

# ASSESSING THE CLIMATE MITIGATION POTENTIAL OF BIOFUELS DERIVED FROM RESIDUES AND WASTES IN THE EUROPEAN CONTEXT

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## EXECUTIVE SUMMARY

In recent years, biofuels from residues and wastes have gained greater attention in low-carbon fuel regulations. Such fuels have a substantial potential role in reducing GHG emissions from the transport sector and hence contribute to economy-wide GHG emission reduction goals. To help accelerate their emerging development, these advanced biofuels are eligible for “double counting” incentives within the 10% renewable energy content requirements in the transport sector under the existing Renewable Energy Directive (RED). To further advance the growth of sustainable biofuels from residues and wastes, an enhanced support system is being discussed that would provide increased multiple credits or a sub-target for cellulosic biofuels from waste and residues.

The partner study in this project on the availability of waste and residue feedstock in Europe (Searle & Malins, 2013) identified that if all of the sustainably available resource could be collected and used, up to 13% of EU road transport fuel in 2020 could, in principle, be produced this way. While previous life cycle analysis (LCA) studies have tended to confirm the strong performance of these biofuels with regard to carbon emissions, their calculations have sometimes ignored potentially important emissions sources. Accurately assessing the magnitude of climate benefits offered by wastes and residues requires incorporating all major sources of greenhouse gas (GHG) emissions, including indirect emissions, but the existing RED methodology for estimating GHG emissions of biofuels omits soil carbon loss and indirect GHG emissions from diverting residues and wastes from their existing uses. The goal of this study is to estimate the GHG carbon intensities and GHG emission savings of cellulosic biofuels by percentage from residues and wastes compared with gasoline and diesel. The study uses a comprehensive carbon accounting approach that incorporates both direct and indirect GHG emissions, including soil carbon loss.

This paper conducts a novel analysis of the carbon intensity of several advanced biofuel pathways and processes. We use the United Kingdom Department for Transport biofuels carbon calculator as a LCA framework, adding modules to capture additional GHG emissions in the expanded system boundary and considering a project time frame of 20 years. We analyze eight types of agricultural residues, one type of forest residues (“slash,” which refers to tree tops, twigs and branches), biogenic municipal solid waste, and sawdust. These feedstocks are based on the potentially sustainably available feedstocks in the EU. For each feedstock, we consider three biofuel pathways: biochemical ethanol, Fischer-Tropsch diesel, and pyrolysis diesel.

Our study shows that cellulosic biofuels derived from agricultural residues offer substantial GHG savings exceeding 60% for all three biofuel pathways, even given the expanded system boundary. The GHG benefits are even higher for biogenic municipal solid waste, where feedstock collection can result in avoided methane emissions. There is also an extra methane credit for using rice straw. Biofuel from sawdust is also shown to offer more than 60% GHG savings despite appreciable indirect emissions.

The GHG emission savings of cellulosic biofuels produced from slash are found to be dependent on the magnitude of soil carbon loss due to residue harvest, as well as on expected residue decomposition rates. Still, provided that soil carbon loss is minimized, biofuel from slash offers 20-year GHG savings greater than 50%, even considering these additional emissions sources. Additional long-term empirical studies on biomass decomposition rates and soil carbon loss due to slash removal will provide clarity on the potential roles advanced biofuels from slash can play in climate change mitigation.

This study demonstrates that creating further incentives for the production of biofuel from cellulosic wastes and residues in general through the RED has potential to

deliver carbon savings, without the same level of indirect land use change concerns or sustainability effects associated with production of biofuel from food commodities. However, it is to be noted that not all wastes and residues will provide substantial GHG emission reductions. As Europe considers the support mechanisms for cellulosic fuels, it is important that the criteria for wastes and residues do not over-incentivize biofuels from these feedstocks whose carbon footprints are comparable to those of fossil fuels. For example, while the pathways analyzed here all offer significant carbon savings, previous studies have shown that due to indirect effects, there may be little or no environmental benefits from policies incentivizing the use of animal fat as biofuel feedstock. Additional incentives for using wastes and residues will be most effective if targeted at the feedstocks that deliver the largest environmental benefit when comprehensive carbon accounting is undertaken.

## INTRODUCTION

Previous life cycle analysis (LCA) studies of cellulosic biofuels produced from agricultural and forest residues and municipal solid waste (MSW) have suggested that these fuels offer huge potential for GHG reductions when replacing fossil fuels. It is also expected that such fuels will have less impact on the environment than fuels produced from crops, and have less potential to cause indirect land use change (iLUC) or other indirect factors that increase emissions. As a result, there is a strong interest in promoting residue- and waste-derived biofuels. In the EU, the European Commission's October 2012 proposal to amend the Renewable Energy Directive (RED) includes provisions for double and quadruple counting the energy content of waste- and residue-based biofuels. Proposed amendments by the European Parliament would reduce the use of multiple counting, but would set a sub-target of 2.5% for biofuels from non-crop feedstocks. Either of these frameworks would provide a substantial incentive for cellulosic biofuel production from wastes and residues.

### MOTIVATION

Most LCA studies on cellulosic biofuels from agricultural residues focus on corn stover and wheat straw. There are also a number of published studies on LCA of forest residues (Gustavsson, Eriksson, & Sathre, 2011; Repo et al., 2012), but they primarily focus on electricity production. Table 1 provides a non-exhaustive summary of the carbon intensities of cellulosic biofuels from various LCA studies. As shown in Table 1, the reported carbon intensity of cellulosic biofuels from residues can range from negative to the low 40s in gram carbon dioxide equivalent per megajoule, suggesting that cellulosic biofuels produced from wastes and residues have the potential to contribute to climate change mitigation goals.

There are, however, some limitations to previous analyses. For one, these LCA studies typically ignore soil carbon loss from residue removal, whereas scientific studies suggest that this loss could be potentially significant (Smith et al., 2012, Petersen, Knudsen, Hermansen & Niels, 2013; Powlson et al., 2011; Strömgren et al., 2013). Acknowledging this, the Intergovernmental Panel on Climate Change (IPCC, 2006) has developed a methodology for estimating soil carbon loss from agricultural residue removal. The RED/FQD methodology for calculating the GHG emissions of biofuels treats wastes and residues as having zero emissions up to the point of collection, and hence any soil carbon loss from residue removal is omitted from the scope of RED/FQD-compliant analyses. Secondly, when residues are removed, additional fertilizers are needed to compensate for nutrient loss and maintain soil fertility. Thirdly, in some cases materials that we categorize as wastes or as residues have existing uses, and displacing these feedstocks from those uses may indirectly add to emissions. For forest residues, there is a fourth issue: the temporary carbon sink provided by forest residues that are not harvested for cellulosic biofuels. Depending on climate, residue diameters and other factors, the decomposition rate for residues left in place could vary such that in some systems, much of the carbon would remain undecomposed after 20 or 30 years. For example, for slash in Northern European countries, between 2% to 30% of carbon in residues may still remain sequestered 25 years out (Repo et al., 2013; Hyvönen et al, 2000), changing the counter-factual case (for other residues such as tree stumps, this fraction could be somewhat higher). Without considering all of these potentially important factors for emissions, it is not possible to be confident that incentivizing the use of cellulosic wastes and residues as biofuel feedstock will deliver large net carbon savings.

In this study, we undertake a comprehensive LCA analysis by accounting for emissions often ignored in the existing literature, based on the list of available European waste and residue feedstocks given by Searle & Malins (2013).

**Table 1.** Carbon intensities of cellulosic biofuels derived from wastes and residues reported in the literature (note: where carbon intensities are not reported directly, they were indirectly calculated based on reported % GHG savings)

Feedstock	Process	Final product	g CO <sub>2</sub> e/MJ	Reference
<b>Corn stover</b>	Biochemical	Ethanol	-27.5	Regulation of Fuels and Fuel Additives: Changes to Renewable Fuel Standard Program; Final Rule, 2010
	Thermochemical	Ethanol	6.6	Same as above
	Thermochemical	Diesel	8.5	Same as above
	Biochemical	Ethanol	20.6	Sheehan et al., 2003,
	Biochemical	Ethanol	0.2	GREET, 2012
	Thermochemical	Ethanol	12.2	GREET, 2012
	Thermochemical	Diesel	16.6	GREET, 2012
	Thermochemical	Gasoline	16.6	GREET, 2012
<b>Forest residue</b>	Biochemical	Ethanol	15.4	GREET, 2012
	Thermochemical	Ethanol	15.4	GREET, 2012
	Thermochemical	Diesel	31.2	GREET, 2012
	Thermochemical	Gasoline	31.2	GREET, 2012
<b>Waste wood</b>	Thermochemical	Diesel	3.6	UK DFT biofuels carbon calculator
<b>MSW</b>	Biochemical-GPV	Ethanol	21.4	Kalogo et al., 2007
<b>Wheat straw</b>	Biochemical	Ethanol	11.2	Borrion et al., 2012
	Biochemical	Ethanol	43.2	Roy & Dutta, 2012
	Biochemical	Ethanol	12.6	UK DFT biofuels carbon calculator
<b>Rice straw</b>	Biochemical	Ethanol	-23.8	Roy et al., 2012

## SCOPE

Searle & Malins (2013) identify substantial potential for production of cellulosic biofuels from agricultural and forestry residues, and from MSW. Based on that work, we analyze biofuel production from 11 waste and residue feedstocks, as shown in Table 2. Agricultural residues are considered from eight different crops. Forest residues analyzed here consist of slash (twigs, branches, and treetops). Leaves are typically left behind in the field, and because this is important for sustainability, we exclude leaves from the analysis here. Tree stumps were not considered sustainable by Searle & Malins (2013) and thus are not assessed here—on the practical side, harvested stumps are generally heavily contaminated with soil, which may make them undesirable as feedstock for many cellulosic biofuel processes. We consider MSW as a single stream, and also consider sawdust as a processing residue.

This study is focused on transport fuels produced with advanced cellulosic biofuel technologies, and therefore we only consider liquid fuels pathways and not direct combustion or biogas production (although some biogas could be used for road transport applications). For each feedstock except MSW, three biofuel pathways are analyzed as shown in Figure 1. These three processes are ethanol production via enzymatic hydrolysis and fermentation, renewable diesel production via fast pyrolysis, and FT-diesel production via gasification and Fischer-Tropsch (FT) synthesis. For MSW, we have analyzed only a single ethanol pathway based on the patented technology known as gravity pressure vessel (GPV) process (Kalogo et al., 2007).<sup>1</sup>

In biochemical ethanol conversion, a feedstock is usually pretreated with acid, alkali, or steam to make cellulose amenable to enzymatic hydrolysis, which is followed by hydrolysis of cellulose to sugars and finally fermentation of sugars to ethanol. In this study we assume acid pretreatment. In hydrolysis, cellulose-degrading enzymes break down cellulose into simple sugars such as glucose. In a fermentation step, yeast convert simple sugars into ethanol.

The Kalogo et al. (2007) process for MSW conversion is somewhat similar to the biochemical ethanol pathway, except that it involves a high-pressure acid hydrolysis process followed by fermentation, rather than the pretreatment plus enzymatic hydrolysis modeled for the other feedstocks. In the case of MSW, we have considered the biogenic fraction of the MSW stream destined for landfills (i.e., not otherwise recycled/reused).

In thermochemical conversion via fast pyrolysis, a feedstock is subjected to elevated temperatures in the absence of oxygen, resulting in bio-oil, bio-char, and pyrolysis gas. Pyrolysis gas can be consumed by the plant as process energy or used as a hydrogen and/or methane source. Bio-oil can be upgraded to diesel and gasoline by hydrocracking and hydro-treatment. In hydrocracking, a heavier molecule such as bio-oil is broken down into the lighter hydrocarbons gasoline and diesel in the presence of hydrogen and a catalyst. Hydrotreatment also involves hydrogen and catalysts and converts unsaturated hydrocarbons to saturated hydrocarbons.

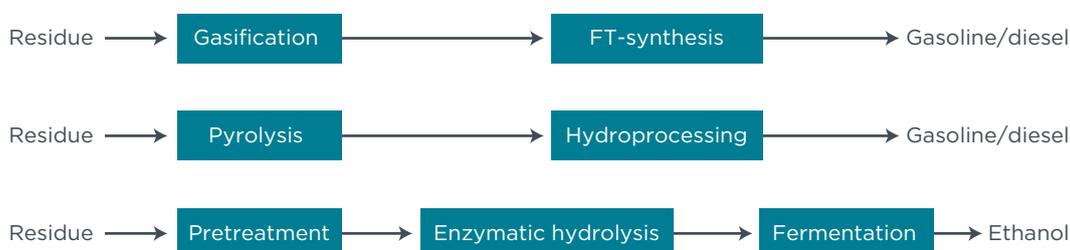
A feedstock can also be converted into FT-diesel via gasification and FT-synthesis. Gasification involves decomposition of biomass into syngas, a mixture of CO<sub>2</sub>, H<sub>2</sub>, and CO at higher temperatures (>700 degrees Celsius) and in the presence of limited

<sup>1</sup> We assume that the biogenic fraction of MSW destined for landfills will be used for biofuel production. This is the only process we are aware of being reported in the peer-reviewed literature that converts all biogenic materials in MSW to ethanol. Fiberight, a company based in the US, has developed a proprietary technology that can produce cellulosic fuel from biogenic MSW. There are other studies looking at the conversion of specific components of biogenic MSW such as paper and cardboard to ethanol. MSW can also be converted to diesel and other fuels via thermochemical processes. We did not analyze these processes due to limited availability of detailed data for modeling. A range of carbon intensities is possible for MSW biofuels depending on the method of production.

amounts of oxygen and/or steam. The syn gas is converted using FT-synthesis. In this process, H<sub>2</sub> and CO are converted into diesel and gasoline in the presence of catalysts and at temperatures of 150-300 degrees Celsius.

**Table 2.** List of residue and waste analyzed

Agricultural residues	Forest residue	Waste/processing residues
Barley straw	Slash	MSW
Corn stover		Sawdust
Oat straw		
Rapeseed straw		
Rice straw		
Rye straw		
Sunflower stover		
Wheat straw		



**Figure 1.** Three biofuel conversion pathways analyzed in this study

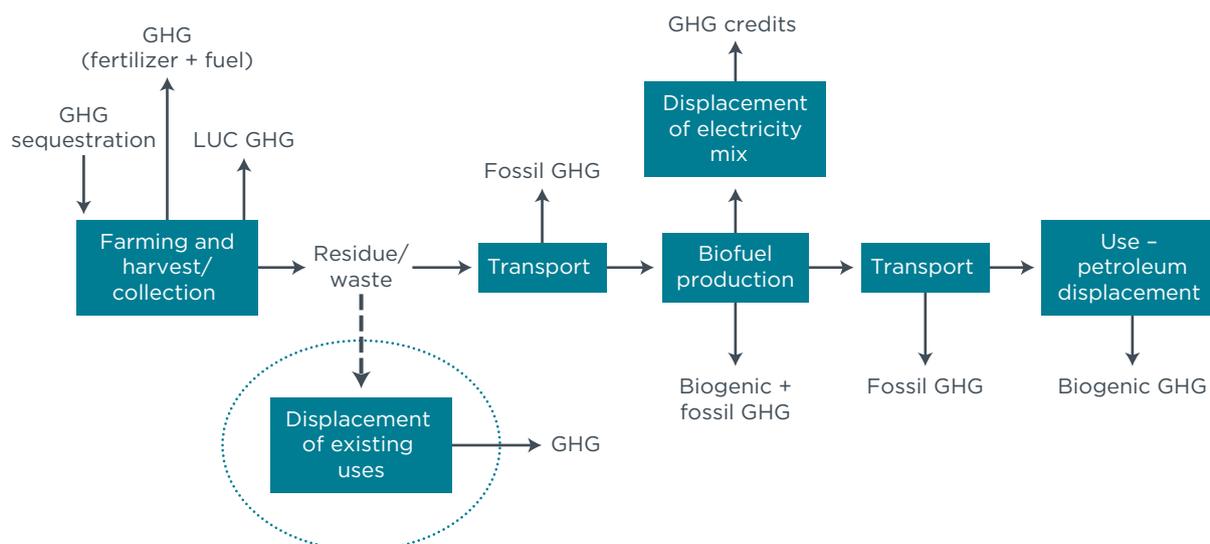
## METHOD AND DATA

In this section we provide a detailed description of the methodology, system boundary, data sources, and assumptions used for calculating indirect GHG emissions from displacement effects.

### MODEL DEVELOPMENT

As mentioned, we have undertaken our analysis using the UK Department for Transport biofuels carbon calculator.<sup>2</sup> This calculator is used for regulatory reporting under RED/FQD in the UK, is consistent with the RED/FQD methodology, and includes modular pathways with the typical/default emissions for a variety of biofuel feedstocks and technologies. We have modeled the carbon intensity of cellulosic biofuels from residues and wastes by modifying the generic modules already included in the calculator as appropriate to reflect additional feedstocks, our chosen conversion pathways, and the inclusion of emissions sources (soil carbon change, indirect emissions, etc.) not normally covered by the calculator. The motivation behind choosing the biofuels carbon calculator is to make the analysis consistent with the RED methodology to the extent possible (at least for direct emissions). Most of the default input data for the biomass production and biofuel process modules are modified, whereas the default values for feedstock transport, biofuel transport, storage, fuel dispensing, and use have not been modified. The system boundary of the study is shown in Figure 2.

<sup>2</sup> <https://www.gov.uk/government/publications/biofuels-carbon-calculator>



**Figure 2.** System boundary for estimating carbon intensities of cellulosic biofuels from waste and residue

We assign zero emissions up to the point of collection for municipal waste and sawdust. For agricultural and forest residues, GHG emissions from cultivation are assigned to the main crops only, but we allocate to the residues emissions from extra fertilizer requirements and soil carbon loss due to residue harvest. We have assumed 5% biomass loss during storage and transport.

It is beyond the scope of this study to determine exactly the inputs and energy consumption in biofuel production for each individual feedstock identified in Table 2. Rather, we have gathered publicly available data for a few feedstocks and used these to estimate inputs for other residues based on comparing feedstock chemical composition, energy content, biofuel yields, and energy conversion efficiency. Raw input data and biofuel yields for agricultural residues and sawdust are based on the GREET model (GREET 1, 2012, rev. 2).<sup>3</sup> Yields and technologies for biofuel production are representative of what can be achieved between the current day and 2020. For MSW, yield and raw input data are obtained from Kalogo et al. (2007). Electricity credits from lignin combustion for a pathway of biochemical ethanol from agricultural residues are estimated based on the ratio of lignin content of a given agricultural residue to that of corn stover, for which electricity credits are available from the GREET model (Table A). Data on feedstock composition such as holocellulose content (cellulose and hemicellulose combined), lignin content, energy content, and nutrient content primarily come from the Phyllis2 database.<sup>4</sup> Phyllis2, developed by the Energy Research Center of the Netherlands, is the most comprehensive database available on residues and wastes. This approach enables us to reasonably estimate individualized GHG emission profiles for each feedstock without having to undertake full bottom-up modeling in every case. Table B (Appendix) summarizes residue yields per hectare, soil carbon loss, and fertilizer requirements for various residues, whereas Table C summarizes biofuel yields per tonne for various biofuel pathways.

Where such adjustments are not possible, we use the yield and energy consumption data for corn stover as a proxy for all agricultural residues and data for “forest residue” as proxy for slash and sawdust as done for pyrolysis diesel pathway.<sup>5</sup> For example, the

<sup>3</sup> Available at <http://greet.es.anl.gov/>.

<sup>4</sup> Energy Research Center of the Netherlands, <http://www.ecn.nl/phyllis2>

<sup>5</sup> Ideally, feedstock specific process data are preferable. In the absence of better data, such an adjustment is necessary.

liquid fuel yield (gasoline and diesel combined) for forest residue is 0.32 tonnes/dry tonne biomass and 0.28 tonnes/dry tonnes for corn stover (GREET 1, 2012, rev. 2).

In the case of the pyrolysis diesel pathway for agriculture residues, GHG emissions are allocated between co-products bio-char and liquid fuel (diesel and gasoline) based on energy content. We assume that pyrolysis gases are consumed on site. In pyrolysis diesel production from forest residues and sawdust, no bio-char is produced because it is consumed internally during the biofuel production step.

In biofuel production from MSW, several valuable co-products can be obtained with further processing and energy inputs, such as residuals from decomposition of lignin present in the sludge, plastic pellets from preprocessing of MSW, and gypsum. Any credits associated with emissions allocation to these co-products are not accounted for in this study, following Kalogo et al. (2007). Hence, it should be noted that the GHG savings of MSW ethanol could be higher than estimated in this study.

## SOIL CARBON AND ABOVEGROUND BIOMASS CARBON LOSS

Agricultural and forest residues are important in maintaining soil fertility, reducing soil erosion, and contributing to soil carbon. Residues return a fraction of carbon to soil through humification, which delivers to the soil stable humic substances and organo-mineral complexes with long residence times (Lal, n.d).

Hence, residue removal, even when done in line with sustainable practices, is likely to have a negative impact on soil carbon sequestration potential, a conclusion supported by both empirical and modeling studies (Pearson et al., 2013, Powlson et al., 2011). The IPCC has also developed a methodology to estimate soil carbon loss due to residue removal (IPCC, 2006). We believe that long-term empirical studies on soil carbon are more reliable than modeling studies, and therefore estimate soil carbon loss due to agricultural residue removal based on Powlson et al. (2011). In particular, we use the soil carbon loss estimated at a site in Rothamsted, UK, where a wheat straw removal experiment was conducted over a period of 22 years and soil carbon loss up to a depth of 22 cm was analyzed. This site is continuously cultivated for cereal production, and we consider it an appropriate proxy for estimating typical soil carbon loss in the EU from residue removal. This is, however, where additional empirical evidence covering a wider geographical range would be extremely valuable. We extrapolate the estimates from this study to other agricultural residues such as corn stover and rice straw, assuming that soil carbon loss is proportional to the amount of the residue removed. Based on Powlson et al. (2011), for every tonne of residue removed the average soil carbon loss is estimated to be 73.5 kg CO<sub>2</sub>.<sup>6</sup>

For forest residues, information about soil C loss due to residue removal is obtained from empirical studies. Several empirical studies have failed to find evidence of a statistically significant increase in soil carbon loss from slash removal compared to stem only removal (Olsson et al., 1996, Bjorkroth, 1993), although Strömberg et al. (2013) and other modeling studies do suggest that slash removal may lead to increased soil carbon loss (Aber, Botkin, & Melillo, 1978, Agren & Hyvonen, 2003). It has been noted that high loss of carbon due to clear-cutting itself may statistically mask the effects of residue removal (Olsson et al., 1996), and there are obvious reasons to believe that residue removal may have some impact (as it certainly removes carbon from the system that could in principle be returned to the soil). Still, in the absence of clear evidence, we assume no carbon loss for slash removal in our central case, but as a

<sup>6</sup> It is noted that overabundance of residues may also affect the carbon-to-nitrogen ratio in the soil. Too much incorporation of residues in the soil may lead to higher carbon content that binds nitrogen, rendering it unavailable to the following crop.

sensitivity analysis we consider a loss of 3 tonnes C/ha based on the range reported by Strömberg et al. (2013). In slash harvest, leaves are assumed to be left behind in both the central and sensitivity cases.

We note that while the evidence is inconclusive about the soil carbon impact of slash removal, there is more evidence for substantial soil carbon loss (organic layer and mineral soil combined) from empirical studies of stump removal (Hope, 2007; Zabrowski, et al., 2008). This is an additional reason to prefer slash to stumps as biofuel feedstock.

When residues are left behind in the forest, not all of the material is decomposed in a time frame of 20–30 years, especially in colder climates such as that of northern Europe. The decomposition rates vary depending on the types of forest residue (leaves, branches, stumps), climate, and other conditions. Research has shown that 2–30% of slash may remain undecomposed 25 years later (Repo et al., 2011, Hyvonen et al., 2000). The carbon that would be stored in the undecomposed portion of forest residues when left in the field would be released if used for bioenergy, and thus this can be seen as a carbon loss when considering emissions over a 20-year time frame. In the longer term we would expect total decomposition, so this can be seen as conservative approach to considering carbon storage on the forest floor.

## SOIL NUTRIENT REPLACEMENT

Since residues contain macro-nutrients such as nitrogen (N), phosphorus (P), and potassium (K) in appreciable amounts, their removal from fields or forests results in loss of nutrients that would otherwise return to soil via recycling.<sup>7</sup> This implies that to maintain soil fertility, we need to apply inorganic fertilizers, manure, or other residues to compensate for nutrient loss. In this analysis, we assume that nutrient loss is compensated by using additional chemical fertilizers (N, P, and K). Nutrient replacements are estimated based on the nutrient contents of residues removed and assuming 1:1 replacement of N, P, and K on a mass basis. Nutrient content data are primarily obtained from Phyllis2. Due to variability in nutrient contents of a given residue/waste reported in Phyllis2, we average the reported nutrient contents for each residue. In reality, however, we recognize that there is inter-and intra-field variability.

## INDIRECT EMISSIONS

Wastes and residues generally have inelastic supply in response to demand (the supply of residues/wastes increases only if production of the primary crops/products increases). As a result, the overall supply will not increase in response to biofuel demand. To some extent, residues and wastes are already used for a variety of purposes, from animal husbandry to recycling goods to energy generation. Depending on the extent of excess availability and the current level of use, diverting these resources for use as biofuel feedstock could cause displacement effects leading to indirect GHG emissions. Even where there is an excess of a resource in principle, in practice biofuel producers are likely to look to the existing supply chain, and the new demand may be met partly by displacement rather than increased collection. For example, if wheat straw is diverted from biopower (electricity/heat) to biofuel, an alternative material such as willow may have to be used for biopower. Since there are GHG costs associated with growing and harvesting willow, diversion of wheat straw to biofuel would then entail indirect emissions. Such indirect effects are not currently

<sup>7</sup> Although chemical fertilizers are rarely used in current forest management practices, research has shown that harvesting forest residue can lead to nutrient depletion in the long run (Helmisaari et al., 2011, Jacobson et al., 2000). Harvesting residues for energy and other purposes is a relatively new practice. Considering the longer-term yield implication, and for methodological consistency with our treatment of agricultural residues, we included fertilizer use to compensate for nutrient loss from forest residue harvest.

accounted for in the RED/FQD methodology but are important for confidently assessing the climate mitigation potential of cellulosic biofuel.

Below we discuss the approach and assumptions in calculating indirect emissions of various wastes and residues. To estimate indirect emissions, we follow the following steps similar to those laid out by Brander et al. (2009).

- » Set biofuel production targets from wastes and residues;
- » Identify the existing uses;
- » Determine the order of displacement where there are multiple existing uses. If it is not possible to determine the order, assume that existing uses will be displaced proportionally;
- » Estimate the emission factor(s) of the replacement material(s) used when residue/waste is displaced from an existing use. If there are more than one uses and replacement materials and the order of displacement is not known, take the weighted average of emission factors;
- » Multiply the emission factor (weighted or not weighted) with the amount of a replacement material(s) used to obtain indirect GHG emissions.

We also analyze a sensitivity case assuming no displacement effects.

## AGRICULTURAL RESIDUES

It is estimated that the sustainably available potential for agriculture residues in the EU is about 122 million tonnes (Searle & Malins, 2013). This allows for 33% of residues to be left in the field to maintain soil fertility, and sets aside 33% for existing uses. For this analysis, we assume an aspirational target of 10 billion liters of biofuel production from agricultural residues. The 122 million tonnes of available residues are more than sufficient to produce the target volume, so in theory no displacement of existing uses *needs* to occur. However, in the real world, it is likely that a certain portion of biofuel may come from residues already used for other purposes, since there may not be decision-making and information sharing mechanisms in place to target residues from additional harvesting only, and some residues are hard to collect due to the lack of existing infrastructure. A key determinant of whether increased harvesting will occur is the delivered cost of residues compared to the cost of alternatives such as *Miscanthus*. If the delivered costs of residues are low, residue harvest is likely to increase to meet the demand for both biofuel and other uses. However, if prices are more comparable, we would expect some displacement effect. In this analysis, in the absence of suitable data we assume that 50% of biofuel production from agriculture residues comes from their diversion from existing uses, and the remaining production from additional harvesting of residues available in the EU. We believe that this can be considered to provide a reasonable ceiling on likely diversion effects from using residues as biofuel feedstock in the period to 2020. Soil carbon loss and GHG emissions associated with extra fertilizer use for residues diverted from existing uses are excluded to avoid double counting.

Of the agricultural residues that are already used in the EU, the majority is used for animal bedding. In addition, they are used in mushroom cultivation, insulating materials and pulp and paper, and energy generation. Based on the study by Scarlat et al. (2010), Table 3 approximates the makeup of existing agricultural residue use.

**Table 3.** Residue use in Europe

Animal bedding = 89%
Insulating materials and pulp and paper = 2%
Mushroom cultivation = 3%
Energy = 6%

It is assumed that agricultural residues used in animal bedding, insulating materials and pulp and paper will be replaced by *Miscanthus* on a 1:1 mass basis (Brander et al., 2009). Brander et al. (2009) also assume *Miscanthus* as replacement material for wheat straw. For mushroom cultivation, 1 kg of residue is assumed to be replaced by 1.2 kg of *Miscanthus* based on Brander et al. (2009). In the case of energy, replacement materials are assumed to be 50% *Miscanthus* and 50% willow. One megajoule of *Miscanthus* or willow replaces one megajoule of agricultural residues in energy generation due to expected similar efficiencies. Given these replacement assumptions, *Miscanthus* will replace more than 95% of displaced residues, hence the indirect GHG emissions of residue diversion to biofuels will be dictated by the emission factor of increased *Miscanthus* cultivation.

*Miscanthus* is a fast-growing perennial crop with a likely yield of about 8.5 tonnes/ha in large-scale commercial plantations, although modeling and plot levels studies show that yields could be higher<sup>8</sup> (Mishra et al., 2013, Kahle et al., 2013). *Miscanthus* requires less fertilization than most other crops and (as a perennial) also allows increased carbon to be sequestered in the soil (2.3 tonnes CO<sub>2</sub>/ha.yr) (Brandao et al., 2011). On the other hand, sequestration will be forgone when abandoned<sup>9</sup>/formerly set aside land is converted to *Miscanthus* plantation. We assume that dedicated energy crops are most likely be grown on abandoned or formerly set aside land. This assumption is likely to be reasonable provided that food prices remain significantly higher than *Miscanthus* prices, and farmers therefore target *Miscanthus* cultivation in areas that provide limited potential for food crops, but the assumption could change if the value of energy crops as biofuel feedstock increases in the future. In addition, there are GHG emissions from site preparation, establishment, harvest, and transport. Even considering all these factors, the total expected carbon sequestration slightly outweighs cultivation, harvest, and transport emissions when averaged over a 20-year period. As a result, our emission factor for *Miscanthus* is negative (-0.4 g CO<sub>2</sub>e/MJ or - 7 kg CO<sub>2</sub>e/dry tonne).<sup>10</sup> This is similar to Brander et al. (2009), who find a small but positive emission factor. In the case of willow, the emission factor is positive (9 g CO<sub>2</sub>e/MJ or 162 kg CO<sub>2</sub>e/dry tonne), because carbon sequestration is not large enough to offset the emissions from its farming, harvest, and transport. Because willow constitutes less than 5% of the replacement materials, with the remaining being *Miscanthus*, the net indirect emissions from diversion of agricultural residues to cellulosic biofuels are still going to be marginally negative.

## FOREST RESIDUES

The current use of forest residues in Europe for commercial energy production and household energy is small relative to availability. We therefore assume that using forest residues for biofuel will not cause a displacement effect, although there will still be soil carbon loss and GHG costs associated with nutrient replacement when residues are removed.

8 Yields obtained from plot-level and modeling studies are often difficult to replicate at commercial-scale plantations.

9 Abandoned land encompasses a range of land types and is often abandoned for economic, social, or environmental reasons. It is likely that *Miscanthus* would be grown on land with marginal economic and productive returns, but not on all abandoned land.

10 A range of soil carbon sequestration rates has been reported in the literature, from 1-11 tonnes CO<sub>2</sub>/ha.yr depending on sites, growth rates, and climate. This will influence whether *Miscanthus* has a net positive or negative emission factor. The majority of studies suggest a narrow range from 1-3 CO<sub>2</sub> tonnes/ha.yr.

## PROCESSING RESIDUE (SAWDUST)

Sawdust is a byproduct of the sawmilling of logs. It is used to produce biopower as well as in construction materials and furniture. Since all sawdust currently produced has other uses in the EU, its diversion to cellulosic biofuel will inevitably result in displacement, and hence indirect GHG emissions. Data on the proportions of sawdust used for biopower and material is not readily available at the EU level, but we assume that 10% of sawdust is used for biopower and 90% for material uses, based on figures regarding the uses of sawdust and solid residues in Great Britain that show that more than 90% of sawmill co-products are sold to wood processing and other industries (Forestry Commission, 2000). Considering this uncertainty, we also analyze a sensitivity case that involves 50% displacement of sawdust from material use and 50% displacement from energy use. The order of displacement is not known. It is assumed that willow will be used as a replacement material for sawdust in construction materials and furniture. Although short-rotation poplar and eucalyptus could also fill this gap, we chose willow because it has received the most attention and has also been produced on a commercial scale in the EU. Willow replaces sawdust on a 1:1 mass basis. For diversion of sawdust from biopower, willow and *Miscanthus* are assumed to be replacement materials. For every MJ of sawdust displaced, we assume that it will be replaced by 0.5 MJ each of *Miscanthus* and willow. As discussed above, willow has a small but positive emission factor, and as it is the predominant replacement material for sawdust, the indirect emissions from sawdust diversion to biofuel are also positive.

## MUNICIPAL SOLID WASTE

MSW consists mainly of household waste such as paper, cardboard, garden waste, kitchen waste, containers, plastics, and metals. In the EU, 37% of MSW destined for landfilling (after recovery and recycling) is estimated to be biodegradable (mostly cellulosic) and the rest is non-biodegradable (EEA, 2013). There is a growing movement toward reducing the amount of waste heading to landfills, driven in large part by EU waste policies. The European Landfill Directive (1999/31/EC) requires member states to progressively reduce the amounts of biodegradable municipal solid waste (BMSW), with a target of a 75% reduction below 1995 levels by 2016 (2020 for some countries). The EU's Waste Framework Directive requires that member states recycle 50% of household waste by 2020. Moreover, there are programs aiming to increase recycling of MSW such as Landfill Allowance (Trading) Schemes (LAS) and the Landfill Tax Escalator in the UK. The number of countries recycling more than 30% of MSW has increased from 10 in 2001 to 16 in 2010 (EEA, 2013).

We assume that up to 4 billion liters of cellulosic biofuels will be produced from MSW in the EU. Due to heavy emphasis on recycling of household waste and reducing the volume of MSW that is landfilled, it is most likely that any future supply of cellulosic biofuel will come from that portion of the MSW currently destined for landfilling. It is estimated that about 63 million tonnes of cellulosic MSW are potentially available for biofuel production in 2010 (Searle & Malins, 2013). In 2030, this is expected to drop to about 44 million tonnes due to an increase in recycling rates. The amount of biogenic MSW currently landfilled is more than sufficient to provide an aspirational target of 4 billion liters of ethanol from the GPV process modeled in this study, which requires 38 million tonnes of MSW. It means that even if the recycling/recovery rates increase in the future for its use in composting, biogas, incineration, etc., enough MSW may still be left behind for biofuel production. Due to the strong mandate to move away from landfilling, it is unlikely that already recycled cellulosic materials such as paper and cardboard will be used for cellulosic biofuels, or that biofuel demand will displace other existing waste management practices such as MSW incineration, composting, or anaerobic digestion.

Because MSW in a landfill releases methane (a potent GHG) and CO<sub>2</sub> if it is flared, its diversion from landfilling would result in GHG savings. Brander et al. (2009) estimate that MSW diversion from a landfill results in avoided GHG emissions of 0.5 kg CO<sub>2</sub>e/ kg wet MSW. This estimate is based on the assumptions that 75% of methane and 65% of heat generated by landfill facilities are captured. In our analysis, we use this value as the GHG credits of MSW when used for cellulosic biofuels.

We assume that post recycled/recovered MSW to be used for biofuel production is further sorted out at a transfer facility to isolate the biogenic fraction from the non-biogenic fraction such as metals and plastics. The electricity used in MSW classification (i.e., the sorting out of MSW) is allocated between the biogenic and non-biogenic fraction based on mass. As mentioned earlier, about 37% of the post recycled/recovered MSW is biogenic. After MSW classification, the biogenic residue is transferred to an ethanol facility. Because the transfer of MSW to a landfill site will occur in the reference (business-as-usual (BAU)) scenario anyway, energy used and associated GHG emissions in transporting the biogenic MSW to an ethanol facility are omitted under the assumption that distances between a transfer facility and landfill site and a transfer facility and an ethanol plant are similar.

## RESULTS AND DISCUSSIONS

### Emission profiles

In this section, we provide a breakdown of GHG emissions for a representative feedstock from each feedstock category (wheat straw as an agricultural residue, slash as a forest residue, plus MSW and sawdust). This allows us to identify the life cycle stages responsible for major emissions and explore the opportunities for GHG reductions. The breakdown of GHG emissions for biochemical ethanol and FT-diesel pathways is shown in Figures 3 and 4. GHG emission profiles for pyrolysis diesel pathway are similar to FT-diesel and hence are not shown—carbon intensities for the full set of technologies and feedstocks are listed in Table 4.

The harvesting stage is the major source of GHG emissions for agricultural residue (wheat straw) and forest residue (slash). This is attributed to soil carbon loss and/or extra fertilizer requirements from residue removal. In particular, N<sub>2</sub>O emissions from fertilizers contribute to GHG emissions. N<sub>2</sub>O is a potent GHG with a global warming potential of 298. We use the default RED emission factor for N<sub>2</sub>O emissions from N-fertilizer as provided in the UK biofuels carbon calculator. In the case of forest residue, aboveground biomass carbon loss (biomass that would have otherwise remained undecomposed in a 20-year time frame) also provides a meaningful contribution to GHG emissions. For wheat straw, harvesting accounts for about 11.6 g CO<sub>2</sub>e /MJ of total life cycle GHG emissions for a biochemical ethanol pathway and 10.9 g CO<sub>2</sub>e/MJ for an FT-diesel pathway. Similarly, for the FT-diesel pathway for slash, the harvesting stage accounts for 91% of total GHG emissions.

Except for MSW where in-plant energy (natural gas and electricity) is purchased from outside, ethanol production does not contribute appreciable GHG emissions, because it is assumed that most of the energy need is met through combustion of process by-products such as lignin. The same applies to the FT-diesel pathway. However, for pyrolysis diesel, the biofuel production step uses electricity and natural gas in the pathway detailed in the GREET model.

For sawdust and MSW, where harvesting has no implications for nutrient loss and soil loss, the emissions before the fuel production step are small.

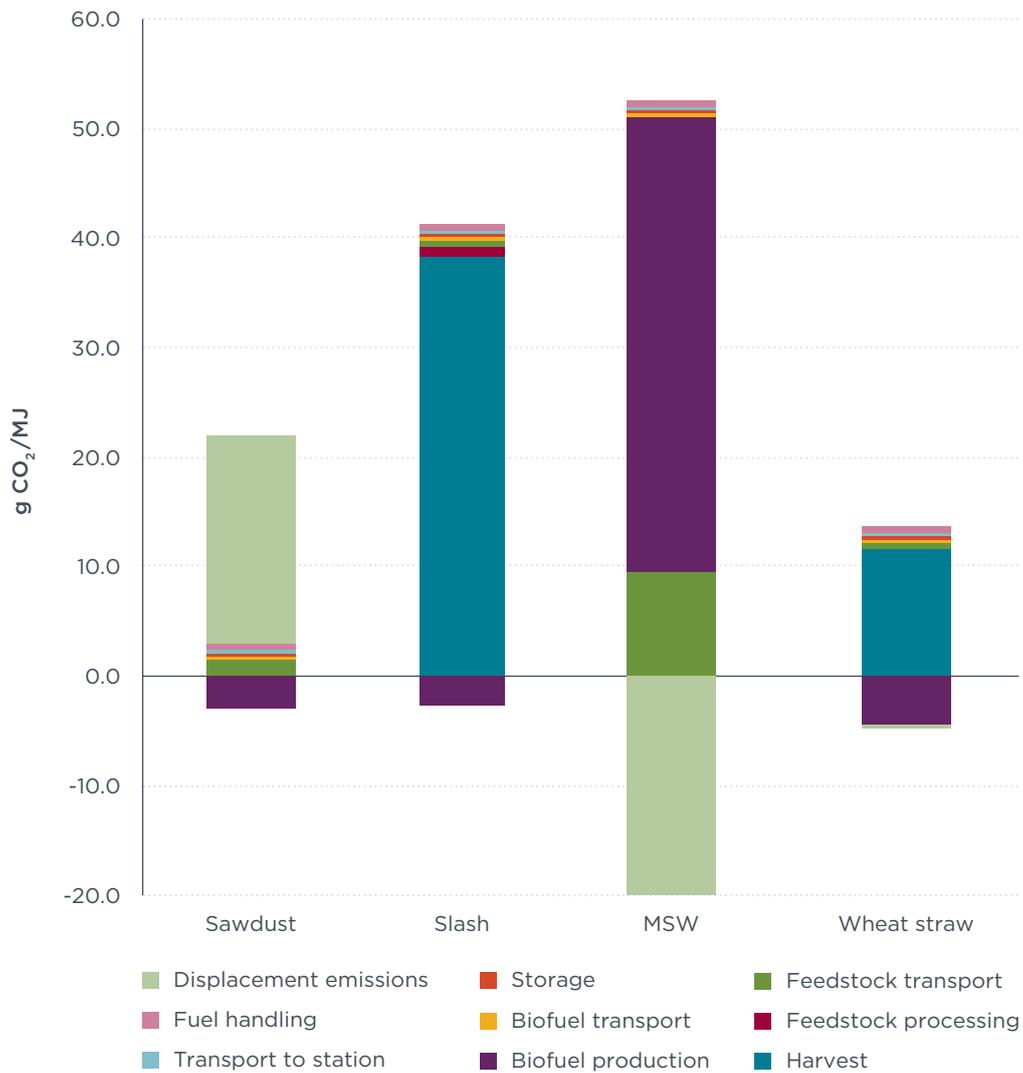
Where displacement of existing uses occurs, displacement emissions (indirect) can be an important contributor to life cycle GHG emissions in a positive or negative way depending on whether there will be a net offset or emissions from the displacement. As seen in Figures 3 and 4, displacement emissions for sawdust and MSW are appreciable with opposite implications.

The displacement emissions for MSW are negative, and the largest among feedstocks analyzed. This is because for every tonne of biogenic MSW removed, 500 kg of CO<sub>2</sub>e emissions would be avoided due to reduced landfill methane. Because ethanol yield per tonne (wet) of MSW is low for the reported GPV process, at about 0.08 tonnes per wet tonne of MSW, these indirect savings can be very large per unit of ethanol produced. For this pathway, the displacement GHG emissions for ethanol from MSW amounts to -225 g CO<sub>2</sub>e/MJ. Although we believe that the most likely outcome of increased MSW use for biofuel is MSW diversion from landfills, it's possible that under some circumstances, MSW used for cellulosic biofuels could be diverted from incineration or composting. Under such scenarios, these indirect savings would not be as high, as we forego GHG savings from these waste management options. In such a case, the GHG savings of MSW ethanol would be reduced, though they would likely still be high compared to most first-generation biofuels.

In the case of biofuel derived from sawdust, there are GHG costs associated with growing and harvesting willow due to displacement. These displacement emissions are 19 g CO<sub>2</sub>e/MJ for a biochemical pathway and 16 g CO<sub>2</sub>e/MJ for an FT-diesel pathway.

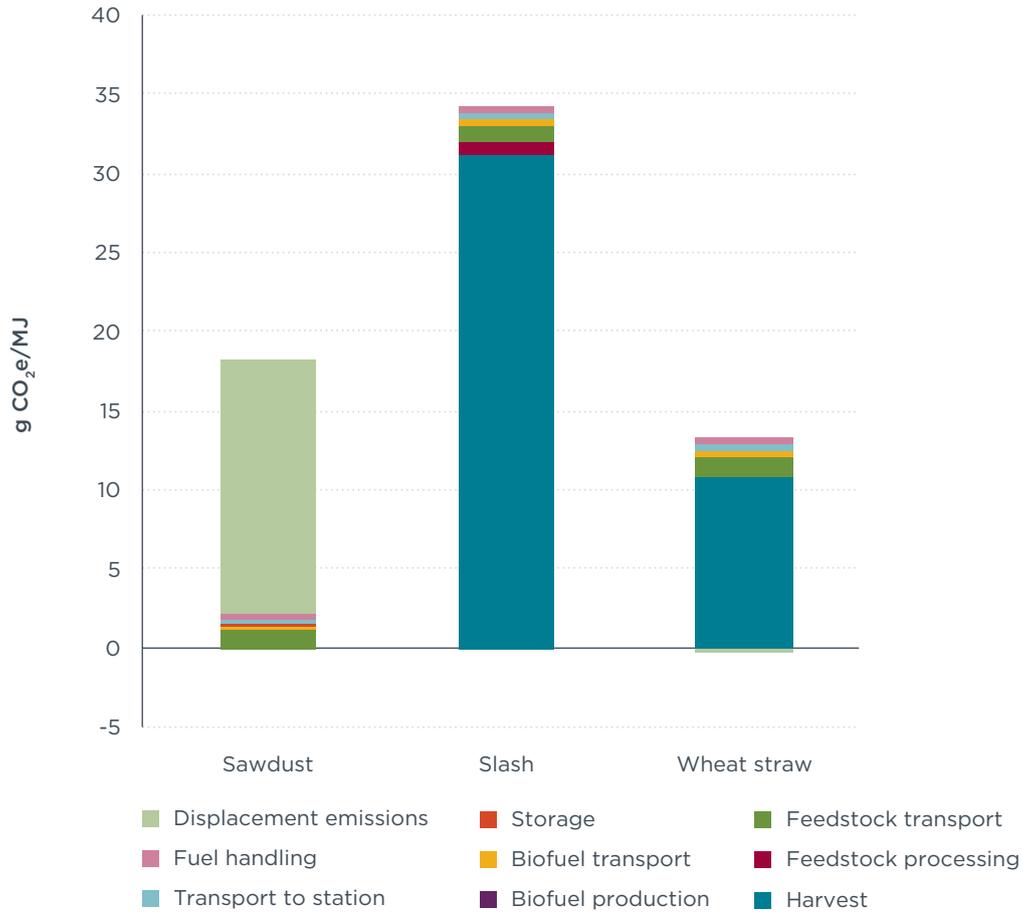
Because *Miscanthus* on abandoned land, which has a slightly negative emissions factor, is assumed to act as the main replacement material when residues are diverted from existing uses, there is a small indirect emissions credit for agricultural residues. On top of that, displacement actually improves the emissions profile for agricultural residues. This is because emissions from soil carbon loss or extra fertilizer associated with the displaced residues would not longer be counted, as these emissions would occur anyway in the business-as-usual scenario.

For forest residues, no displacement effects are assumed, hence there are no displacement emissions.



**Figure 3.** Breakdown of GHG emissions for representative feedstocks by life-cycle stages for biochemical ethanol pathway.

**Note:** The displacement emissions column of MSW is truncated, because displacement emissions are very large (-225 g CO<sub>2</sub>e/MJ)



**Figure 4.** Breakdown of GHG emissions for representative feedstocks by life-cycle stages for FT-diesel pathway

## GHG EMISSIONS COMPARISON

Table 4 summarizes the life cycle of GHG emissions and percent GHG savings of the full set of cellulosic biofuels obtained from biochemical ethanol, FT-diesel, and pyrolysis diesel pathways.

### Agricultural residues

Among the agricultural residues analyzed, carbon intensities range from -61 g CO<sub>2</sub>e/MJ for rice straw ethanol to 23 g CO<sub>2</sub>e/MJ for rapeseed straw ethanol, with corresponding GHG savings of 173% and 73%, respectively. The GHG savings are calculated using the RED standard comparators of 83.8 g CO<sub>2</sub>e/MJ for both diesel and gasoline. The negative carbon intensity for rice straw ethanol is due to avoided CH<sub>4</sub> emissions based on the IPCC estimate (as mentioned in Koga and Tajima, 2011). It has been shown that rice straw removal results in a reduction of methane emissions, because rice straw left behind releases methane emissions through anaerobic decomposition in the next cropping cycle (Koga and Tajima, 2011). Not considering avoided CH<sub>4</sub> methane lowers GHG savings, by almost half from 173% to 80% for rice straw ethanol (Table 4), but even in that case, this pathway delivers large reductions. Among agricultural residues, the slightly higher carbon intensity and lower GHG savings of rapeseed straw ethanol is attributed to higher N-fertilizer replacement requirements, because rapeseed straw contains higher N content.

For an FT-diesel pathway, agricultural residues have carbon intensities in the range of -63 for rice straw to 20 g CO<sub>2</sub>e/MJ for rapeseed straw, with GHG savings ranging from

77% to 176%. Similarly, diesel obtained from fast pyrolysis of agricultural residues has carbon intensities ranging from -34 to 17 g CO<sub>2</sub>e/MJ, with GHG savings ranging from 80% for rapeseed straw to 140% for rice straw.

Overall, cellulosic biofuels derived from agricultural residues have been found to offer substantial GHG savings for all three biofuel pathways, exceeding 60% in all cases.

**Table 4.** Carbon intensities and percent GHG savings of cellulosic biofuels derived from residues and wastes using from thermochemical and biochemical conversions

Feedstock/fuel pathway	Biochemical ethanol		FT-diesel		Pyrolysis diesel	
	g CO <sub>2</sub> e/MJ	% GHG savings	g CO <sub>2</sub> e/MJ	% GHG savings	g CO <sub>2</sub> e/MJ	% GHG savings
<b>Agricultural residue</b>						
<b>Corn stover</b>	12	86	14	84	12	85
<b>Wheat</b>	9	89	13	84	12	86
<b>Barley straw</b>	10	88	15	82	13	85
<b>Rye straw</b>	11	87	14	84	12	85
<b>Oat straw</b>	8	90	14	83	13	85
<b>Rice straw<sup>a</sup></b>	-61 (17)	173 (80)	-63 (17)	176 (80)	-34 (12)	140 (86)
<b>Rapeseed straw</b>	23	73	20	77	17	80
<b>Sunflower stover</b>	13	84	16	81	15	82
<b>Forest residue</b>						
<b>Slash<sup>b</sup></b>	39 (79)	54 (6)	34 (67)	59 (21)	33 (56)	61 (33)
<b>Processing residue/waste</b>						
<b>Sawdust</b>	19	77	18	78	22	74
<b>MSW</b>	-164	296	-	-	-	-
<b>Carbon intensity of diesel and gasoline comparator</b>	83.8 g CO <sub>2</sub> /MJ					

a For rice straw, data in parentheses represent carbon intensities and percent GHG savings without taking into account avoided methane emissions from rice straw removal.

b Data in parentheses represent values assuming soil carbon loss of 3 tonnes/ha for slash removal

## Forest residues

In comparison to agricultural residues, the slash delivers relatively higher carbon intensities and lower GHG savings for all three biofuel pathways. Using slash for cellulosic biofuels offers GHG savings ranging from 54% for an ethanol pathway to 61% for a pyrolysis diesel pathway. Assuming soil carbon loss of 3 tonnes per ha reduced savings considerably, with numbers ranging from 6% savings for ethanol to 33% for pyrolysis diesel, suggesting a strong sensitivity towards soil carbon loss.

The reason slash may offer lower GHG savings in the short term compared to agricultural residues is because it acts as a temporary carbon sink if not harvested for biofuels.

Since conventional logging occurs at longer time intervals (>25 years) than the time frame of 20 years used in the RED methodology, we consider only one harvest event in this analysis. As both aboveground and soil carbon loss will eventually stabilize in the subsequent harvests, the GHG performance of forest residues would look more favorable over further harvest cycles.

### **Processing residue and MSW**

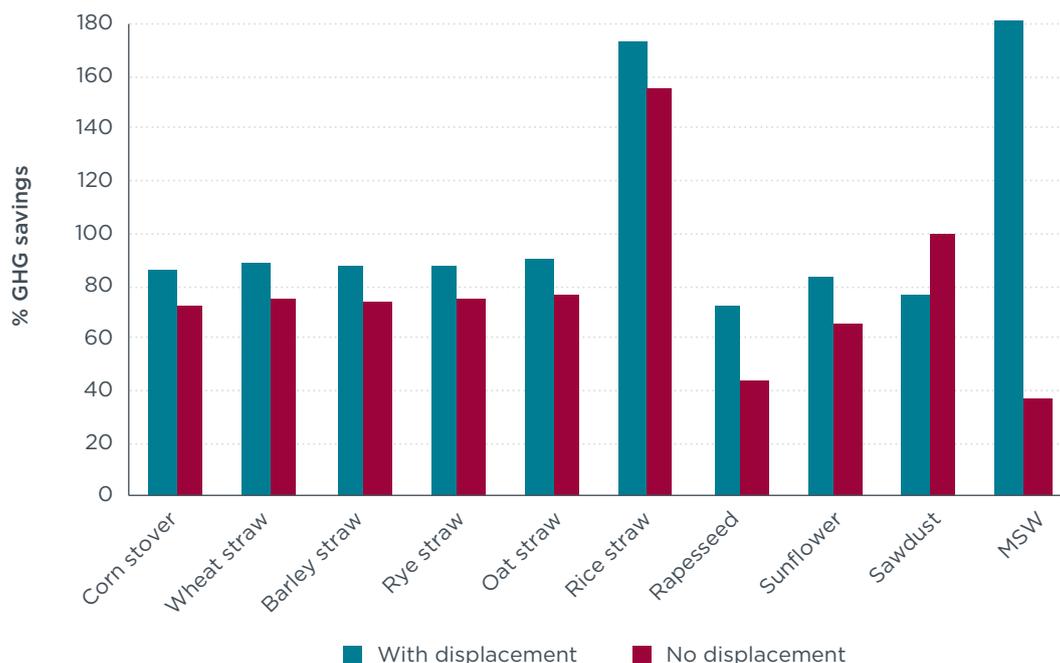
As in the case of agricultural residues, cellulosic biofuels derived from sawdust and MSW have very favorable carbon intensities, resulting in substantial GHG savings. In the case of sawdust, GHG savings range from 74% for pyrolysis diesel to 78% for ft-diesel. This is despite the appreciable and positive displacement emissions when sawdust is diverted from existing uses to biofuel production. These estimates are based on the assumption that 90% of sawdust used for biofuel comes from its diversion from existing material uses and 10% from existing energy uses. If we assume that sawdust is diverted equally from existing energy and material uses (i.e., a 50:50 ratio), GHG savings improve slightly, ranging from 77% for pyrolysis diesel to 82% for biochemical ethanol.

GHG savings are even larger for MSW, at 296%, due to the GHG credit for avoiding disposal in landfill (500 kg CO<sub>2</sub>e/tonnes MSW, or 6 tonnes CO<sub>2</sub>e per tonne ethanol). Even when some displacement occurs from the existing uses of MSW, such as incineration and composting, the benefits would still include substantial GHG reductions. If carbon intensity is considered in isolation without reference to total tonne carbon savings, this could be seen to imply that there may not be any benefits in terms of carbon intensity (or percent GHG savings) from improving the efficiency of MSW ethanol production; GHG emission savings from lower inputs will be offset by lower GHG credits because less MSW will be diverted from the landfill. But looking in terms of the total tonnes of GHG avoided, the best outcome is always to maximize both ethanol yield and total MSW diversion.

### **Additional sensitivity analysis**

In addition to sensitivity cases discussed earlier, we carry out sensitivity analysis toward two main assumptions: no displacement of agricultural residues from existing uses, and changes in biofuel yields. For sensitivity to yields, we assume 5% higher ethanol yield for a high-yield scenario and 25% lower ethanol yield for a low-yield scenario.

Figure 5 compares carbon intensities and percent GHG savings for biochemical ethanol pathways with and without displacement effects. When no displacement of agricultural residues is assumed, carbon intensities increase and percent savings decrease appreciably even though displacement emissions are small. This is because in the central scenario with 50% displacement, GHG emissions from soil carbon loss or nutrient replacement for the displaced feedstock are not counted, given that these emissions would occur anyway in the BAU scenario. Nonetheless, GHG savings are still 50% or more for agricultural residues for biochemical ethanol production (except for rapeseed straw) even when no displacement is considered.



**Figure 5.** Comparison of carbon intensities and percent GHG savings with and without displacement effects for biochemical ethanol pathway.

**Note:** For MSW with displacement from the existing landfill, the % GHG savings column is truncated because it is very large (296%)

For MSW ethanol, omitting avoided GHG emissions (i.e., no indirect emissions) when MSW is diverted from a landfill would reduce GHG savings considerably, from 296% to 37%. This is because GHG credits associated with MSW diversion from landfill are quite high, as explained earlier, and because the MSW-to-ethanol pathway modeled here has relatively high energy intensity. We anticipate that lower energy-intensity pathways for MSW processing will be available in the future, and indeed other demonstrated pathways may already have better energy performance than the Kalogo study. For sawdust, not including displacement effects improves GHG savings from 77% to 100%.

Varying ethanol yields did not have a substantial impact on GHG savings for ethanol obtained from agricultural residues. For example, lowering ethanol yields by 25% reduces GHG savings by less than 5%. This relative insensitivity is due to the fact that lower yields mean higher electricity credits per unit of ethanol produced, which partly offsets increase in GHG emissions from increased inputs. On the other hand, for the MSW pathway, changes in ethanol yield have appreciable effects on GHG savings because of very large credits associated with MSW when diverted from a landfill site, actually improving the carbon savings. If ethanol yields were lower by 25%, it would improve GHG savings by 23%. Of course, for any technology, reduced yields are likely to be economically undesirable, and it is important to consider not only percentage savings but also the total fossil fuel displacement achievable by using a given resource.

### Synthesis

Table 5 summarizes ranges of possible carbon intensities and GHG savings for residues and wastes when used to produce cellulosic biofuels via thermochemical and biochemical conversions.

**Table 5.** Summary of climate mitigation potential of wastes and residues

Feedstock	Biochemical ethanol (% GHG saving)	FT-diesel (GHG saving)	Pyrolysis diesel (% GHG saving)	Remark
<b>Agriculture residue</b>	73-173	77-176	80-140	>60% GHG savings, good potential for climate change mitigation
<b>Forest residues (slash)</b>	54	59	61	>50% GHG savings subject to soil C loss minimization
<b>Processing residue (sawdust)</b>	77	78	74	>60% GHG savings, good potential for climate change mitigation
<b>MSW</b>	296	-	-	>100% GHG savings possible, large potential for climate change mitigation

Even considering GHG costs of fertilizer replacement and soil carbon loss from residue harvest and displacement effects, this study shows that sustainable harvest of agricultural residues can contribute to climate change mitigation goals. For all the biofuel pathways for agricultural residues analyzed here, GHG savings are greater than 60% when biofuel displaces gasoline or diesel. Similarly, processing residues such as sawdust can also contribute to climate mitigation, although their contribution may not be as high as that of agricultural residues due to potential displacement emissions, and competition with existing uses will limit their availability. MSW is particularly appealing as biofuel feedstock, as there is a plentiful supply of it and it enjoys large GHG credits from its diversion from landfill sites.

While slash seems to deliver savings above 50% provided that there is no soil carbon loss, with potential to deliver savings greater than 60%, there are potential sustainability problems with residue removal, such as biodiversity effects. For example, one study suggested that slash removal after stem harvesting could cause a 12% loss of soil microarthropod population in a mixed conifer hardwood forest after 17 months of harvest (Bird & Chatarpaul, 1986). To avoid and minimize forest residue harvesting’s negative effects on biodiversity and soil, operative guidelines have been developed in many countries (Stupak et al., 2012). These guidelines determine restrictions on sensitive areas and set a minimum volume of residue to be left on-site. For example, Finland’s guidelines state that a minimum of 30% of logging residues is to be left on-site after clear cutting (Helmisaari, 2012). There is a need for additional long-term empirical research before the suitability of different forest residues’ use for cellulosic biofuel can be fully and conclusively assessed, particularly on the long-term impact of forest residue removal. Some long-term studies are already ongoing (E. Virtanen, personal communication, November 2013).

## CONCLUSIONS AND POLICY IMPLICATIONS

The novel contribution of this study is to assess the comprehensive life cycle GHG emissions of cellulosic biofuels derived from residues and wastes, considering not only the emissions covered by the RED/FQD methodology but also soil carbon loss, potential displacement emissions, and emissions associated with nutrient replacement to compensate for nutrient loss from residue removal. The results show that cellulosic biofuel from agricultural residues, processing residues, and MSW can offer GHG emission reductions of greater than 60%. This largely confirms the thinking that many advanced and cellulosic biofuels obtained from wastes and residues have the potential to reduce the carbon intensity of transport fuel in Europe. Forest slash also has potential, providing that soil carbon losses due to slash removal are limited. With the EU aiming to establish the mandate for biofuels from non-food based crops, these feedstocks can play an important role in meeting carbon reduction goals under the RED/FQD.

For forest residues, since GHG savings are highly sensitive to soil carbon loss and decomposition rates, and long-term empirical studies on soil carbon loss from forest residue removal and decomposition rates are limited, more long-term empirical research is warranted to fully understand the climate mitigation potential of forest residues. To be consistent with the RED methodology, we have considered a project time horizon of 20 years; therefore, we have not captured any potential longer-term impact or benefits from residue harvesting. A consideration of a longer time horizon for forest residues would also reduce the estimated carbon sink potential of residues. At the landscape level, it is possible that utilization of such residues for cellulosic biofuels could increase the economic value of forests enough to drive marginal forest expansion, resulting in increased carbon sequestration but also (potentially) indirect land use change. An attempt to assess these possibilities is beyond the scope of this study, but warrants further research.

This study demonstrates that further incentivizing the production of biofuel from cellulosic wastes and residues in general through the RED has potential to deliver carbon savings, without the same indirect land use change concerns or sustainability impacts associated with production of biofuel from food commodities. That said, we also note that not all residues may provide substantial GHG emission reductions, as indicated by the sensitivity analysis of slash (Table 4), especially when soil carbon losses are high. As Europe considers the support mechanisms for cellulosic fuels, it is important that the criteria for wastes and residues do not give too great an incentive to biofuels from residues whose carbon footprints are on par with fossil fuels. The criteria for awarding multiple credits or otherwise assessing eligibility for enhanced support should go beyond the simple physical characteristics of wastes and residues and incorporate life cycle emission thresholds based on comprehensive carbon accounting. Since soil carbon loss and fertilizer requirements are an important contributor to GHG emissions of residues, measures that improve biofuel yields and lessen soil carbon impact can go a long way in improving overall climate mitigation potential of residues.

Cellulosic ethanol technologies are incrementally moving from the research and development phase to commercialization, with a few commercial-scale plants completed in 2013 and more expected to come online in 2014. The carbon intensities and carbon emission savings estimated in this study should be taken with a measure of caution, as they are based on modeling studies of advanced biofuel technologies rather than data collection at actual commercial plants. As data becomes available for operating facilities, it will be important to consider actual achieved yield performance, and new data will continue to inform life cycle modeling efforts on new biofuel sources and processes in the future.

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## APPENDIX

## Feedstock composition

Residues	Nutrient content (kg/dry tonne) <sup>a</sup>			Chemical composition (%) <sup>a</sup>		Energy content (MJ/dry tonne) <sup>a</sup>
	N (wt %)	P <sub>2</sub> O <sub>5</sub> (wt %)	K <sub>2</sub> O (wt %)	Holo-cellulose	Lignin	
Wheat straw	0.64	0.12	0.52	64.6	18.5	17.2
Barley straw	0.72	0.38	1.75	66.1	18	17.6
Rye straw	0.42	0.2	1.17	62.2	13.3	15.9
Oat straw	0.58	0.12	0.52	62	15.4	17.3
Rice straw	0.85	0.5	1.61	57.9	12.1	14.0
Corn stover	0.76 <sup>b</sup>	0.22 <sup>b</sup>	0.13 <sup>b</sup>	63.6	15.5	17.0
Sunflower stover	1.3	0.12	0.52	71.3	17.5	18.8
Rapeseed straw	2.25	0.14	0.94	61.9	19.3	18.7
Slash	0.48	0.14	0.37	-----	-----	20.1
Sawdust	0.1	0.01	0.06	-----	-----	19.0

a Phyllis2 database

b From GREET

## Residue yields, soil carbon loss, and fertilizer requirements

	Residue yield per hectare—field residues only (tonnes/ha)	Sustainable harvestable yield (tonnes/ha)	Soil CO <sub>2</sub> loss (kg/ha.yr)	Fertilizer requirements (kg/ha) <sup>a</sup>		
				N	P <sub>2</sub> O <sub>5</sub>	K <sub>2</sub> O
Wheat straw	5.8	3.9	287	28.0	4.7	20.2
Barley straw	4.6	3.1	228	24.3	11.6	53.5
Rye straw	4.1	2.7	199	12.7	5.3	31.8
Oat straw	3.7	2.5	184	19.6	3.7	15.9
Rice straw	9.0	6.0	441	57.0	30.2	96.5
Corn stover	6.0	4.0	294	34.1	8.9	53.2
Sunflower stover	3.4	2.2	162	31.8	2.7	11.6
Rapeseed straw	3.4	2.3	169	57.6	3.2	21.6
Slash	40.4	----- <sup>b</sup>	0	189.9	49.8	

a Nitrogen fertilizer requirements estimates take into account 10% N loss from volatilization.

b The sustainable harvestable yield has not been reported, so harvested biomass of slash as reported by Strömberg et al. (2013) are used in estimating GHG emissions.

### Biofuel yields for various biofuel pathways (tonne/dry tonne)

	Pathway	Output	Yields	Comments
<b>Wheat straw</b>	Thermochemical—gasification and FT synthesis	FT-diesel	0.20	50% energy conversion efficiency (GREET)
	Thermochemical—pyrolysis	Pyrolysis diesel	0.14	Pyrolysis and stabilization, and upgrading at integrated biorefinery from GREET based on Iowa State University data. For all other agricultural residues the same yield of 0.14 tonnes/ dry tonne is assumed, the combined diesel and gasoline yield is 0.28 tonnes/dry tonne.
	Biochemical—hydrolysis and fermentation	Ethanol	0.30 <sup>a</sup>	
<b>Barley straw</b>	Thermochemical—gasification and FT synthesis	FT-diesel	0.20	50% energy conversion efficiency (GREET)
	Thermochemical—pyrolysis	Pyrolysis diesel	0.14	
	Biochemical—hydrolysis and fermentation	Ethanol	0.31 <sup>a</sup>	
<b>Rye straw</b>	Thermochemical—gasification and FT synthesis	FT-diesel	0.20	50% energy conversion efficiency (GREET)
	Thermochemical—pyrolysis	Pyrolysis diesel	0.14	
	Biochemical—hydrolysis and fermentation	Ethanol	0.29 <sup>a</sup>	
<b>Oat straw</b>	Thermochemical—gasification and FT synthesis	FT-diesel	0.20	50% energy conversion efficiency (GREET)
	Thermochemical—pyrolysis	Pyrolysis diesel	0.14	
	Biochemical—hydrolysis and fermentation	Ethanol	0.29 <sup>a</sup>	
<b>Rice straw</b>	Thermochemical—gasification and FT synthesis	FT-diesel	0.16	50% energy conversion efficiency (GREET)
	Thermochemical—pyrolysis	Pyrolysis diesel	0.14	
	Biochemical—hydrolysis and fermentation	Ethanol	0.27 <sup>a</sup>	
<b>Corn stover</b>	Thermochemical—gasification and FT synthesis	FT-diesel	0.20	50% energy conversion efficiency (GREET)
	Thermochemical—pyrolysis	Pyrolysis diesel	0.14	
	Biochemical—hydrolysis and fermentation	Ethanol	0.30	From GREET
<b>Sunflower stover</b>	Thermochemical—gasification and FT synthesis	FT-diesel	0.22	50% energy conversion efficiency (GREET)
	Thermochemical—pyrolysis	Pyrolysis diesel	0.14	
	Biochemical—hydrolysis and fermentation	Ethanol	0.33 <sup>a</sup>	

	Pathway	Output	Yields	Comments
<b>Rapeseed straw</b>	Thermochemical—gasification and FT synthesis	FT-diesel	0.22	50% energy conversion efficiency (GREET)
	Thermochemical—pyrolysis	Pyrolysis diesel	0.14	
	Biochemical—hydrolysis and fermentation	Ethanol	0.29 <sup>a</sup>	
<b>Slash</b>	Thermochemical—gasification and FT synthesis	FT-diesel	0.23	50% energy conversion efficiency (GREET).
	Thermochemical—pyrolysis	Pyrolysis diesel	0.17	Pyrolysis, stabilization and upgrading at integrated biorefinery assumed; generic yield for forest residue from GREET based on Pacific Northwest Laboratory data (PNL); the combined diesel and gasoline yield is 0.32 tonnes/dry tonne
	Biochemical—hydrolysis and fermentation	Ethanol	0.30	Generic yield for forest residue from GREET
<b>Sawdust</b>	Thermochemical—gasification and FT synthesis	FT-diesel	0.22	50% energy conversion efficiency (GREET)
	Thermochemical—pyrolysis	Pyrolysis diesel	0.17	Generic yield for forest residue assumed, PNL data used by GREET, the combined diesel and gasoline yield is 0.32 tonnes/dry tonne
	Biochemical—enzyme hydrolysis and fermentation	Ethanol	0.30	Generic yield for forest residue from GREET
<b>MSW</b>	Gravity pressure vessel process-acid hydrolysis and fermentation	Ethanol	0.08 per wet tonne	Assuming 25% higher yield rate than a conservative estimate by Kalogo et al. (2006); for approximation, we assume that biogenic compositions of MSW in the US and EU are similar

<sup>a</sup> For a biochemical ethanol pathway involving enzyme hydrolysis and fermentation, yields of all agricultural residues are calculated relative to the reported yield of 0.30 tonne ethanol/ dry tonne corn stover by GREET. This is done by adjusting the yield based on the ratio of holocellulose content of the residue in question to that of corn stover. That is, if the holocellulose content of the residue is 1.05 times higher than that of corn stover, its ethanol yield would be 1.05 times more than that of corn stover.