WHITE PAPER

OCTOBER 2013

# AVAILABILITY OF CELLULOSIC RESIDUES AND WASTES IN THE EU

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# SUMMARY

The demand for renewable energy has grown in the EU over recent years with policy support through the Renewable Energy Directive, Fuel Quality Directive, and Emissions Trading Scheme. While, at the time of writing, global cellulosic biofuel production is still low compared to other biofuels, there is significant potential for sustainable energy from cellulosic biomass in the future.

This study aims to estimate the sustainable availability of certain cellulosic wastes and residues in the EU. We calculate the availability of the cellulosic fraction of waste, agricultural residues, and forestry residues, while considering current uses of these materials and the environmental impact of utilization.

The total amount of paper, wood, food, and garden waste produced in the EU is considerable, in the order of 900 million tonnes per year. However, a large fraction of this is not truly "waste," but low-value input materials from industrial processing and livestock care. A good example is sawdust, a "waste product" of milling wood that is then used to make products such as fiberboard. Agricultural residues, or the leaves and stalks of plants left over after harvesting, are "waste" from the consumer's perspective but often have other agricultural uses, such as animal bedding. Some wastes and residues do not have industrial uses but still provide valuable environmental services, such as the twigs and leaves left over from logging, which house small wildlife and return nutrients to the soil to support future forest growth. Diversion of these materials from their current uses would have potentially negative knock-on effects on industry and the environment. Accounting for various industrial uses and sustainability restrictions, about a quarter of the total production of these cellulosic materials is available for energy use, now and through 2030. The estimated sustainable availability in each category is shown in Table 1. The total available cellulosic biomass is found to be about 220 million tonnes per year, with the majority coming from crop residues (Table 1).

**Table 1.** Present and future (2030) sustainable availability of wastes and residues in the EU.

| Category | Subcategory | Current availability (Mtonnes/yr) | 2030 Availability (Mtonnes/yr) |
|---|---|---|---|
| **Waste** | Paper | 17.5 | 12.3 |
| | Wood | 8 | 5.6 |
| | Food and garden | 37.6 | 26.3 |
| **Crop residues** | | 122 | 139 |
| **Forestry residues** | | 40 | 40 |
| | **Sum** | **225** | **223** |

The quantity of available cellulosic resource represents a sizable opportunity to produce sustainable, low-carbon-intensity energy on a large scale. If all the EU-based sustainably available cellulosic biomass was processed for transport fuel, and accounting for energy losses in conversion, these renewable feedstocks could supply a little under 1 million barrels of oil equivalent per day. This biofuel could potentially displace 13% of road fuel consumption in the EU in 2020, and 16% in 2030.

At the same time, it is critical to understand that using any resource, even if it appears to be available in excess, can have complex downstream effects on markets, other uses, and the demand for other resources. Environmental impact stems from both the direct utilization of the wastes and residues analyzed here and also from the indirect effects on other industries, and this impact is not fully assessed here. It should be recognized that there will be competition for feedstocks within the energy sector, so the above estimate should be understood as the upper bound on the available sustainable energy resource for transport fuels. In addition, there are many industrial challenges in achieving such a major new deployment of sustainable low carbon fuels. Among these challenges is the question of how to create the right policy and fiscal incentives to reduce investment risk for the advanced biofuel industry, thereby allowing for such a substantial scale-up. Even with robust and effective policy support, some fraction of this resource is likely to be impossible to economically mobilize—the stronger the support framework, the more could be achieved.

# INTRODUCTION

## BACKGROUND ON THE PUSH FOR CELLULOSIC BIOFUEL IN THE EU

Since 2009, European policy has supported biofuels through two major directives: the Renewable Energy Directive (RED) and the Fuel Quality Directive (FQD). The RED mandates a certain volume of renewable energy: 20% of total energy must be from renewable sources by 2020, and as part of this target, 10% of transport energy must be from renewable sources. The FQD mandates greenhouse gas reduction in transport fuels: fuels used in cars, trucks and non-road mobile machinery must have a 6% lower average lifecycle carbon intensity in 2020 than they did in 2010.

With respect to transportation fuels, progress towards these mandates has largely been fulfilled through food-based biofuels, made from crops such as wheat, rapeseed oil, palm oil, sugarcane, and so forth. The large-scale use of food for fuel has become controversial as biofuels have been accused of raising food prices and consequently incentivizing the increased conversion of land to agricultural use, an effect called *indirect land use change (iLUC)*. GHG emissions associated with iLUC have been estimated to make some biofuels (notably from oilseeds) more greenhouse-gas-intensive than petroleum (Laborde, 2011).

Responding to concern about iLUC and effects on food security, there has been an increasing focus on support to commercialize non-food-based biofuels that do not cause iLUC. This includes a European Commission proposal to double or quadruple count the energy content of certain non-food biofuel feedstocks to the RED target. An area of particular interest is the use of biomass with low economic value, such as wastes and residues, to make biofuels. It is anticipated that biofuels from wastes and residues may have low carbon intensities, especially in cases where the biomass would otherwise probably have decomposed. Low-value biomass can include residues from agriculture and forestry, as well as household food and garden waste. This last category may have an especially low carbon footprint, as using it for biofuel would mean avoiding potential climate-warming methane emissions from landfills.

## PURPOSE OF THIS STUDY

This study aims to estimate the environmentally sustainable availability of wastes and residues for cellulosic biofuel production in the EU. Availability is estimated for the present and for the year 2030. The feedstock categories included here are:

- The cellulosic fraction of collected waste
    - Paper and cardboard waste
    - Wood waste (processing residues and post-consumer wood)
    - Food and garden waste
- Agricultural crop residues
- Forestry harvesting residues

For each of these categories, we present the total availability or generation of the waste or residue. If the material has other existing uses, we discuss displacement effects in the context of the “waste management hierarchy” (UNEP, 2011). This concept prioritizes the usage of waste in the following order: prevention of waste generation, re-use, recycling (including composting), energy recovery, and, when no other options are available, disposal. It is possible that in some circumstances, energy recovery might be an environmentally preferable outcome to uses such as composting, so we consider the hierarchy as a guide rather than a rigid rule. We also discuss how the collection of agricultural and forestry residues can impact soil carbon and biodiversity.

This report does not judge whether biomass should be used for biofuel or biopower. Some experts have shown that greater GHG reductions can be achieved by using biomass for electricity generation instead of fuel, as biofuel requires additional processing energy and thus produces more emissions (Frass & Johansson, 2009; Campbell et al, 2009), and because coal produces more $CO_2$ per unit of energy derived than does petroleum (Staffell, 2011), so displacing coal is associated with higher GHG savings. Other experts believe biomass resources should be targeted for biofuel production, because while the electricity sector can eventually be decarbonized without biomass (using solar, wind, geothermal, etc.), there are relatively few options other than biomass to decarbonize liquid transport fuels. The fact that competition exists between the power and fuels industries for biomass does need to be recognized. Diverting biomass from power generation will have indirect consequences, such as increased use of other energy sources, just as using all biomass for power may lead to greater consumption of petroleum. In the worst case, reduced biomass availability could result in increased use of coal—but given the existence of binding renewables targets, it could also result in increased deployment of alternative renewable power generation. This study does not make any assumption about these displacement effects. The economics of biomass utilization matter a great deal, and the use of higher-value products (potentially including cellulosic biofuel) may support greater use of biomass overall.

This report focuses on the quantity of cellulosic wastes and residues generated and discusses factors constraining this availability for biofuel; subsequent reports for this project will address the greenhouse gas intensity of these feedstocks and conversion pathways, the economics of cellulosic biofuel production, and the potential for biomass production from dedicated energy crops.

# CELLULOSIC FRACTION OF WASTE

The major cellulosic components of collected municipal waste include discarded wood, paper, food, and garden waste. Some of this material is then recovered and recycled into other uses or incinerated for heat and power, and the rest is permanently disposed, typically in landfills. This section provides estimates of the quantity of each type of waste produced and its fate. The fraction of waste that can most sustainably be used for biofuel is that which would not otherwise be recovered for any use. Where there are existing uses, there is an opportunity cost from diverting the material to biofuel processing, as well as possible displacement effects. These effects must be evaluated before determining whether processing into biofuel represents a good use for that resource.

## PAPER AND CARDBOARD

According to the Confederation of European Paper Industries (CEPI), the industry association, about 81.5 million tonnes of paper and cardboard were consumed in the EU in 2011 (CEPI, 2012). Paper and cardboard have a very short lifespan and are usually discarded after one to two years (Marland, 2010). In 2011, 59% of paper and cardboard, or 48.4 million tonnes, was recycled (Table 2). In addition to this, CEPI reports that about 0.4 million tonnes (0.5%) were composted, 0.2 million tonnes (0.2%) recycled in other ways, and 5.5 million tonnes (7%) incinerated, some for energy (Eurostat estimates that about 90% of paper and cardboard incineration is for energy recovery) and the rest to avoid landfill disposal.

**Table 2.** Fate of paper and cardboard consumed in the EU in 2011 (source: CEPI, 2012)

| Fate | Quantity (million tonnes/yr) | Sustainably available |
|---|---|---|
| **Generation of paper and cardboard waste** | **81.5** | |
| **Recycled for further paper and cardboard production** | 48.4 | X |
| **Net trade of paper for recycling** | 8.9 | X |
| **Composting** | 0.4 | X |
| **Incineration** | 5.5 | – |
| **Other recovery** | 0.2 | – |
| **Landfill and other non-collectible disposal** | 17.5 | ✓ |

A substantial amount of waste paper and cardboard is not put to any productive function. Using this paper (which would otherwise be disposed of in landfills or incinerated with no energy recovery) for biofuel would likely deliver environmental benefits. The waste hierarchy prioritizes recycling (including composting) above energy recovery because materials are considered to have a higher value than that reflected by their raw energy content alone. Diverting waste paper from any recovery stream, including that which is composted or incinerated for energy, should be done with caution, as doing so will create demand for other materials. Using waste paper and cardboard for biofuel could be unsustainable if it leads to this kind of displacement, so care should be taken to ensure that it does not skew demand.

## WOOD WASTE

The fraction of wood waste recycled is lower than that of paper and cardboard. According to Mantau (2012), 26 million tonnes[1] of post-consumer wood (i.e. wood products such as furniture that are discarded) was generated in 2010 (Table 3). Of this, 7.8 million tonnes was recycled into other products and 10.3 million tonnes was burned for energy in power plants or households.[2] About 8 million tonnes was permanently disposed of or incinerated (not for energy).

Wood wastes are also produced in the course of processing logs into boards, and then into final products (e.g, furniture or home construction materials). These wastes, sometimes called wood processing residues, include wood chips, sawdust, and black liquor; they are produced at industrial facilities and are thus easy to collect and reuse. In fact, Mantau (2012) and an earlier paper by the same author (Mantau, 2010), estimate that all wood processing residues are utilized in some way, with 59% of them burned for energy and 41% recycled into other products, such as paper or fiberboard. When processing residues are included with post-consumer wood, the total recycling rate of wood wastes rises from 30% to 39%.

Eurostat gives a higher estimate of EU wood waste than Mantau, about 57 million tonnes in 2010 (Table 3). At least part of the discrepancy is likely because this estimate includes some processing wastes from forestry (39.4 million tonnes of wood waste are classified as originating in the agriculture, forestry, and fishing sectors). Eurostat shows similar rates to Mantau of wood recycling (44% vs. 39%) and incineration for energy (50% vs. 54%), and for the fraction that is permanently disposed of (7% vs. 7%).

**Table 3.** Fate of post-consumer wood in the EU in 2010, as estimated by Mantau (2012) and Eurostat. Post-consumer wood waste comprises final wood products that have been discarded (e.g., furniture); total wood waste includes post-consumer waste as well as processing residues. Percentages of total wood waste generation are shown in (%).

| Fate | Post-consumer wood waste—estimated by Mantau (2012) (million tonnes/yr; % of total) | Total wood waste—estimated by Mantau (2012) (million tonnes/yr; % of total) | Total wood waste—estimated by Eurostat (million tonnes/yr; % of total) | Sustainably Available |
|---|---|---|---|---|
| **Generation of wood waste** | 26 | 114.2 | 56.8 | |
| **Recycled into other products** | 7.8 (30%) | 44.2 (39%) | 24.9 (44%) | x |
| **Incinerated for energy** | 10.3 (40%) | 62.2 (54%) | 28.3 (50%) | – |
| **Permanently disposed in landfills or incinerated (not for energy)** | ~8 (31%) | ~8 (7%) | 3.7 (7%) | ✓ |

The resource of waste wood that is not used for any purpose and is thus sustainably available for energy is rather small compared with the size of the wood products sector in Europe. A substantial amount of waste wood is being burned for energy recovery in power plants and households; this resource could potentially be utilized for energy products of higher value (i.e., cellulosic biofuel). If large amounts of wood waste are diverted to biofuel in the future, it is important to recognize that some other resource will likely be drawn in to meet the demand for heat and electricity.

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[1] Calculated from 52.0 $Mm^3$ using a typical wood density of 0.5 t $m^3$ (Mantau, 2010)

[2] In Mantau (2010), the same author estimated that 55.4 $Mm^3$ or 22.7 million tons of post-consumer wood is generated annually in the EU.

## FOOD AND GARDEN WASTE

A fair amount of cellulosic waste comes from uneaten food and garden clippings (lawn grass, tree branches, etc.). FAO (2011) has estimated per capita food wastage of 95–115 kg per year in the EU, which translates to 53 million tonnes per year overall. Eurostat estimates that 108 million tonnes of "animal and vegetal waste" was produced in the EU in 2010. Of this, 25.5 million tonnes is classified as animal and vegetal waste from households, and of that amount, 19.7 million tonnes is vegetal waste. Presumably much of the 19.7 million tonnes of household vegetal waste is garden clippings, and the remainder of household animal and vegetal waste is from food. This figure is roughly consistent with another from EUR-Lex, which gives combined generation of garden waste and "bio-waste" (not defined) of 35–40 million tons in 2005 (2008). Eurostat estimates that 12 million tonnes of animal and vegetal waste is produced in the services industry (presumably largely restaurant food wastage and supermarket discards) and 39 million tonnes comes from the agriculture, forestry, and fishing sectors.[3] The latter includes 16.5 million tonnes of animal excrement. Also using Eurostat data, the European Commission (2010) estimated that 89.3 million tonnes of food is wasted in the EU each year, a higher figure than that of the FAO.

**Table 4.** Animal and vegetal waste in the EU. Eurostat data is for 2010; other estimates of present food wastage are from the Food and Agricultural Organization (FAO, 2011) and the European Commission (2010).

| | Category | Amounts from EUROSTAT (million tonnes per year) | Other estimates (million tonnes per year) | Sustainability |
|---|---|---|---|---|
| **Generation of animal and vegetal waste** | Total | 108.5 | | |
| | Household yard clippings | 19.7 | | |
| | Household food waste | 4.8 | 52.9 (FAO)<br>89.3 (EC) | |
| | Services | 12.1 | | |
| | Agriculture, forestry, and fishing | 38.8 | | |
| **End use of animal and vegetal waste** | Composting and digestion | 33.9 | | X |
| | Incineration for energy | 1.8 | | – |
| | Other recovery | 35.2 | | – |
| | Incineration (no energy) | 0.2 | | ✓ |
| | Disposal to landfill or other | 37.4 | | ✓ |

A substantial amount of animal and vegetal waste is currently not used for any productive purpose (it is put into landfills, incinerated without energy recovery, or other disposal), and therefore could be used for cellulosic biofuel with few consequences. However, care should be taken to consider the displacement effects if a large-scale diversion of waste material to biofuel production results in increased usage of non-waste materials for power plants, compost, etc.

In addition, it should be noted that the fraction of this waste pool that is non-cellulosic (i.e. animal waste, plant oils, etc.) is unknown. It is likely that the majority of animal and vegetal waste is from plant material, so the availability of cellulosic waste from food and yard clippings may still be large. But this heterogeneous material is of lower quality than waste paper or wood, so the cost of separating the material into higher quality components must

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[3] This statistic is from 2008; data on generation of animal and vegetal wastes from the agriculture, forestry, and fishing sectors was not available for 2010 at the time of writing.

be carefully considered. Some biofuel conversion processes are likely more tolerant than others; for example, gasification processes may be able to convert oils, but enzymatic processes may be sensitive to non-cellulosic contamination. For conversion processes such as that used to make biogas, which can utilize the entire biogenic fraction of waste, it should be noted that some additional non-cellulosic categories, not reported here, may be available. However, Eurostat does not identify any such major categories of significant quantities other than animal manure, which is not considered in this report.

## PROJECTED AVAILABILITY IN 2030

Several initiatives have been taken in the EU to reduce waste generation and increase recycling rates. The EU Waste Framework Directive calls for EU member states to take action to reduce waste and increase recycling, and sets a minimum 50% target for recycling of household paper by 2020.[4] Pulp and paper industry associations in Europe have signed the European Declaration on Paper Recycling 2011–2015, which sets a target of 70% paper recycling by 2015.[5] The industry target for paper recycling is likely higher because it includes paper from industrial and commercial sources, which is easier to collect and recycle than from households.

Generation of municipal solid waste (MSW) has been increasing over time, and the European Environment Agency (Bakas et al, 2011) projects that the EU will continue to create more waste in the near-future period to 2020. But rates of recycling and incineration have been increasing at a faster rate, such that landfilled MSW has been declining. The EEA projects that the EU will increase incineration rates (both for energy recovery and for disposal) from about 20% today to 23% in 2020, and recycling rates will increase from 40% to 49%.

Recycling rates of the cellulosic waste components considered here are generally higher than the rate for total waste, which was estimated to be 40% in 2008 (Bakas et al, 2011). Still, it is reasonable to assume that EU efforts to reduce landfilling will result in higher recycling rates for all waste streams over the coming decades.

A summary of availability of waste in 2010 and projected availability in 2030 is shown in Table 5. Here, the category "all potentially available waste" includes all waste that is not recycled for material use—this includes waste that is disposed of, incinerated (for energy or disposal), and "other recovery," but not recycled or composted waste. "Sustainably available waste" in this table refers only to waste that is disposed of with no other use. These projections were calculated based on EEA's projection for recycling to 2020. We considered EEA's rate of change of non-recycled waste (from 60% in 2010 to 51% in 2020) and extrapolated this to 2030 (42%). The percentage of non-recycled waste in 2030 is thus projected to be 70% of the 2010 share (42% compared with 60%). We then multiplied the availability of non-recycled cellulosic waste in 2010 by 70%, and the resulting values are shown in Table 5.

**Table 5.** Summary of EU waste that is potentially available (disposal, incineration, and other recovery—does not include recycling) and sustainably available (disposal only) in 2010, and projections of availability in 2030. All values in millions of tonnes per year

| Waste category | All Potentially available waste | | Sustainably available waste | |
|---|---|---|---|---|
| | 2010 | 2030 | 2010 | 2030 |
| **Paper and cardboard** | 23.2 | 16.3 | 17.6 | 12.3 |
| **Wood** | 62.2 | 43.5 | 8.0 | 5.6 |
| **Food and garden** | 74.6 | 52.2 | 37.6 | 26.3 |
| **Sum** | **160.0** | **112.1** | **63.2** | **44.2** |

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[4] http://ec.europa.eu/environment/waste/framework/

[5] http://www.paperforrecycling.eu/uploads/Modules/Publications/Declaration-digital_CORR.pdf

# CROP RESIDUES

Here, we estimate the availability of crop residues, or parts of cropped plants that are not consumed as food. This includes the stem and leaves of grain crops such as wheat, as well as chaff (the seed coating), corn husks, and cobs. Residue availability for 12 of the EU's most produced crops is presented. Total residue production for these crops was calculated using FAOSTAT data on yields and total yearly production of these crops from 2002–2011. Calculations for crop residues and forestry residues (see below) follow the basic statistical method in the Best Practices and Methods Handbook (Vis & Van den Berg, 2010).

## RESIDUE PRODUCTION RATIO

The field residue production ratios (RPR, or the ratio of residues to harvested crop) of nine of these crops were estimated using regressions determined by Scarlat et al. (2010) through extensive literature review, where the RPR is negatively correlated with yield of the grain or seed. The yield of each crop, averaged over the 10-year period from 2002–2011 and across EU member states, weighted by each state's total production, was input into these equations. These estimates were similar to those reported in other studies (e.g. Koopman & Kopejan, 1997; Murali, 2007; Dalianis & Pantasou, 1995 as cited in Nikolau et al., 2003) and those assumed in previous estimates of residue potential (U.S. Department of Energy, 2011; Kim & Dale, 2004). Where Scarlat et al. (2010) assumed a residue moisture content other than that of typical traded residues (15%), we adjusted the RPR to calculate residues at 15% moisture. Estimated fractions of process residues (chaff, husk, cobs) were added to the field RPRs for coarse and small grains from Collins et al. (1990) and from the literature review presented in Koopman & Kopejan (1997). This was not done for oilseeds, as crushed oilseed meal is used in animal feed (Farahat et al., 2013). The RPR for soybeans was taken from Koopman & Kopejan (1997), and that for sugar beet was calculated from an estimate of 38 t ha$^{1}$ residues at the central location in Beeri et al. (2005) and 10-year average U.S. sugar beet yields (USDA, 2013). For comparison, the European Commission reports the sugar beet residue ratio to be 0.99 (EC, 2011), but much of that is below-ground fine roots, the collection of which is not considered for any crop in this analysis. The RPR for triticale was estimated to be the average of the fractions for wheat and rye, as triticale is a hybrid of these two plants and no estimated fractions were found for triticale specifically. The total RPRs for these 12 crops varied from 0.12 (olives) to 3.50 (soybeans) (Table 6).

**Table 6.** Calculation of total agricultural residue production in Europe.

| Crop type | Crop production (Mtonnes) | Field residue production ratio* | Proccessing residue production ratio | Total residue production (Mtonnes) |
|---|---|---|---|---|
| **Barley** | 55.2 | 0.94 | 0.24 | 65 |
| **Maize** | 48.6 | 0.80 | 0.47 | 62 |
| **Oats** | 8.0 | 1.07 | 0.24 | 10 |
| **Olives** | 8.4 | 0.12 | | 1 |
| **Rapeseed** | 16.4 | 1.08 | | 18 |
| **Rice** | 1.3 | 1.32 | 0.27 | 2 |
| **Rye** | 8.0 | 1.13 | 0.24 | 11 |
| **Soybeans** | 0.5 | 2.50 | 1.00 | 2 |
| **Sunflower** | 5.2 | 1.77 | | 9 |
| **Triticale** | 9.9 | 1.04 | 0.24 | 13 |
| **Wheat** | 122.1 | 0.94 | 0.24 | 144 |
| **Sugar beet** | 111.3 | 0.27 | | 30 |
| **Sum** | **394.9** | | | **367** |

* Residue production ratio is the ratio of residue to harvested grain or crop. Values greater than 1 indicate that more residue is produced compared to the utilized part of the crop, and values less than 1 indicate that less residue is produced than the utilized part of the crop.

## SOIL QUALITY

With modern harvesting technology (combine harvesters that cut, separate, and thresh the grain in the field; FAO, 1994), almost all residues remain in the field for most crops considered here. For example, cereals are typically harvested with a combine, which cuts off the top of the plant. A thresher, attached to the combine, then separates the grain from the chaff. While the grain is collected, the straw and chaff are returned to the field. Residue collection systems can be attached to the combine, but using these systems has been found in some studies to be too expensive to be profitable at current biomass prices (Erickson & Tyner, 2010; Timmenga & Abeetnoff, 2008).

Not all residue production should be considered available for bioenergy. It is widely acknowledged that in sustainable farming, a fraction of residue should remain in the field to reduce erosion and protect soil organic carbon (SOC) and nutrients. In addition, a fraction of residues are currently collected and have other uses, mainly for animal bedding.

In the EU, the primary motivation for residue retention is to increase soil carbon, although residues may also play an important role in soil stabilization and soil moisture retention. Unfortunately, experimental studies in the EU on the effect of residue retention on soil carbon status have been less common than in the US (see text box on U.S. research below). In seven studies reviewed in Powlson et al. (2011) in Denmark, the UK, France, Sweden, and Belgium, straw (mostly from wheat and barley) incorporation into the soil resulted in an average of 1% increase in soil carbon content per year; however, the results were highly variable (study averages range from 0.09-2.52 % $yr^{-1}$) and were statistically significant in only one of these studies. Many of these studies compare a treatment of 100% residue retention with one of 0% retention, and as far as we were able to determine there has been little research published in the EU determining a threshold amount of residues necessary to achieve this effect of soil carbon increase.

Without this information, we rely on the current best practice of incorporation of one-third of total residues, as advised by the JRC (2009). This is consistent with the current practice of European farmers who do incorporate residues (Kretschmer, 2013; IEEP, 2013). In our analysis, we assume one-third of residues remain in the field. It is important to understand the high uncertainty associated with this number: It has not been empirically determined; the ideal residue retention rate varies enormously by location, soil type, slope, erosion, precipitation patterns, etc. and should be determined on a local level. In addition, higher residue retention may be advised in all cases to protect crop yields against losses due to year-to-year weather variability, for example to guard soil moisture in very dry years. There is a significant chance that guidance on the residue retention rate in Europe will change in the near to medium-term future as new research is published.

## U.S. RESEARCH ON RESIDUE RETENTION RATES

A body of research in the US has established that residue retention on the soil surface is necessary to slow erosion and corresponding soil carbon loss. For this purpose, the fraction of residues needed to prevent soil erosion is generally assumed to be 60–85% in studies that estimate residue availability (e.g., Kim & Dale, 2004; Gregg & Smith, 2012; UCS, 2012; WWF, 2012). A comprehensive review by the U.S. Department of Agriculture (Andrews, 2006) found that in general, 70% of residues needed to be left on the soil surface to prevent erosion and corresponding losses in SOC and nutrients. This figure was selected based on findings that erosion levels off with residue retention of higher than 70% (Lindstrom, 1986, as cited in Andrews, 2006), a similar finding to that in Papendick & Moldenhauer (1995). Other studies on soil quality give similar results for the ideal residue retention rates: 70% in Graham et al. (2007); 100% for conventional till, 82% for reduced till, and 55% for no till in the U.S. Department of Energy's Billion Ton Study (2011); and 75% for corn with conservation tillage at typical yields and 100% for corn-soybean rotations or conventional till with any crop in Wilhelm et al. (2007). It is recommended that residues be left on the soil surface, as plowing them into the soil is not effective at reducing erosion and SOC loss (Papendick & Moldenhauer, 1995, and Reicosky et al., 2002 and Clapp et al., 2000 as cited in Andrews, 2006). While it is possible that a lower proportion of carbon from the residues is returned to the soil when residues remain on the surface rather than being incorporated into the soil, the benefit of preventing SOC loss through erosion outweighs this factor. Indeed, in a review of the literature from both the U.S. and EU, Powlson et al. (2011) found that only six of 25 long-term studies showed residue incorporation to significantly increase soil carbon content compared with treatments with no residue incorporation. On the other hand, erosion rates are significantly lower in the EU than in the US. (2.76 t $ha^{-1}$ $yr^{-1}$ vs. 11.9 t $ha^{-1}$ $yr^{-1}$) (USDA, 2013; Eurostat, 2013), so European farmers tend to worry less about preventing erosion from their fields.

Because it is the total amount of residues on the soil surface rather than the fraction of total residue production that matters, it may not be advisable to harvest residues from lower-yielding crops such as soybean or sunflower. In addition, the low C:N ratio of soybean plants allows these residues to decompose at a faster rate than others, providing less protection from erosion (Shelton et al., 1991). We have allowed for 30% of residues from those crops to be collected in our total availability estimate, but it should be understood that the most sustainable regime of residue use would not be based on simple blanket rules (like 30% collection) but would be sensitive to specific local circumstances.

Lastly, we note that the evidence for residue incorporation significantly increasing soil carbon over time is not convincing, and that the amount of carbon expected to be sequestered is relatively small. On this point, Powlson et al. (2011) writes, “It has been estimated that using straw for electricity generation is more effective in mitigating climate change, through replacement of fossil fuel, than through the C sequestration that might be achieved by incorporation in soil.” The tradeoff between using residues for soil carbon sequestration and for energy, in terms of GHG reduction, is a complex issue that is beyond the scope of this report.

## OTHER USES

Some amount of crop residues is collected for use as animal bedding and fodder, mushroom cultivation, and various horticultural uses. The total amount or proportion of residues consumed in these uses is not generally well understood.

In a well-cited study, ADAS estimated that 5.8 million tonnes, or 42%, of residues are used in animal husbandry in the UK each year (2008). This estimate was generated through interviews with farmers and agricultural experts. Using a similar approach with interviews, Scarlat et al. (2010) estimated that 11% of residues are used in animal husbandry over the whole of the EU. These authors speculated that the EU finding may be lower than ADAS’s UK estimate because more farms in other countries such as France are very large- scale and do not have as high a ratio of livestock to crop on site (personal communication with N. Scarlat and J.F. Dallemand).

Much of the residue consumption for livestock is thought to occur on site, i.e., the same farmer who harvests cereals and collects the straw feeds it to his or her livestock; this type of consumption is difficult to quantify. Some residues are sold to other parties, and this amount is easier to track. Studies have estimated off-farm residue use to amount to 5% (Kadam & McMillan, 2003) to 6% (Glassner et al., 1999, as cited in Kim & Dale, 2004). Some types of processing residues that are generated at the processing site, such as olive pits, are used for power generation or other industrial purposes.

Here, we assume one-third of residues have other uses. This assumption is conservative in the sense that it may underestimate actual residue availability, but we can be reasonably confident that at least that quantity of material is sustainably available. Diversion of residues from other uses may have complicated downstream effects and would likely have a net negative environmental impact. For example, if the demand for crop residues for cellulosic biofuel rises, this will increase the price of these residues across the whole sector. Farmers who had previously been using residues as animal bedding may find it more profitable to sell the residues to bioenergy producers and replace the bedding with wood chips. This could in turn divert wood chips that would previously have been combusted in power plants, raising wood chip prices and potentially resulting in some degree of switch back to coal. Meanwhile, a higher price of wood chips might slightly increase the incentive for additional forestry harvesting, but also additional forestry establishment, with knock-on effects on carbon storage, biodiversity, and ecosystem services. This illustration is an example of the types of unintended and complex consequences that may arise in diverting any stream of resources to a new use.

Using these assumptions that one-third of total residue production remains in fields and another third is used for livestock and horticulture, we estimate the following current availability of crop residues (Table 7).

**Table 7.** Current net availability of crop residues for bioenergy.

| Crop | Total residue production (million tonnes) | Residue retention in field (million tonnes) | Residues in other uses (million tonnes) | Net availability of residues (million tonnes) |
|---|---|---|---|---|
| **Barley** | 65 | 22 | 22 | 22 |
| **Maize** | 62 | 21 | 21 | 21 |
| **Oats** | 10 | 3 | 3 | 3 |
| **Olives** | 1 | 0 | 0 | 0 |
| **Rapeseed** | 18 | 6 | 6 | 6 |
| **Rice** | 2 | 1 | 1 | 1 |
| **Rye** | 11 | 4 | 4 | 4 |
| **Soybeans** | 2 | 1 | 1 | 1 |
| **Sunflower** | 9 | 3 | 3 | 3 |
| **Triticale** | 13 | 4 | 4 | 4 |
| **Wheat** | 144 | 48 | 48 | 48 |
| **Sugar beet** | 30 | 10 | 10 | 10 |
| **Sum** | **367** | **122** | **122** | **122** |

## PROJECTED AVAILABILITY IN 2030

To estimate the availability of crop residues in 2030, we follow the European Commission's (2012) projections of agricultural production to 2022. From this, we linearly extrapolate changes in crop production to 2030. The EC projects gentle linear increases in production of all major crops. While this is a generally sensible approach, we acknowledge the following uncertainties in these projections. Some major crops have not followed a gentle linear increase over the past decade: Wheat production has remained stagnant, rapeseed production has increased drastically, and sugar beet production has decreased sharply over the past several years (calculated from FAOSTAT). Additionally, any increases in total crop production that arise from increases in per hectare yields are likely to be accompanied by smaller increases in residues, as yield gains are often attained through decreased biomass allocation to the nonedible parts of the plant (Scarlat et al., 2010; Calderini et al., 1995). All this being said, assuming a linear gentle increase in the production of all crops considered here is still the most reasonable approach to take without strong evidence otherwise. Certainly, it seems unlikely that residue availability will change radically in that time frame. Projected residue availability in 2030 is shown in Table 8.

**Table 8.** Projected production and availability of crop residues in 2020 and 2030, compared to present availability

| Crop type | 2011 Residue availability (million tonnes) | 2020 Total residue production (million tonnes) | 2020 Residue availability (million tonnes) | 2030 Total residue production (million tonnes) | 2030 Residue availability (million tonnes) |
|---|---|---|---|---|---|
| **Barley** | 22 | 70 | 23 | 74 | 25 |
| **Maize** | 21 | 66 | 22 | 70 | 23 |
| **Oats** | 3 | 11 | 4 | 12 | 4 |
| **Olives** | 0 | 1 | 0 | 1 | 0 |
| **Rapeseed** | 6 | 20 | 7 | 22 | 7 |
| **Rice** | 1 | 2 | 1 | 2 | 1 |
| **Rye** | 4 | 12 | 4 | 12 | 4 |
| **Soybeans** | 1 | 2 | 1 | 2 | 1 |
| **Sunflower** | 3 | 10 | 3 | 12 | 4 |
| **Triticale** | 4 | 13 | 4 | 14 | 5 |
| **Wheat** | 48 | 154 | 51 | 163 | 54 |
| **Sugar beet** | 10 | 31 | 10 | 32 | 11 |
| **Sum** | **122** | **393** | **131** | **417** | **139** |

## LITERATURE COMPARISON

Table 9 shows literature estimates for amount of residues currently available without other uses in the EU. Generally, the results from this study are commensurate with others. There are some discrepancies in residue estimates between studies. For example, Bloomberg New Energy Finance (BNEF, 2012) extrapolated residue production to 2030, and assumes a higher fraction of residues are required for soil quality and other uses (82.5%) than Kim & Dale (2004), who assume 60% for soil quality and none for other uses, or DeWit & Faaij (2009), who assume 50% availability. The residue availability we calculate (122 million tonnes, Table 6) is within the range of literature estimates shown here. Our estimate is lower than that of Kim & Dale and de Wit & Faaij because they assume a greater proportion of residues is available, and is lower than that of BNEF because they assume future increases in residue yields (the likelihood of which is discussed below). Our estimate is greater than that of Ericsson & Nilsson because they assume on average lower RPRs (they likely do not account for processing residues). Other differences in assumptions or data sources may account in part for discrepancies in estimates.

**Table 9.** Literature estimates for residue availability in the EU (million tonnes $yr^{-1}$) and relevant assumptions used in calculations. Values for de Wit & Faiij (2010) and Nilson (2006) were calculated from EJ $yr^{-1}$ using a heating value of 17 GJ $t^{-1}$. RPR = residue production ratio; SOC = soil organic carbon

| | Scarlat et al. (2010) | Kim & Dale (2004) | BNEF (2012) | De Wit & Faaij (2010) | Ericsson & Nilsson (2006) | This study | This study |
|---|---|---|---|---|---|---|---|
| **Present or future** | Present | Present | Future (2030) | Present | Present | Present | Future (2030) |
| **RPR** | 0.8-3.2 | 1-1.4 | 2* | Not available | 1–1.3 | 0.7–3.5 | 0.7–3.5 |
| **% for SOC** | 50–60% | 60% | 75% | 50% | 75% | 33% | 33% |
| **% for other uses** | 11% | 0% | 7.5% | 0% | 8% | 33% | 33% |
| **Total residue availability (million tonnes)** | **62-109** | **225** | **151** | **182-229** | **35-53** | **122** | **139** |

* According to IEEP (2012).

# FORESTRY RESIDUES

When wood is harvested from trees, a significant fraction of the tree's total aboveground biomass is not used. This comprises leaves, small branches (including the top of the tree), and stumps (Figure 1). These forestry residues are bulky, difficult and expensive to collect and transport, and currently have little commercial value. If the market made collection profitable, some of this material could be considered available for bioenergy purposes.

Wood processing residues (e.g. sawdust from milling logs) are covered in the earlier section on cellulosic fraction of waste.

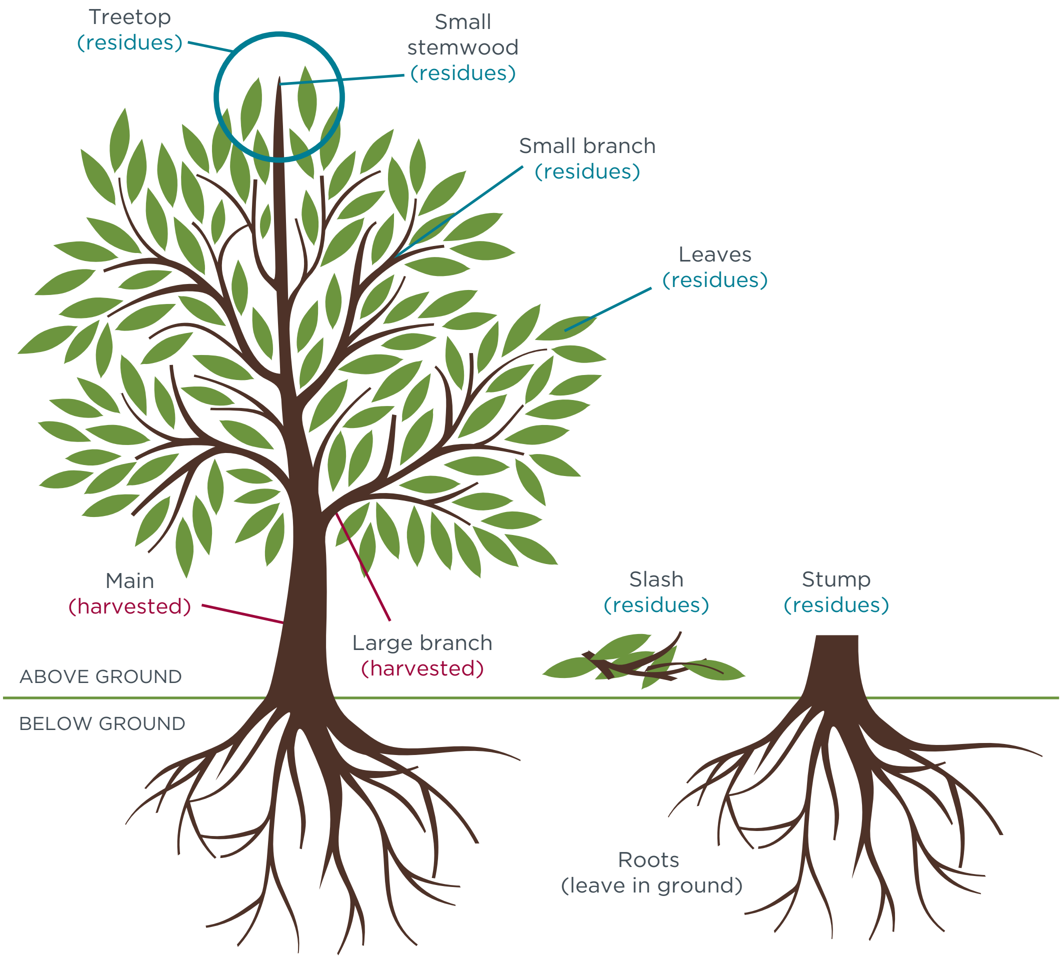

**Figure 1.** Schematic of tree components.

## TOTAL PRODUCTION OF FORESTRY RESIDUES

For the purposes of analysis in this section, forestry residues consist of stumps, leaves,[6] small branches, and small stemwood at the top of the tree. The ratio of residues to harvested wood varies widely with species and harvesting technique. Estimates of the proportion of aboveground biomass that is residues range from 31% (University of Montana, 2011) to 42% (Energy Saving Group, 2012). In a literature review, Koopman & Kopejan (1997) reported that a common rule of thumb in forestry is 50:50 for the proportions of the tree that are residues and harvested wood respectively, while other literature they reviewed gave estimates of 30–40% residues. A scenario analysis in Mantau (2011) assumed a residue proportion of 10–48% depending on scenario. Mantau (2012) showed that 24.3% of total above-ground

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[6] Including needles of conifers such as pine. Slash consists of leaves and small branches.

tree biomass remains in the forest as residues. For this analysis, Here we assume the estimate of 24.3% from Mantau (2012). This is lower than the other estimates given here, but is from a recent publication that may reflect more modern harvesting techniques in Europe and will provide a conservative estimate of total residue availability.

Calculation of total forestry residue production in the EU is as follows. Data on the production of total roundwood (for all uses, including fuelwood) in the EU27 was taken from FAOSTAT for the years 2002–2011. The estimate of current availability here is based on the 2011 data (most recent year for which data was available). FAO reports that this data is estimated for underbark wood, or wood after the bark has been removed. Our understanding is that bark is typically harvested with the stemwood and is then used for industrial (e.g., mulch) or heating purposes; these processing residues were discussed in the earlier section on cellulosic fraction of waste. We assume bark is 15% of total stemwood volume (IPCC, 2006), thus multiply total underbark wood from FAO by 1.176[7] to account for bark. As discussed above, assuming that 24.3% of the tree is residues, the ratio of residues to harvested wood is then 0.243/(1-0.243), or 0.32. Lastly, we assume the density of wood to be 0.5 t $m^{-3}$ on average (Mantau, 2010). Following these calculations, we estimate that the total production of forestry residues in the EU was 80.7 million tonnes in 2011.

Some forestry residues are currently collected, but according to ECF (2013), the Scandinavian countries are the only EU member states that currently harvest any significant quantities of them. This report gives a figure of ~3% for current usage of forestry residues in the EU. In a memo to the Biomassa-upstream Stuurgroep, Kuiper (2006) writes that 1.3 million $m^3$ out of a potential 45 million $m^3$ of forestry residues are currently collected in Finland. Applying this fraction to all roundwood produced in Finland, Sweden, and Denmark (data from FAOSTAT), and assuming no residue harvests in other EU countries, we calculate that 8% of total EU forestry residues are currently used. Because this fraction (3–8%) is small compared to the amount of residues necessary for biodiversity and erosion protection (see below), and is likely within the margin of error of our calculations, we do not account for it in our availability estimate. Furthermore, since this collected material is virtually all used for biopower and heat, one may consider it potentially available for other energy uses.

## SOIL QUALITY AND BIODIVERSITY

Use of residues from logging in unmanaged forests (presumably undertaken to obtain raw materials for wood products) would have a negative impact on biodiversity (Bird & Chatarpaul, 1985), soil carbon (Smith et al., 1994), and soil nutrients, as nutrients in the tree are concentrated in the leaves (Smith et al., 1994; Hendrickson et al., 1989; Merino et al., 1999, 2003; Jacobson et al., 2000). Reduction in soil nutrient availability would result in reduced growth in the next cycle (Smith et al., 1994; Merino et al., 1999, 2003; Jacobson et al., 2000; Olsson et al., 1995; Walmsley et al., 2009; Proe & Dutch, 1994; Proe et al., 1996; Alam et al., 2012). Stump removal may affect biodiversity more severely than other residue fractions (de Jong et al., 2012). To some extent, nutrient loss resulting from residue harvest could be addressed by adding fertilizer to harvested areas (U.S. Department of Energy, 2011), but this can have negative environmental consequences in particular on water quality in lower catchment areas.

For these reasons, it is both impractical (for the purposes of ensuring high future yields in the same managed forest) and environmentally irresponsible to remove all forestry residues without measures to mitigate any harm. The negative impacts of residue removal may be substantially lessened by removing only small branches and stemwood, leaving

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[7] 1+0.15/(1-0.15)

stumps to protect against erosion and leaves to return nutrients to the soil. However, the feasibility of harvesting twigs without leaves attached to them is not addressed here.

It should be noted that the amount of forestry residues necessary to protect ecosystem function, soil carbon, and future yields varies considerably by location, species, slope, weather patterns, etc. Ideally, residue retention rates would be determined on a local level. For estimation purposes, we assume one typical rate of residue retention here.

To be conservative and to avoid other unintended consequences, we assume that 50% removal of forestry residues may be sustainable if combined with good management practices (e.g., ensuring adequate soil cover or adding organic fertilizers such as animal manure after harvest). Proper forestry management practices, such as evidenced by certification by the Forest Stewardship Council or the Programme for Endorsement of Forest Certification, may to some extent mitigate the environmental damage of residue removal. But using even the most sustainable forest management practices to harvest residues will unavoidably have some impact on forest ecosystems. In some sense, our assumption that 50% of forestry residues may sustainably be removed includes an assumption that this is done responsibly; for example, sustainable management may require zero harvesting of certain residue elements such as stumps and nutrient-rich leaves.

Calculations showing the total production and sustainable availability of forestry residues are shown in Table 10.

**Table 10.** Estimation of the total production and availability of forestry residues in the EU in 2002, 2007, and 2011.

| | 2002 | 2007 | 2011 |
|---|---|---|---|
| **Total roundwood (million m³)** | 389 | 458 | 427 |
| **Roundwood with bark (million m³)** | 457 | 539 | 503 |
| **Roundwood with bark (million tonnes)** | 229 | 270 | 251 |
| **Total residues (million tonnes)** | 73 | 87 | 81 |
| **Sustainably available residues (million tonnes)** | 37 | 39 | 40 |

## PROJECTED AVAILABILITY IN 2030

Although there is year-to-year variation, there has been no clear trend towards more or less wood harvesting in the EU over the 10-year period prior to 2011 (Figure 2). There may be reasons to believe that total wood production will increase or decrease. For example, the EU population has been growing (mostly from immigration), which would tend to increase total demand for wood products, all other things being equal. On the other hand, EU wood harvests and imports over 2002–2011 remained relatively constant while exports increased (calculated from FAOSTAT), indicating that per capita use of roundwood in Europe may be on the decline. Use of forest biomass for heat and power has increased over the past several years due to the Renewable Energy Directive targets, but current proposals to change the RED and substantial policy uncertainty about the post-2020 period make it difficult to project how these trends will change in the future. Without any clear evidence one way or the other, we assume that total sustainable availability of forestry residues in 2030 will be similar to what we have calculated for 2011.

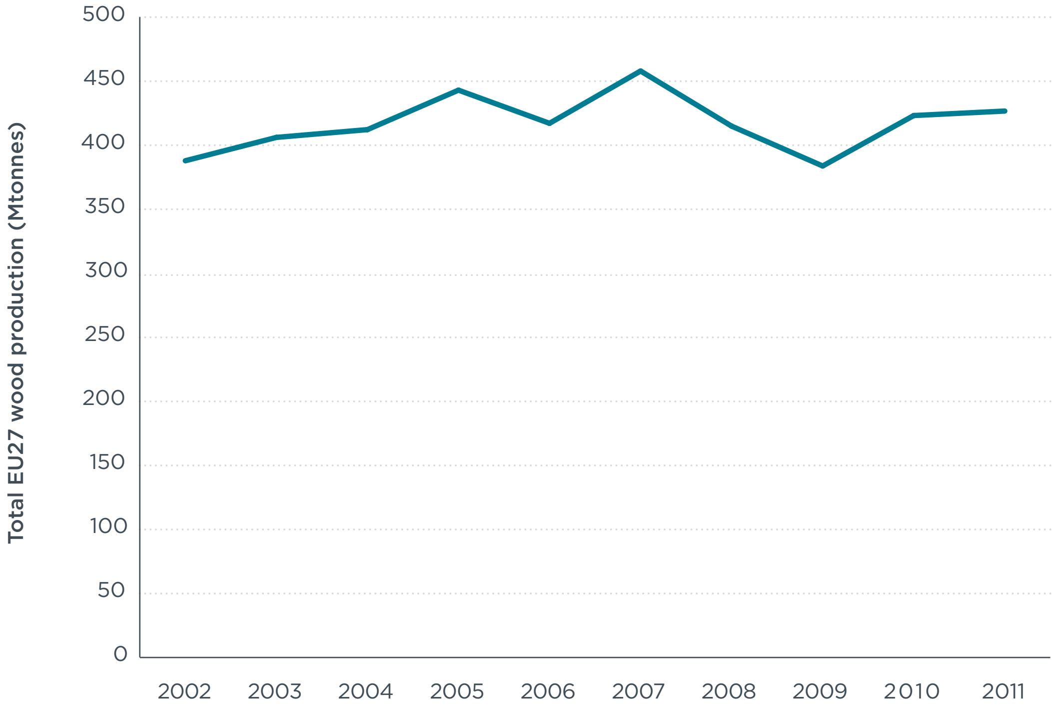

**Figure 2.** Total wood production in the EU over 2002–2011.

## LITERATURE COMPARISON

While there have been a number of studies in recent decades estimating the potential of excess forestry biomass for bioenergy (e.g., Rotiyanskiy et al., 2009; Smeets et al., 2007; Fischer & Schrattenholzer, 2001), there have been relatively few studies on the availability of forestry residues in the EU specifically (Table 11).

**Table 11.** Literature comparison of estimates of forestry residue availability in the EU.

| study | Current potential from forestry residues (million tonnes/yr) | 2030 Potential from forestry residues (million tonnes/yr) | Environmental safeguards considered |
|---|---|---|---|
| **De Wit & Faaij (2009)** | 74-284* | N/A | None |
| **Mantau (2010), Chapter 4** | 59** | 28-72 | Some (not specified) |
| **This study** | 40 | 40 | 50% residue retention |

* Calculated from 1.4-5.4 EJ $yr^{-1}$ using a heating value of 19 GJ $ton^{-1}$.
** Volumes were read off graph, then converted to mass based on 0.5 tons $m^3$.

Our estimate is lower than that of de Wit & Faaij (2009), and this is likely because that study does not appear to allow for any residues to remain in the forest to ensure sustainability. Our estimates for both the present and for 2030 are in the ballpark of Mantau (2010), and these small differences are likely due to different assumptions about the residue retention ratio necessary for sustainability and differences in forestry data.

# CONCLUSIONS

In this paper we estimate the quantity of cellulosic wastes and residues in the EU that can sustainably be used for bioenergy without major negative impacts on other industries or the environment. We analyzed the availability of paper, wood, food, and yard waste, wood processing residues, agricultural residues, and forest harvesting residues. Much of these "waste" streams are already being used as low-value inputs for industrial and agricultural processes and cannot be diverted to bioenergy production without knock-on effects on markets, increased demand for other materials, and indirect environmental consequences. Some fraction of these "wastes" plays a valuable environmental role in protecting soil quality, preventing erosion, and supporting biodiversity. Thus, the amount of wastes and residues that can be sustainably harvested for cellulosic biofuel is significantly lower than their total production.

Care should be taken in interpreting the quantities of available cellulosic material presented here. Diversion of any resource, even if there appears to be excess available, will likely have unintended consequences by raising the price of that resource. In particular, care should be taken in diverting both wood and paper wastes, as these resources can be substituted for one another for some uses. It is also important to recognize that the mere availability of wastes and residues for bioenergy feedstock does not in itself mean that those resources will be preferentially used by a growing bioenergy industry. For instance, in the case of the UK's Drax power plant, it has been demonstrated that wood to fuel the plant is being supplied by felling trees in the US, despite the availability in principle of the wastes and residues mentioned here. In addition, costs of collection and transport of these cellulosic materials will limit availability to some extent; this has not been assessed here. Even though long-haul transport of wastes and residues would be very expensive, it is possible that policy incentives could create a market for international trade of these feedstocks. Lastly, there will very likely be competition for feedstocks within the energy sector, between biofuels, biopower, and heating, so the quantities of cellulosic material reported here should not be assumed to be fully available for one industry or the other.

Despite these limitations, 200 million tonnes of material is a significant resource and large compared to the likely demand for cellulosic biofuel by 2020. If all this material were converted to biofuel at current yields, it could supply 36.7 Mtoe $yr^{-1}$, or 12% of current road fuel consumption in the EU (13% in 2020; 16% in 2030).[8] Because all the wastes and residues discussed here are eligible for double counting in the RED, this amount of biofuel would count as 73 Mtoe $yr^{-1}$, or 24% of current EU petroleum consumption. In other words, biofuel from cellulosic wastes and residues, if fully utilized, has the potential to meet the 2020 RED target for 10% biofuel in transport without any additional contribution from food-based biofuels. In summary, available cellulosic wastes and residues in the EU represent a large opportunity for low-carbon fuels.

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[8] Calculated assuming biofuel conversion efficiency of 4 tons ethanol to 1 ton biofuel, energy density of ethanol is 30 MJ/kg and diesel is 46 MJ/kg (total of 36.7 Mtoe of ethanol), and 0.832 kg/L density of diesel. Current and projected road fuel consumption from European Commission (2013). This estimate is different from the amount of feedstock necessary to displace 10% of gasoline in Bloomberg New Energy Finance (2012) because this estimate includes diesel as well as gasoline.

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