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Assessment of agroforestry residue potentials for the bioeconomy in the European Union

Andrea Thorenz*, Lars Wietschel, Dennis Stindt, Axel Tuma

Resource Lab, Institute of Materials Resource Management, University of Augsburg, Universitaetsstr. 16, 86159 Augsburg, Germany

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ABSTRACT

The biobased chemical industry is characterised by strong growth. Innovative products and materials such as biopolymers have been developed, and current European demand for biopolymers exceeds the domestic supply. Agroforestry residues can serve as main sources of the basic building blocks for chemicals and materials. This work assesses sustainably available agroforestry residues to feed a high added-value materials and product bioeconomy. To evaluate bioeconomic potential, a structured three-step approach is applied. Cultivation practices, sustainability issues, legislative restrictions, technical limitations and competitive applications are considered. All data regarding bioeconomic potential are processed on a regional level and mapped by ArcGIS. Our results identify wheat straw as the most promising source in the agricultural sector, followed by maize stover, barley straw and rape straw, which all contain a total concentration of lignocellulose of more than 80% of dry matter. In the forestry sector, residue bark from two coniferous species, spruce and pine, is the most promising source, with approximately 70% lignocellulose. Additionally, coniferous bark contains considerable amounts of tannin, which has attracted increasing interest for industrial utilisation. A sensitivity analysis concerning removal rates, residue-to-crop ratios, changes in farming technologies and competing applications is applied at the end of the study to consolidate our results.

1. Introduction

The transformation of traditional industrial processes to sustainable patterns is compulsory given limited resources and adverse environmental effects. In this context, the establishment of a biobased economy is a major responsibility. The aim of biobased economies is to substitute emission-intensive and non-renewable resources with renewable resources (McCormick and Kautto, 2013).

This article assesses the resource potential in the European Union for a biobased chemical industry from agroforestry residues. The chemical industry is one of the largest sectors in the EU-28, with revenues of over 500 billion EUR, a fuel and power consumption equivalent to 52.6 million tonnes of oil and greenhouse gas emissions of approximately 130 million tonnes CO_2 equivalent (CEFIC, 2017). Many innovative products and materials based on renewable input sources—so-called “biomaterials”—have already been developed within the concept of a biobased economy. By using biobased materials on a large scale, significant fractions of oil can be substituted by renewables. To do this, the supply of lignocellulose feedstock (LCF) needs to be secured in a sustainable manner. Lignin, cellulose, hemicellulose, and tannin are main constituents of the considered second generation feedstocks. Platform chemicals for the industry can be produced by mechanical, chemical, thermochemical or biological conversion of the biomass. The most promising sources are by-products from agricultural and forestry activities, which consist of large amounts of industrially interesting substances (Kamm and Kamm, 2004). A future-oriented bioeconomy, where basic building blocks from renewable resources replace oil-based materials and chemicals, can meet important environmental, social and economic requirements for sustainable development. Additionally, such a transformation supports the geostrategic goals of the European Union: by substituting oil with agroforestry products, the EU gains independence from oil-exporting countries and intensifies utilisation of domestic resources. However, misuse of industrial utilisation of biomass can also be associated with ecological and ethical concerns. For instance, arable land for growing biomass feedstock is limited, and thus industrial applications may compete with food production, and strain on environmental resources may have negative effects

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* Corresponding author.
E-mail address: andrea.thorenz@mrm.uni-augsburg.de (A. Thorenz).

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on humans, animals and plants. Therefore, an analysis of the European LCF potentials, taking into account sustainability issues and competitive application, is crucial.

Terminology in the current discussion of concepts for the assessment of biomass potential is inconsistent in the existing literature (Hennig et al., 2015). Despite this, some initiatives provide guidance for harmonisation of the calculation of potentials (Brosowski et al., 2016; Thrän and Pfeiffer, 2015; Vis and van den Berg, 2010). Brosowski et al. (2016) recently published a comprehensive review of publications on the biomass potential of wastes and residues in Germany. The review compiles the status quo for the theoretical and technical potential and proposes the reference unit “metric tonnes of dry matter”. However, research focuses on the energy use of biomass residues, either for direct combustion or, with increasing interest, to feed advanced biofuel production (also known as “second-generation biofuels”) (Kretschmer et al., 2012; Scarlat et al., 2010). Thrän and Pfeiffer (2015) and Vis and van den Berg (2010) suggest potential analysis in energy reference units (e.g. joule). In the light of a bioeconomy based on a material use of lignocellulose, the available feedstock needs to be assessed in mass. Therefore, Hennig et al. (2015) call for a reassessment of contemporary concepts of energy utilisation of biomass, which must be assessed when those already “tapped” raw materials are more beneficial in high-value applications.

The reviewed research on biomass potential concentrates on energy utilisation. Research analysing the potential of biobased industrial transformations that considers economic and ecological strains is rare, and comprehensive studies on the regional dispersal of sources and interdependencies with primary production processes are lacking (Scarlat et al., 2010). No research is available for the determination of the potential of agroforestry waste for high value-added applications addressing regional potentials, competitive applications (e.g. animal bedding, horticulture) and the content of focal substances (e.g. lignin, tannin, cellulose, hemicellulose), which are essential for the design of biopolymers as a precursor of high value-added industrial products. Consequently, no potential levels are described for biomass utilisation other than for energy use.

To fill this void, we herein apply a method for the assessment of potential agroforestry products as inputs for a European biobased industry. Based on this methodological work, the following application-orientated research questions are addressed:

- *Which agroforestry residue sources offer the largest potential as inputs for biomaterials, considering the feedstock quantity and biochemical composition?*
- *How large is the sustainable potential of selected agroforestry sources on a regional level in the EU-28?*

2. Materials and methods

To thoroughly address the research questions, a structured research process is implemented. The applied method sets out to quantify the bioeconomic potential for the use of high added-value bio-products, taking into account sustainable farming and forestry practices as well as competitive applications. Kretschmer et al. (2012) noted that existing literature on biomass is discordant in the classification of available potentials. Fig. 1 shows a transparent distinction between three levels of biomass potential we applied in this study, based on Vis and van den Berg (2010) and Thrän and Pfeiffer (2015).

Theoretical potential includes all parts of the total harvested biomass that have no direct use in food, feed or industrial production. The primary product (e.g. industrial roundwood or grains) and the theoretical potential sum to the total biomass. Due to factors such as sustainable harvesting practices (e.g. balancing humus quality, see Helwig et al., 2002; Münch, 2008) and legislation (e.g. restriction of the removal of treetops and small branches from forests), only a fraction of the theoretical potential is accessible for further utilisation. These facts are considered in the calculation of technical potential, which we define as the amount of residue that can be technically, legally and sustainably removed from the field or forest. Bioeconomic potential is the share of technical potential that is not necessarily used in competing applications. Additionally, refining residues of the primary product can add to the bioeconomic potential.

2.1. Identification of theoretical potential

In the first step, we identify relevant agroforestry sources of lignocellulose-based biomass. In the agricultural sector, we consider cereals, legumes, oil crops, sugar crops and fibre plants, in the forestry sector, we consider both, coniferous and broadleaf trees. Sources assessed in this study constitute an important share of agroforestry residues in general, however not all possible sources are considered. We assess the quantity of residues and their quality based on the main product, the residue-to-crop ratio and the concentration of focal substances (lignin, celluloses, hemicellulose and tannin) within the residues.

Crop production values serve as a proxy for the calculation of the theoretical potential of the lignocellulose feedstock (LCF). The crop production data are obtained from Eurostat (2016a) using the regional level NUTS 1 (Nomenclature des unités territoriales statistiques). The theoretical potential of residues is calculated with the residue-to-crop ratio (R:C ratio), which is derived by a literature study (see Supplementary Information Part 1). The R:C ratio has numerous influencing factors like the seed type, soil condition, weather events, and others and is therefore difficult to estimate. The harvesting index (HI; share of primary product in relation to total biomass above ground) is closely related to the residue-to-crop ratio and Equation (1) shows the connection of the HI to the R:C ratio. Research on the harvesting index addresses questions about the biophysical maximum of a plant, which is estimated to be about 0.65 for wheat grain (Foulkes et al., 2011). For wheat grain, observed values for the harvesting index are approximately 0.5, resulting in a residue-to-crop ratio of 1.0. In contrast to the HI, which has been constant since the early 1990s, crop yield has significantly increased in the last years, leading to higher straw yields (Foulkes et al., 2011). All other R:C ratios for investigated agricultural sources are in the Supplementary Information (see Supplementary Information Part 1).

$$R : C\ ratio = \frac{residue\left(\frac{t}{ha}\right)}{yield\left(\frac{t}{ha}\right)} = \frac{1}{HI} - 1 \qquad (1)$$

To quantify the amount of focal substances, we additionally review the biochemical composition of the identified residues. The composition of reviewed agricultural harvesting residues is similar for most sources, with approximately 15–20% lignin, 30–45% cellulose, and 20–25% hemicellulose (Bakker et al., 2013; Kamm and Kamm, 2004). Table 2 shows the crop specific results of the reviewed studies. The presented values are derived from studies referring to multiple laboratory tests of different samples and must not be confused with data from samples from isolated industrial processes (Monteil-Rivera et al., 2013). Disparities among different studies are due to factors such as the measuring method, pretreatment of the material, and varying climatic conditions in different world regions (Buranov and Mazza, 2008). The literature

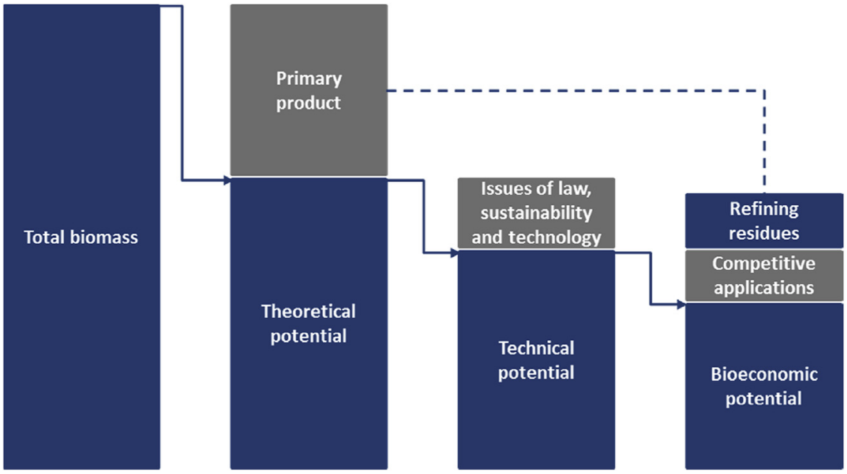

Fig. 1. Definition and context of resource potentials.

Table 1
Calculation specification of straw demand by competitive applications.

Agricultural Application	Calculation	Reference	Total demand 2014, EU-28 (1000 t)
Demand cattle bedding	$D_r = 1.5\left[\frac{kg}{d}\right] \times \frac{1}{4}\,\mathrm{Head}_r \times 365\left[\frac{d}{a}\right]$	Scarlat et al. (2010)	12,093
Demand horse bedding	$D_r = 1.5\left[\frac{kg}{d}\right] \times Head_r \times 365\left[\frac{d}{a}\right]$	Scarlat et al. (2010)	2194
Demand sheep bedding	$D_r = 0.1\left[\frac{kg}{d}\right] \times Head_r \times 365\left[\frac{d}{a}\right]$	Scarlat et al. (2010)	3102
Demand pig bedding	$D_r = 0.5\left[\frac{kg}{d}\right] \times \frac{1}{8}\,Head_r \times 365\left[\frac{d}{a}\right]$	Scarlat et al. (2010)	3382
Animal fodder	No additional demand	Assumption [a]	–
Demand mushroom compost	$D_r = \frac{5}{3} \times m_{r,\,mushroom}\left[\frac{kg}{a}\right]$	n calculation [b]	2172
Demand strawberry production	$D_r = 5\,\frac{t}{ha} \times Area_{r,\,strawberry}\left[\frac{ha}{a}\right]$	n calculation [c]	547
Straw mulching	$D_r = 0.025 \times TP_r\left[\frac{kg}{a}\right]$	n calculation [d]	3563
Energy	Number of large plants in the EU-28	Reference	Demand 2014 (1000 t)
Combined heat and power plants	15	(BEKW, 2016; Pannonpower, 2014; Scarlat et al., 2010)	1622
Second-generation biofuels	Pilot plants only		N/A
Industry	Negligible demands		N/A
Total			28,675

[a] Roughage requirements of animals are covered by straw from bedding.
[b] Straw as one of the three most important bulk ingredients and mushroom yield of 20% of compost.
[c] Based on the assumption that on average 5 tonnes of straw per hectare are used for the strawberry cultivation.
[d] Based on the assumption that around 2.5% of the cereal production is cultivated organically (European Commission, 2013b) and those farms return 100% of the technical potential (TP) into the soil.

study on the biochemical composition of agricultural sources can be found in the Supplementary Information Part 2 and for forestry sources in the Supplementary Information Part 3.

2.2. Identification of technical potential

Technical potential is the amount of biomass that can be removed after consideration of technical, legislative and sustainability constraints. An example of a technical limitation is a combine harvester, which leaves certain parts of the plant on the field (e.g. stubble). During the growth phase, plants gather nutrients containing carbon, nitrogen, phosphor, potassium, magnesium and sulphur. To sustain soil quality, nutrients taken from the ground during the growth phase must be replaced. On cultivated land, this is achieved by animal manure, synthetic fertilisers, incorporation of harvest residues, catch crops during winter and fruit rotation (VLK, 2015). The incorporation of agricultural residues into soil is an important factor for sustaining humus quality (Kretschmer et al., 2012). However, information about removal rate may vary for different soils, locations, crops, production concepts and years. Therefore the removal rate of residues depends on a combination of factors, such as equipment limitations, crop variety, harvest height, R:C ratios, water supply, soil and location (Scarlat et al., 2010). The applied sustainable removal rates of different crops are found in the Supplementary Information Part 4.

The German Institute for Energy and Environmental Research in Heidelberg (IFEU) recommends an average sustainable removal rate (SRR) of approximately one-third, with a range of 10%–60% depending on the location, crop rotation and amount and fertiliser type (Münch, 2008). Organic compost fertilisation can be an

Table 2
Assessment of EU-28 agroforestry lignocellulose feedstock (mean values 2010–2014).

Crop, EU-28 (Ø 2010–2014)	Crop production (1000 t)	Area (1000 ha)	Type of LCF residue	Theoretical potential (1000 t)	Technical potential (1000 t)	Bioeconomic potential (1000 t)	Lignin (%)	Cellulose (%)	Hemicellulose (%)	Tannin (%)	Total focal substances (%)
Agriculture											
Cereals											
Wheat	141,772	26,121	Wheat Straw	141,772	56,709	46,333	17.8	37.3	28.7	N/A	83.8
Grain maize	65,434	9365	Maize Stover	73,940	36,970	30,783	16.7	37.3	25.5	N/A	79.5
Barley	55,321	12,288	Barley Straw	51,449	20,580	16,154	17.2	39.6	24.7	N/A	81.5
Oats	10,840	3795	Oats Straw	12,250	4900	3683	16.1	37.8	28.3	N/A	82.2
Triticale	11,084	2709	Triticale Straw	10,529	4212	3507	19.2	36.3	21.0	N/A	76.5
Rye	8840	2462	Rye Straw	9723	3889	3198	12.3	37.0	24.0	N/A	73.3
Rice	3064	455	Rice Straw	5208	**N/C**	**N/C**	15.2	37.1	25.1	N/A	77.4
Sorghum	689	1316	Sorghum Straw	896	**N/C**	**N/C**	15.5	36.0	18.0	N/A	69.5
Green maize	212,072	5796	No Residue	**0**	**N/C**	**N/C**	N/A	N/A	N/A	N/A	N/A
Legumes											
Soybean	1294	467	Soybean Straw	1941	**N/C**	**N/C**	17.6	25.0	11.9	N/A	54.5
Oil crops											
Rape	19,197	6697	Rape Straw	32,636	16,318	13,883	19.8	40.9	24.4	N/A	85.1
Sunflower seed	7961	4296	Sunflower Straw	21,496	10,748	9533	25.2	34.8	21.8	N/A	81.8
Sugar crops											
Sugar beet	117,001	1613	Sugar Beet Pulp	26,910	N/C	N/C	5.9	18.4	14.8	N/A	39.1
Fibre plants											
Fibre flax	487	76	Flax Shives	146	N/C	N/C	25.3	38.4	18.0	N/A	81.7
Cotton fibre	321	349	Cotton Stalk	707	N/C	N/C	N/A	N/A	N/A	N/A	N/A
Hemp	68	10	Hemp Hurds	120	N/C	N/C	17.6	43.8	N/A	N/A	61.4
Forestry											
Coniferous	110,500	N/A	Bark	13,748	13,748	13,748	30.9	25.8	8.7	10	75.3
Broadleaf	106,836	N/A	Bark	8917	8917	8917	34.9	10.7	11.2	5	61.8

important step for attaining higher sustainable removal rates (Münch, 2008; VHE, 2014). Organic farms can even return up to 100% of straw residues to the soil. However, the positive effects of incorporating harvesting residues can be limited, especially in dry regions where soil humidity is too low for decomposition of residues. Applied sustainable removal rates are presented by Scarlat et al. (2010).

In the forestry sector, harvesting produces large amounts of by-products such as small branches, treetops, trunks, needles and leafs. Contemporary discussions about those residues argue for leaving these fractions within the forest as biomass for plants, fungi and animals. This translates the idea of SRR into the realm of forestry. Legal requirements and FSC certification increasingly urge to leave or return all forestry materials with a diameter of less than 7 cm (FSC, 2012). Hence, those residues are not considered as available lignocellulose feedstock. As barely any data about those kinds of residue exist, the identified theoretical potential already exclude these harvesting residues.

2.3. Identification of the bioeconomic potential

Two factors influence bioeconomic potential: (a) competitive applications further restrict technical potential and (b) residues from subsequent refining steps of the primary product can add to bioeconomic potential. An in-depth understanding of each value chain is needed as well as knowledge of current concepts for managing agroforestry residues. Therefore, we analyse statistical data of competing applications (e.g. number of horses, cattle in a certain region) and review literature and industry reports.

In the agricultural sector the most important step in the identification of bioeconomic potential is the analysis of competing applications. Agricultural residues are predominantly used in three sectors: agriculture, energy, and industry; the agricultural sector itself has the largest demand for straw. Table 1 shows the calculation specification for the considered competing applications.

Animal bedding accounts for the largest straw demand (Edwards et al., 2005) and is expensive and labour-intensive. Alternatively, cattle may be kept in slatted housing units without straw, and horse bedding may be realised by means of alternative material, such as shredded paper or wood chips (RPS-MCOS, 2004). For sheep and pigs, straw is even less important, as only a few farms use straw in pig bedding (Scarlat et al., 2010). Due to its low nutritive value, the use of straw as animal fodder is limited and regulated by European law (European Commission, 2013a; López et al., 2005). However, with modern straw treatment techniques, it is possible to improve its nutritive value, enabling feed containing straw to be combined with other forages such as hay or silage (Heuzé and Noziere, 2016). Tuyttens (2005) outlines a recommended minimum of 10% long fibre roughage in the cattle diet, which is assumed to be satisfied by bedding material that also serves as roughage fodder. For these reasons, there is no significant demand for straw as animal fodder. Industrially cultivated mushrooms are grown on a certain compost normally composed of straw, dust and poultry litter, which serve as the nutrient basis (RPS-MCOS, 2004). The mushroom yield is approximately 20% of the straw mass. Strawberries require straw cover for improved water balance and protection of the fruits against dust and weeds. Straw also protects the soil from erosion. After strawberry harvesting, it is incorporated into the soil as fertiliser. Straw mulching is important in the growing field of ecological farming. Interviews with farmers revealed that up to 100% of the produced straw on the farm is used for surface mulching. Straw delivers important nutrients, improves humus development, prevents soil erosion, and reduces the use of artificial fertilisers. For frost prevention in horticulture, no figures are available, but they are assumed to be rather small compared to the other applications.

Several reports have been published assessing the potential of straw in the energy sector (Lal, 2005; Scarlat et al., 2015). According to our research, 15 large combined heat and power plants (CHP) are operating in the EU, most of which are located in Denmark (Supplementary Information Part 6). Power plants in Hungary and Germany were recently opened. Scarlat et al. (2010) show their straw demand based on the low heating value (LHV) of straw dry matter, which is 17.5 MJ/kg. Straw burning in combined heat and power plants is a growing field. Our analysis neglects small plants for household heat production, as well as the co-firing of straw in coal-fired power plants, due to the lack of reliable data. As inputs in the energy sector, agricultural residues may also serve as second-generation biofuels. These biofuels rely on LCF such as straw and wood residues, in contrast to contemporarily produced first-generation biofuels produced by fermentation and distillation of crops (De Santi et al., 2008). Contemporarily, biofuel production from waste LCF is mostly at the pilot plant stage, with no significant consumption in the EU. However, one plant in Northwest Italy (Crescentino) is producing large amounts of cellulosic bioethanol, with an annual consumption of approximately 200,000 t of straw (mainly wheat straw). The overall consumption of LCF by biofuel production is currently very small but is likely to evolve in the future (EBTP, 2017; Gregg et al., 2017).

In the industrial sector, straw can be utilised as input for the production of pulp and paper in some plants as well as in traditional building material. In recent decades, efforts have been undertaken by researchers and companies to produce pulp from straw (McKean and Jacobs, 1997). Nevertheless, efforts to commercialise pulp made from straw are negligible, especially within the EU (FAO, 2014). Straw as a traditional building material, e.g. as insulation or roof thatching, has been widely substituted by modern materials. In addition to very limited applications, the building sector absorbs minor amounts of straw (Kretschmer et al., 2012; RPS-MCOS, 2004).

Table 1 shows competitive applications for straw. All analysed competing applications can consume various types of straw and are not dependent on a single type. Therefore, bioeconomic valorisation techniques can concentrate on the residue source with the most promising biochemical properties, without compromising the needs of competing applications or sustainable farming practices. Regarding refining residues, our research revealed that refining residues of primary agricultural products are still rich in nutrients and therefore constitute an important component of animal fodder (e.g. press cake from oil seeds or bran from cereals). For the stated reasons, refining residues from agricultural products are not considered in the bioeconomic potential.

In the forestry sector, current utilisation of bark is limited to low-grade applications such as combustion for energy recovery and surface mulching (Ogunwusi, 2013). We consider those competing applications to be of lower value than a substantial recovery in high value-added products (such as insulating foams, Lacoste et al., 2015). Refining residues from the roundwood industry can add to the bioeconomic potential. Sawmills and pulp mills produce large amounts of refining residues like sawdust, wood chips, shaving, or black liquor which contain significant amounts of lignocellulose (Moore and Cown, 2015). Larger particles are recovered as particle- and fibreboard or as plywood (Koopmans and Koppejan, 1998). Finer particles like sawdust or shavings are increasingly incorporated into energetic products like pellets or briquettes. Recently, the pellets industry and bio-energy plants pay even higher prices for those refining residues than e.g. particleboard plants, putting additional pressure on the market (Indufor, 2015). For the stated reasons, this work focuses on the bioeconomic potential of residue bark.

2.4. Regionalisation of the bioeconomic potential

According to the scope of the study, the assessment of lignocellulose feedstock for the European bioeconomy, NUTS 1 regions (Nomenclature des unités territoriales statistiques) are the most appropriate grid level for regionalisation. Production data from identified agricultural and forestry sources as well as data of competing applications are collected at the NUTS 1 level. As described before, most competing applications can use different types of agricultural residues (e.g. wheat straw vs. barley straw). To allocate straw demand of competing applications to the type of straw, we analyse three scenarios to reflect changing demand patterns as a result of variable conditions such as legislation, subsidies or prices.

The **Base case scenario** allocates the type of straw to applications based on production shares. For instance, if wheat straw represents 40% of the straw produced in a region, we assume that the straw demand for competing applications is also satisfied to 40% by wheat straw. This approach accounts for the fact that straw is consumed regionally. The transport of straw is limited due to its large volume and low value.

The **Lower bound scenario** assumes that demand from competing applications is first satisfied with the considered source (e.g. the total demand from the competing application is fulfilled by wheat straw). Other kinds of straw are only used when the preferred source is already depleted in this region. Hence, the amount of this source available after considering competing applications represents the minimum bioeconomic potential.

The **Upper bound scenario** assumes that demand from competing applications is first satisfied with substitutes. The source under consideration is only used when other straws are depleted in this region. This results in a maximum bioeconomic potential.

In the forestry sector, official wood production data are not available on NUTS 1 level. Eurostat provides only aggregated production data on NUTS 0 level (country level). Verkerk et al. (2015) proposed an advanced disaggregation method by calculating harvesting likelihoods. The harvesting likelihood is calculated by regression analysis using different predictors like the tree productivity, tree species composition or terrain ruggedness. The method substantially improves the disaggregation accuracy compared to disaggregation based on forest cover only (Verkerk et al., 2015). We use the results on regional production shares (NUTS 1 production shares of each country) provided by the study from 2000 to 2010 to disaggregate 2010 to 2014 production volumes. In the forestry sector, competing applications are supposed to be of lower value, therefore no allocation is needed.

3. Results

Assessment of European agroforestry potentials is based on the described approach. As a result, Table 2 presents our results on an aggregated view for the whole EU. Production volume and cultivated area are derived from databases and averaged from 2010 to 2014 (Eurostat, 2016a, 2016b). The theoretical, technical, and bioeconomic potentials are calculated with the proposed three step approach. Values of the focal substances are derived from a literature review (Supplementary Information Part 2).

Fig. 2 compares absolute quantities of lignin, cellulose, hemicellulose and tannin available from bioeconomic potentials of considered residues and underlines the importance of wheat straw, maize stover, barley straw, rape straw and coniferous bark as input sources to value-adding bio-refinery systems. Contemporary discussion of the potential of agroforestry residues for a biobased economy lacks information on industrially available magnitudes of lignin, cellulose, hemicellulose and tannin (Hennig et al., 2015). The numbers reveal the opportunity for material recovery of agroforestry residues and show annual production of residues.

3.1. Agriculture

The **agricultural sector** produces large amounts of residues utilisable for bioeconomic purposes. Straw shows the highest potential, with approximately 95 Mt of LCF, of which the most promising are wheat straw (46 Mt), barley straw (16 Mt) and rape seed straw (14 Mt). Apart from straw, significant quantities of maize stover (31 Mt) can be extracted from grain maize production. Fig. 3 shows the theoretical, technical and bioeconomic potential of the most promising agricultural species in Europe (EU-28). The lignocellulose content for these is 80%–85%.

To utilise this potential, the agricultural sector must be developed as a supplier for a biobased economy. Our results show, that currently, less than 8% of the theoretical potential of straw is recovered from fields. The aggregated theoretical potential of considered agricultural residues amounts to about 390 Mt of which only about 29 Mt is recovered from fields (Table 2). Indeed, farmers may perceive the development of a bioeconomy as an opportunity to generate profit from residues that they regard as low-value input materials. Farmers will trade when straw prices exceed the opportunity cost of substituting these materials in contemporary applications (e.g. animal bedding).

Fig. 4 shows the three scenarios for the regionalised bioeconomic potential for wheat straw depending on the scenario. In the base case scenario, which we consider the most realistic scenario, about 46 Mt of wheat straw can be recovered sustainably from fields in the EU. In the upper bound scenario, about 55 Mt of wheat straw can be recovered, while in the lower bound scenario about 28 Mt can be recovered. Table 2 shows the results of the base case scenario for the other relevant agricultural residues. It is evident that from a sourcing perspective, the area around Paris (region "Bassin Parisien") is the most promising region. Crosschecks with trade data confirm our calculations. Regions with an undersupply of straw (red) tend to import to satisfy straw demand, which is for example true for NUTS 1 regions in the Netherlands (UN Comtrade, 2016). Table 3 shows the NUTS 1 regions with highest bioeconomic potential for straw from wheat, maize, barley, and rape seed within the EU-28.

3.2. Forestry

In the **forestry sector**, the bioeconomic potential of bark from conifers (approximately 14 Mt) is dominant compared to broadleaf plants (Fig. 5).

Coniferous bark is advantageous because the wood category of coniferous trees mainly includes two species, spruce and pine, making it a homogeneous material stream compared to broadleaf trees. Secondly, coniferous bark is perceived as residue and is mostly directly combusted, leading to low prices, reduction in the opportunity cost of alternative fuels, and high availability (Kemppainen et al., 2014; Ogunwusi, 2013). Thirdly, bark accumulates in large amounts at discrete locations, such as sawmills and pulp mills, facilitating collection for integration into high value-added processes. These patterns make coniferous bark a very promising source of LCF, although the overall bioeconomic potential is lower than the amount acquirable from the agricultural sector.

Our calculations of the bark share in relation to harvested roundwood are based on Eurostat production data and crosschecks with literature recommend a bark-to-wood ratio of 0.1–0.15 (Eurostat, 2016a; Kemppainen et al., 2014). All weight calculations suppose a dry matter density of 380 kg/m^3 for spruce bark and 400 kg/m^3 for pine bark (Kemppainen et al., 2014). Table 4 shows the regional distribution of bark from conifers on a country level (average 2005–2014).

Coniferous bark potentials are highest in the region of "Manner-Suomi" (Finland), "Norra-Sverige" and "Södra-Sverige" (Sweden), as Table 5 shows.

Therefore, we conclude that future feasibility studies for bioeconomic development in Europe should concentrate on LCF sourced from wheat, grain maize, barley, rapeseed and coniferous trees. Fig. 6 depicts the bioeconomic potential and total concentration of focal substances of the considered lignocellulosic residues.

3.3. Sensitivity analysis

Calculation of bioeconomic potential depends on crop and wood production data as well as assumptions of the R:C ratio and sustainable removal rate. Generalised assumptions of calculation factors limit the validity of results. To address these uncertainties, sensitivity analysis enhances the understanding of central assumptions and demonstrates the robustness of the results. Additionally, varying assumptions reveals the most important opportunities and risks for increasing and decreasing potentials

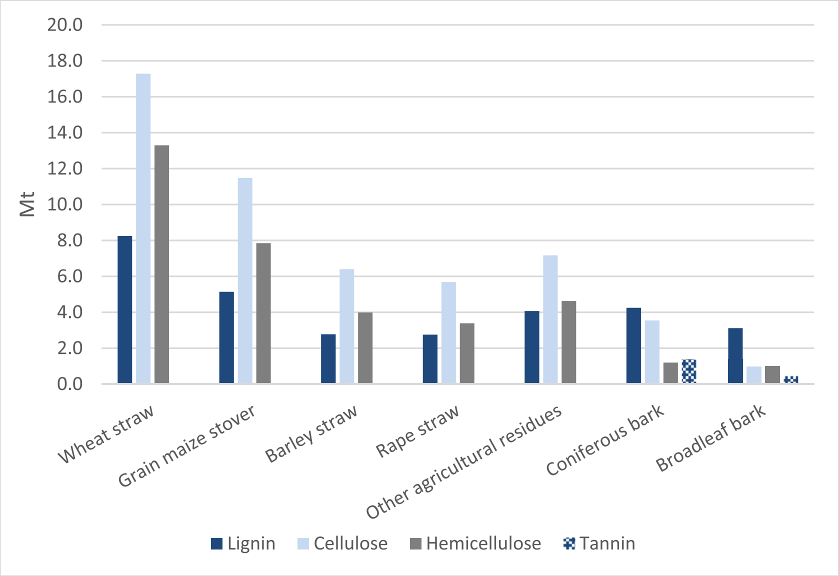

Fig. 2. Absolute quantities of focal substances available from bioeconomic potential of agroforestry residues.

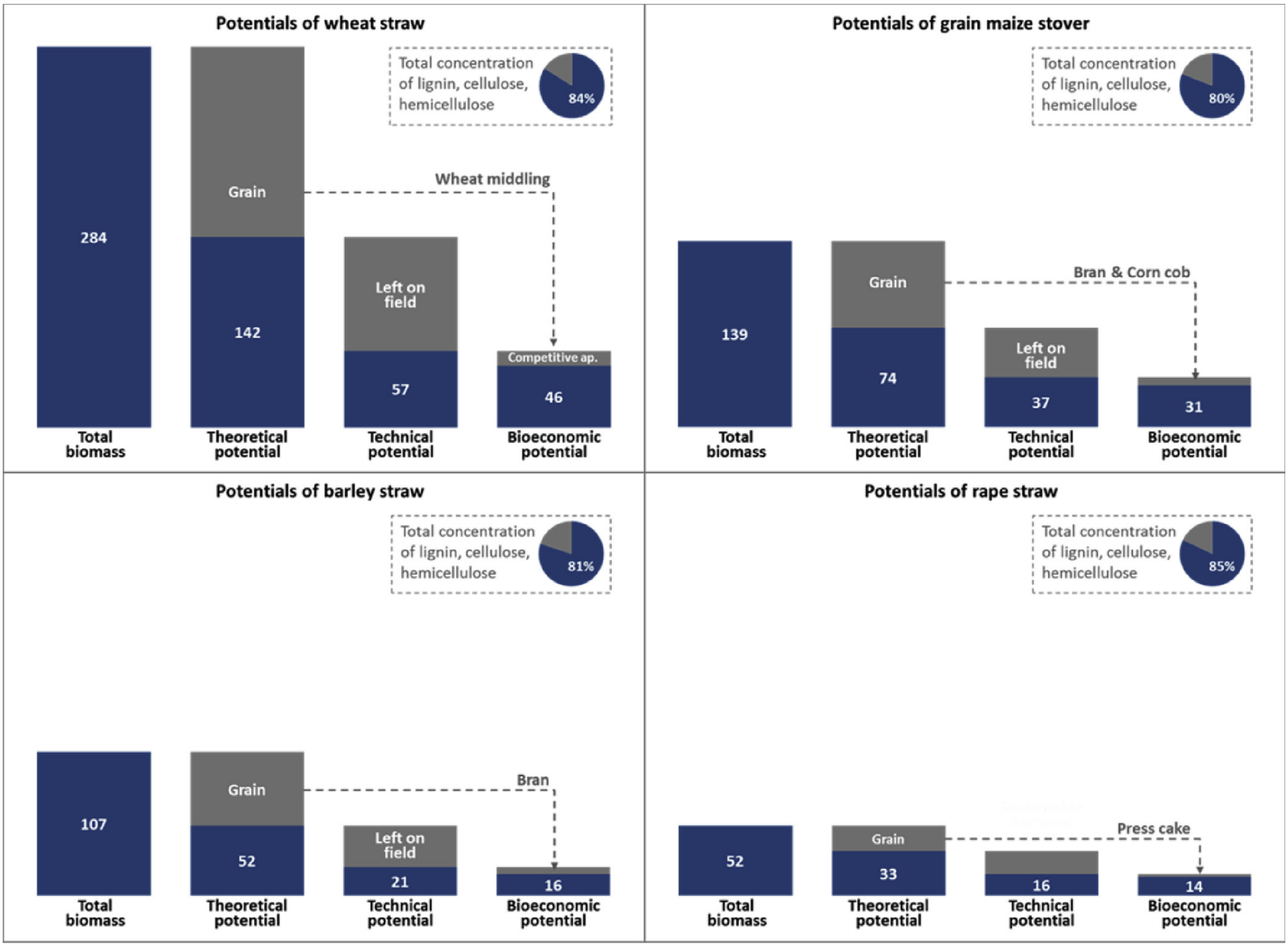

Fig. 3. Theoretical, technical and bioeconomic potential for the most promising agricultural residue sources (all values in Mt).

and can highlight actions for policy makers. Table 6 shows the effect of altering parameters, such as increasing the sustainable removal rate, in the case of wheat straw.

Positive drivers for bioeconomic potential are increased removal rates, increased R:C ratios and substitutions concerning competing applications, especially in animal bedding. A major risk from the perspective of a large-scale chemical industry relying on biomass is posed by maturation of second-generation biofuels. This type of biofuel competes for the same resources. In fact, second-generation biofuels are currently in the development stage, with a few pilot plants in the EU. Nevertheless, biofuels may consume a predominant part of the bioeconomic potential from agroforestry residues in the future.

Coniferous bark from industrial processes, especially bark from spruce and pine, shows a large and comparatively easily accessible bioeconomic potential. As bark is an already-available residue stream in certain industries, the bioeconomic potential should be less volatile than for agricultural goods. Effects on the bioeconomic utilisation of bark from other applications should be less critical, as the contemporary application fields are of low value. A major concept for increasing biomass from forestry is the promotion of the cascading use of wood, along with decreased combustion of valuable wood resources. The fraction of roundwood currently used for energy could be directed to substantial recovery in terms of bioeconomic utilisation, which would free additional potential (approximately 11 Mt of roundwood over bark). A major risk is the continuing utilisation of bark for combustion or as a gardening material (see Table 7).

4. Discussion

In recent years, several papers analysing biomass availability at state level (e.g. Brosowski et al., 2016) as well as for the whole European Union (Scarlat et al., 2010) have been published. In this context Hennig et al. (2015) questions a sustainably available feedstock potential for the material and energy use of biomass in the EU.

Our work extends the existing studies by providing information on biomass constituents (lignin, cellulose, hemicellulose, tannin) that are suitable for valorisation processes and transformation into high added-value products. Under consideration of sustainability criteria (sustainable removal rate, competing applications in the field of agriculture and other), our results show existing feedstock potentials for a material use. The four most relevant agricultural residues could serve for about 20 Mt of lignin, 50 Mt of cellulose and another 30 Mt of hemicellulose. With efficient valorisation technologies, those resources could replace substantial shares of the currently used 50 Mt of crude oil in the chemical industry (CEFIC, 2017).

We apply a three-step approach to calculate the regionalised

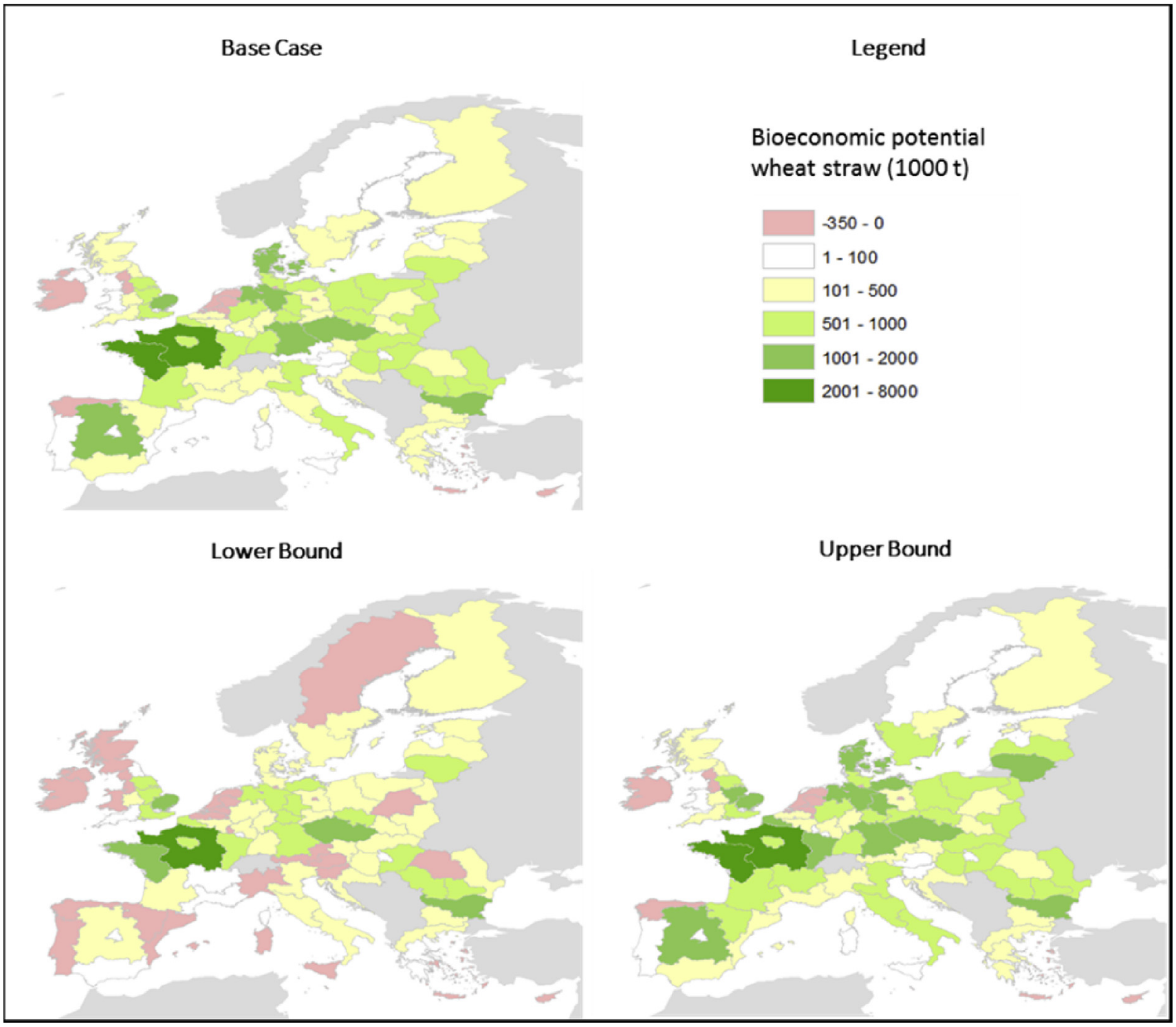

Fig. 4. Regionalised bioeconomic potential of wheat straw.

Table 3
Geographical distribution of straw residues.

Crop	Agricultural bioeconomic potentials in NUTS 1 regions in the base case scenario (values in 1000 t)				
Wheat straw	Bassin Parisien (FR2) 6848	Ouest (FR5) 2389	Czech Republic (CZ0) 1660	Severna I Iztochna Bulgaria (BG3) 1617	East of England (UKH) 1305
Maize stover	Sud-Ouest (FR6) 2121	Nord-Est (ITH) 1913	Macroregiunea Doi (RO2) 1870	Nord-Ovest (ITC) 1783	Ouest (FR5) 1766
Barley straw	Bassin Parisien (FR2) 1936	Centro (ES4) 1537	Danmark (DK0) 782	Scotland (UKM) 674	Bayern (DE2) 625
Rape straw	Bassin Parisien (FR2) 1944	Severna I Iztochna (BG3) 1271	Czech Republic (CZ0) 954	Mecklenburg-Vorpommern (DE8) 708	Sachsen-Anhalt (DEE) 543

bioeconomic potential of lignocellulose agroforestry residues available for high added-value applications. As all plants contain lignocellulose, a preselection of the most relevant residues in terms of quantity and quality is necessary. Concerning the agricultural sector, we consider residues of cereals, legumes, oil crops, sugar crops, and fibre plants only. In the forestry sector, we focus on bark from coniferous and broadleaf. Other feasible residues like pruning from olive tree (e.g. Spinelli and Picchi, 2010), vineyards, fruit tree orchards, and forest thinning (e.g. Indufor, 2015) are not considered in this study.

The calculation of the theoretical potential is based on primary production volumes. The residue-to-crop ratios (bark-to-wood ratio) are derived from literature. In our calculation, we assume constant residue-to-crop ratios for the EU without taking into account regional specifications. Other works show possible correlations between residue-to-crop ratios and grain yields, however with often low coefficients of determination (Rivera-Amado et al., 2014). The sustainable removal rates, which are important for the calculation of the technical potential, are also derived from a literature study. Therefore, we assume constant values for the EU. Different soil types as well as several other regional factors are neglected. In the sensitivity analysis, we address those limitations

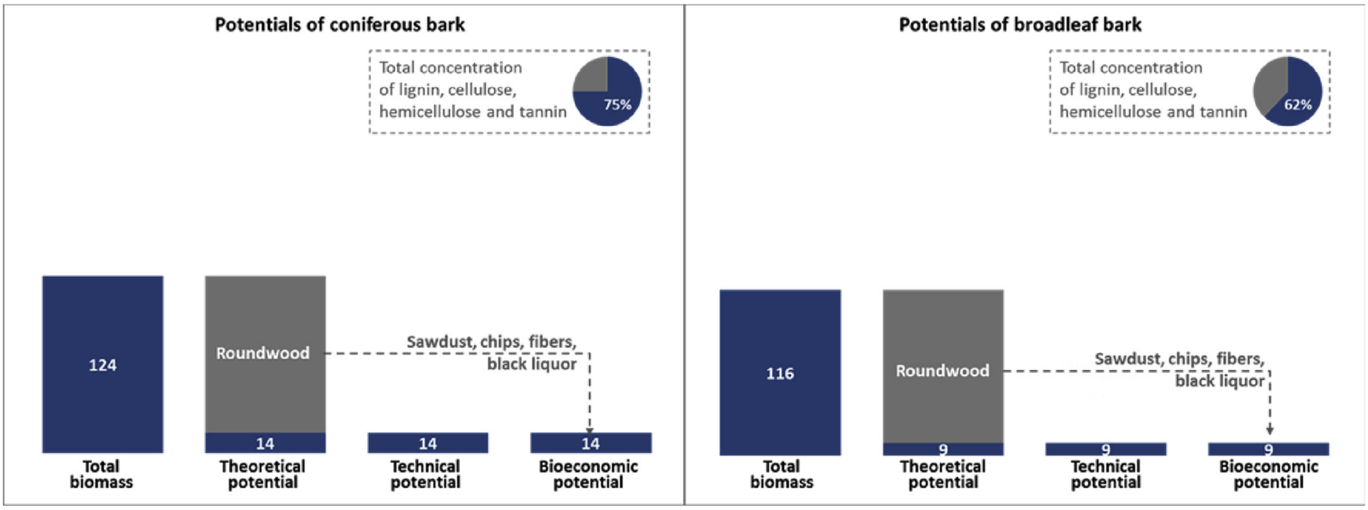

Fig. 5. Theoretical, technical and bioeconomic potential for the most promising forestry sources (all values in Mt).

Table 4
Geographic distribution of coniferous bark residues in Europe (literature study in the Supplementary Information Part 5).

EU-28, (Ø 2005–2014)	Spruce (%)	Pine (%)	Other (%)	Bark (1000 m^3)	Spruce (1000 m^3)	Pine (1000 m^3)	Bark (1000 t)	Spruce (1000 t)	Pine (1000 t)
Coniferous				36,179			13,748		
Sweden	63.4	36.6	0.0	9048	5737	2100	3020	2180	840
Finland	52.0	48.0	0.0	5600	2912	1398	1666	1107	559
Germany	69.3	23.3	7.4	5313	3682	858	1742	1399	343
Poland	9.1	84.6	6.3	3128	285	241	205	108	96
France	21.1	30.1	48.8	2443	515	155	258	196	62
Austria	69.0	N/A	N/A	1733	1196	N/A	N/A	454	N/A
Czech Republic	51.5	16.7	31.8	1805	930	155	415	353	62
Other countries	N/A	N/A	N/A	7109	N/A	N/A	6442	N/A	N/A
Broadleaf				14,861			8917		

Table 5
European regions with the highest coniferous bark potentials.

Crop	Bioeconomic potentials in selected NUTS 1 regions (in 1000 t)				
Coniferous bark	Manner-Suomi (FI1)	Norra Sverige (SE3)	Södra-Sverige (SE2)	Czech Republic (CZ0)	Bayern (DE2)
Total	2111	1600	1343	686	610
Spruce	1098	1014	851	353	423
Pine	1013	586	492	333	187

and show the variations in available potentials through different assumptions.

To improve regionalised calculations, specific studies on NUTS 1 or NUTS 2 level concerning the residue-to-crop ratios, the bark-to-wood ratios and sustainable removal rates are needed. A further uncertainty for the estimation of future bioeconomic potentials come from competitive applications like upcoming second-generation biofuels, which could potentially consume major shares of the sustainably available lignocellulose feedstock. As different utilisation concepts oppose each other, policy should promote the most efficient and advantageous utilisation concepts of biomass. Another crucial step for the effective utilisation of biomass is the development of cascading use of such resources. Hennig et al. (2015) claims to reconsider the energy use of biomass to redirect already tapped resources. In terms of a circular economy, material use of biomass first with subsequent energy use seems in many cases more beneficial. On principle, to establish a sustainable resource efficient bioeconomy, reliable forecasting tools have to be developed.

5. Conclusion

The scope of this article is twofold. First, a methodology for the assessment of the bioeconomic potential of agroforestry residues for biopolymers as precursors of high value-added products is developed. Based on this approach, the bioeconomic potential of endemic sources (cereals, oil crops, sugar crops, fibre plants, coniferous and broadleaf) is determined on a regional level (NUTS 1). The most promising source in the agricultural sector is wheat straw (46 Mt), followed by maize stover (31 Mt), barley straw (16 Mt) and rape straw (14 Mt), all containing a total lignocellulose content of more than 80%.

The NUTS 1 regions with the highest bioeconomic potential for wheat straw are the North of France (Bassin Parisien: 6.8 Mt; Ouest: 2.4 Mt) and the Czech Republic (1.7 Mt). Maize stover is most abundant in France (Sud-Ouest: 2.3 Mt; Ouest: 2.0 Mt) and North-east Italy (Nord-Est: 2.0 Mt). The Paris region (Bassin Parisien) is with 2.1 Mt the region with the highest barley straw potentials, followed by Central Spain (Centro: 1.8 Mt) and Denmark (1.3 Mt).

In the forestry sector, residue bark from two coniferous species,

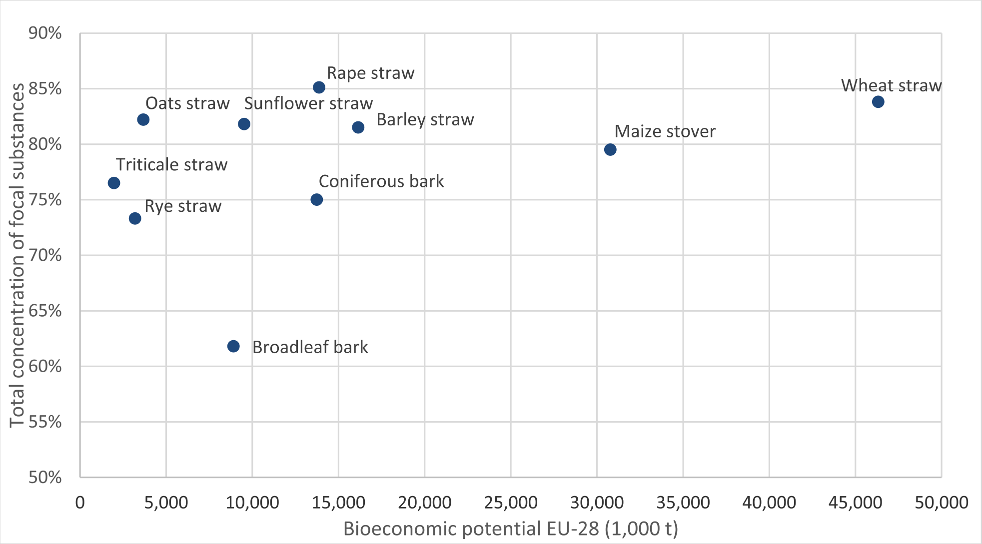

Fig. 6. Bioeconomic potential versus total concentration of focal substances for different agricultural residues.

Table 6
Sensitivity analysis for wheat straw.

Description	Effect on wheat straw bioeconomic potential (total bioeconomic potential)	Description and field of activity
Opportunities		
Increase in sustainable removal rate by 10% to an average of 50%	+14 Mt (total: 60 Mt)	Substitution by organic compost fertilisation
Utilisation of crop species with higher residue-to-crop ratios (+10%)	+5 Mt (total: 50 Mt)	Substitution of high crop yield cultivations by cultivation with higher residue-to-crop ratios
Switching animal bedding technology (slatted housing)	+10 Mt (total: 56 Mt)	Promotion/subsidisation of straw-free bedding technologies
Substitution of wheat straw in energy production	+1 Mt (total: 47 Mt)	Promotion/subsidisation of renewable energies not based on biomass feedstock
Reduction of livestock by 10% (alteration of societal diet patterns)	N/A	Less straw demand due to reduction in livestock
Threats		
Lower sustainable removal rate of 30%	- 14 Mt (total: 32 Mt)	New research insights into the SRR
Crop species with lower residue-to-crop ratios (−10%)	- 5 Mt (total: 40 Mt)	New cereal cultivations with lower ratios
50% additional demand for agricultural applications	- 5 Mt (total: 40 Mt)	Changing demand patterns
Duplication of energy production in straw-burning combined heat and power plants (CHP)	- 1 Mt (total: 45 Mt)	Expansion of contemporary energy production from straw
Second-generation biofuels	N/A	Second-generation biofuels based on lignocellulose residues, such as straw. Additional demand depends on the subsidisation and expansion of biofuel technologies

Table 7
Results of sensitivity analysis for coniferous bark.

Description	Effect on coniferous bark bioeconomic potential	Description & field of activity
Opportunities		
Increase in coniferous wood consumption by industry of 20%	+2.8 Mt (total: 16.5 Mt)	Promotion of natural building materials
Utilisation of black liquor (refining residues)	N/A	Promotion of substantial recovery instead of energy recovery. Worldwide up to 50 Mt lignin from black liquor (Müssig and Carus, 2014)
Expansion of substantially used wood with less wood used for energy generation	+11 Mt (total: 25 Mt)	Promotion of cascading use of wood
Threats		
Decrease of coniferous wood consumption by 20%	−2.7 Mt (total: 11 Mt)	Climate change can lead to diminishing conditions for coniferous trees, which can affect spruce populations
50% bark demand of competing applications of technical potential	−6.8 Mt (total: 6.9 Mt)	Deviating demand

spruce and pine, is the most promising source, with a bioeconomic potential of 15 Mt and a 70% concentration of focal substances. Scandinavian countries (Manner-Suomi: 2.1 Mt; Norra-Sverige: 1.6 Mt; Södra-Sverige: 1.3 Mt) and Central Europe show the most stable supplies of coniferous bark.

By analysing the procurement and supply chain patterns of bark (centralised supply at observed mills) and agricultural residues (decentralised supply by multiple farmers, some of which are new to the straw trading business), the disadvantages of relatively fewer potentials of bark compared to agricultural residues appear to be compensated by easier procurement and lower procurement costs. The centralised supply from just a few producers would mean a higher stability and reliability of resource procurement.

To prove the robustness of the results, sensitivity analysis concerning alternative removal rates, R:C ratios, changes in farming technologies and competing applications is applied. The sensitivity analysis of wheat straw (the agricultural source with the highest overall potential) as well as coniferous bark, proves the robustness of our results. An increasing removal rate may enhance the amount of straw available for bioeconomic use, whereas the maturation of second-generation biofuels poses a major future risk of competition with biomass. A major concept for increasing the amount of biomass available from forestry is the promotion of the cascading use of wood, along with decreased combustion of valuable wood resources.

Further work covers the design of an economically and ecologically optimised European Supply Chain with robust collection networks to establish a sustainable European bioeconomy.

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Appendix A. Supplementary data

Supplementary data related to this article can be found at https://doi.org/10.1016/j.jclepro.2017.12.143.

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