not energy. For other biomass feedstocks, such as sawnwood, these will need to be considered using a more consequential approach and dynamic economic models (Agostini et al., 2013; Plevin et al., 2013).

Despite these limitations, we show that bioenergy from logging residues does not contribute to climate change mitigation *per se*; in fact, due to the consumption of fossil fuels for processing and to the decrease in forest carbon stock, the systems analysed have an overall positive contribution to surface temperature increase. However, we also demonstrate that bioenergy is generally beneficial to mitigate the surface temperature increase by the year 2100 compared to the use of natural gas and other fossil sources. The choice of biomass feedstock and the timing and rate of bioenergy technologies deployment, though, should be carefully considered by decision-makers. Investing now in the mobilization of tops and branches for heat production can reduce the temperature increase by 2100 both in case of bioenergy as a systemic change (continuous production) or in case of bioenergy as a transitory option (20-years case) as compared to all the fossil options studied. However, sustained production of heat from NG causes a lower temperature increase compared to bioenergy produced using slow-decaying wood (i.e. with decay rate smaller than $2.7\%^*\mathrm{yr}^{-1}$) for more than 100 years, and for almost 200 years if the cumulative impact is considered (Fig. S3). For transitory systems, a delayed market penetration may hinder any temperature increase mitigation by 2100.

4.3. Other environmental impacts

We show that bioenergy systems have higher environmental impacts associated with local pollution than the natural gas alternative. This is not limited to the use of logging residues but it is a more general issue with small and medium-scale bioenergy plants (e.g. Boulamanti et al., 2013; Giuntoli et al., 2013). On the one hand, the composition of the biomass fuels, rich in N and S, causes higher emissions of pollutants such as NOx and SO_2 than natural gas. On the other hand, the small scale of bioenergy installations and the subsequent absence, or limited deployment, of flue-gas cleaning technologies is responsible for higher environmental impacts compared to large-scale, centralized fossil power or heat plants. Technological advancements may help decrease NOx and particulate matter emissions also from small-scale bioenergy installations.

This study confirms that the end-use of biomass is the main responsible for many of the environmental impacts quantified. In order to manage the increase in local air pollution due to bioenergy stoves some actions can be envisioned: some more extreme (e.g. limiting the amount of wood stoves in specific critical urban areas), some with a broad scope (e.g. promoting where possible larger, centralized installations where proper emission control measures can be installed), some with a more targeted scope (e.g. information campaigns on the correct use of wood stoves or promotion of pellet stoves).

Trade-offs exist with the climate cooling properties of some of the pollutants (mainly NOx and the organic carbon fraction of particulate matter). However, the mitigation role of NTCF identified in section 3.1 is very small in the case studied.

Our review also confirms that additional extraction of logging residues may pose potential risks to the forest ecosystem. In the EU, the managed forests are largely certified under a sustainable forest management scheme. However, worldwide a larger share of managed forests, including areas from countries which are current or potential exporters to the EU, is not certified (Sikkema et al., 2014). Furthermore, certification may not always guarantee sufficient protection against new management practices such as slash removal and whole-tree harvest. In order to guarantee long-term soil productivity, best management practices or local harvest guidelines should be promoted, designed and implemented (Sikkema et al., 2014), preferably using quantitative risk indicators (Thiffault et al., 2014).

5. Conclusions

Biomass residues are generally considered to: (1) be able to guarantee high GHG savings and (2) to contribute to climate change mitigation, without (a) affecting other markets or (b) causing negative impacts on the environment.

We show that the first assumption is correct when only supply-chain emissions (excluding biogenic-CO_2) are considered. GHG savings achieved by the three pathways analysed are indeed above the threshold of 70% suggested by the EU.

However, the actual climate impact of bioenergy can only be assessed by accounting for the non-bioenergy uses of biomass feedstock and by including all climate forcers. Concerning the latter, the results suggest that a CO_2-only approach could be an appropriate proxy to rank simple systems (in an attributional LCA perspective) provided that the following conditions apply to all systems: 1) limited emissions of other WMGHG (namely CH_4 and N_2O), 2) limited impacts from NTCFs and a long-term horizon of the analysis and 3) limited impacts from biogeophysical forcers (namely surface albedo change).

We show that the contribution to surface temperature increase by the end of the century of using biomass instead of natural gas depends on the decay rate of the residues used, on the timing and rate of bioenergy deployment and on the strategy for bioenergy production. Investing in the long-term sustained production of bioenergy from slow-decaying wood with decay rates smaller than $2.7\%^*\mathrm{yr}^{-1}$ will not lead to any climate change mitigation, within the year 2100, compared to natural gas systems currently in place. This conclusion, as well as others, may change with the changing future natural gas supplies; however the approach used remains valid and a parity decay rate (higher or lower) may be identified. A different time-horizon may also lead to different conclusions.

Furthermore, we highlight that several environmental impacts are indeed associated with the use of forest logging residues for bioenergy. These issues concern mostly local air pollution, biodiversity loss and, mainly for stumps, physical damages to forest soils.

Forest logging residues are not free of environmental risks. Any action promoting their use for bioenergy should consider: (i) that climate change mitigation depends mainly on the decay rate and on the time of technology deployment, (ii) whether management guidelines aimed at protecting long-term forest health are in place and (iii) whether proper actions for the management of adverse effects on local air pollution are in place.

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Appendix A. Supplementary data

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