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Spatially explicit forecast of feedstock potentials for second generation bioconversion industry from the EU agricultural sector until the year 2030

Lars Wietschel*, Andrea Thorenz, Axel Tuma

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

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A B S T R A C T

Second generation bioconversion industry is a driver towards the post-petroleum age where materials and fuels are made of renewable resources. Agricultural residues are a promising feedstock source for emerging bioeconomic concepts. Research on the forecasting of feedstock potentials is still scarce and available methodologies are not harmonised. Biomass markets are characterised by their regionality, which requires regionalised assessments and forecasting of feedstock potentials. This work dealt with the question of the variables that determine the future development of agricultural harvesting residues. It further examines methodologies allowing a spatially explicit prediction of feedstock potentials. The forecasting approach was applied to wheat straw, corn stover, barley straw, and rapeseed straw, which together account for 80 per cent of cereals and oil crops harvesting residues in the European Union. The results indicate the largest increase of all investigated crops was for corn stover at up to 20 per cent between 2017 and 2030. Barley straw potentials are expected to stay rather constant within the coming decade. Rapeseed is the only crop likely to face a decreasing production in many regions in the coming years. This work identified increasing crop yields as the main driver for advancing feedstock potentials. Especially Central and Eastern European countries show high growth rates. The methodology of the research work contributes to the discussions about sustainable resource potentials of the European bioeconomy. The forecasting results can be used for strategic decision-making in emerging bioconversion concepts.

1. Introduction

In 2012, the European Commission launched the European Bioeconomy Strategy (European Commission, 2012). The strategy was set up to further enforce the European bioeconomy, which was already one of the biggest and most important sectors in the EU. Limited natural resources, food security and the advancing climate change in light of an increasing world population, urges society to deal smarter with available resources. With this background, the European Commission advocated for a renewable resource strategy that, on the one hand secures healthy food and animal feedstuff, and on the other hand helps to move Europe towards a post-petroleum age where materials and biofuels are made of renewable sources. As part of the strategy, a better incorporation of underutilised materials like agricultural residues needs to be achieved (European Commission, 2012). Lignocellulose materials are considered as a major feedstock for a second-generation bioconversion industry. Those materials are likely to play a major role as raw materials for various industries that do not compromise food or feedstuff production (Moreno et al., 2017). Especially agricultural harvesting residues like wheat straw, corn stover, barley straw and rapeseed straw show large sustainably-available potentials (Thorenz et al., 2018). The valorisation of lignocellulose feedstock into intermediates, products and biofuels will take place in biorefineries with different conversion routes. The variety of possible products from biorefineries is large and could be placed on the traditional petrochemical market as well as on a future bio-based market (Kamm et al., 2010). Key challenges in the material and biofuel utilisation of lignocellulose include: its resistance to breaking down into its components cellulose, hemicellulose and

* Corresponding author.
E-mail address: lars.wietschel@wiwi.uni-augsburg.de (L. Wietschel).

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lignin; the large variety of different structures and chemical compositions due to genetic and environmental influences; as well as the large variety of released sugars from the breakdown of cellulose and hemicellulose (Balat, 2011). According to the recently published review of the *2012 European Bioeconomy Strategy*, significant progress has been achieved in the extraction of sugars from lignocellulose and its conversion to biochemicals and biofuels (European Commission, 2017a). Another challenge is the supply chain cost, including the collection, distribution and storage of lignocellulose materials with low density (Balat, 2011). Hennig et al. (2015) claimed that the sustainable feedstock potential and its provisional cost are the major limitation for a bio-based economy. Therefore, long-term monitoring of harvesting residues is required to ensure the efficient and sustainable utilisation of this important feedstock in future (Brosowski et al., 2016).

This work widens the knowledge base on the availability of lignocellulose biomass potentials with respect to the spatial distribution in the European Union as well as its development over time. To successfully implement the utilisation of lignocellulose feedstock on an industrial scale, one has to answer questions about the feedstock availability: What feedstock shows the highest potential? Where is the feedstock spatially allocated? How will the supply develop in future? This research was set out to answer these questions for the EU28 on NUTS 1 level. In the light of an increasing demand for biomass residues available for material and energy use, information on current and future potentials are gaining importance (Brosowski et al., 2016). The current production of primary agricultural goods is well investigated and different approaches on future predictions exist. The annually published Agricultural Outlook is one of the most important global reports on food and feedstuff production (OECD and FAO, 2017). The Organisation for Economic Co-operation and Development (OECD) and the Food and Agricultural Organisation (FAO) of the United Nations bring together their commodity, policy and country expertise for a collaborative assessment of future agricultural commodity markets (OECD and FAO, 2015). For the EU, the model is adapted by the European Commission which annually publish the EU Agricultural Outlook (European Commission, 2017b; OECD and FAO, 2017). In contrast to crops, future predictions on lignocellulose residue potentials is rarely found in literature (Hennig et al., 2016). This work extended the approach for the assessment of agroforestry residue potentials introduced by Thorenz et al. (2018) by a forecast of residue potentials. Wheat straw (common wheat as well as durum wheat), corn stover, barley straw and rapeseed straw make up to 80 per cent of cereals and oil crops harvesting residues (Thorenz et al., 2018). Therefore, this work focused on the future predictions on the lignocellulose feedstock potential of those resources. The forecasting horizon is until 2030, based on the time horizon of the EU Agricultural Outlook (European Commission, 2017b). The central research questions addressed here include:

Q1: What are the underlying variables determining the future development of agricultural harvesting residues?
Q2: What are suitable methods for providing a spatially explicit annual forecast of agricultural residues until 2030?
Q3: How will the theoretical, technical, and bioeconomic potential of agricultural residues develop in the EU28?

This research set out to answer these questions by reviewing existing literature and by analysing historic time series. With the developed methodology, potentials were forecasted on a spatially explicit level (NUTS 1 level) until the year 2030. With a sensitivity analysis and an out-of-sample test, the robustness of the results were verified.

2. Materials and methods

The aim of this research was to develop a methodology for spatially explicit prediction of the theoretical, technical and bioeconomic potential of agricultural residues. The forecasting horizon is medium term and covers the period from 2017 to 2030. As spatial resolution, the 98 NUTS 1 regions (French: Nomenclature des unités territoriales statistiques) of the European Union were chosen, which are based on national administrative subdivisions, mainly for the purpose of collection, development and harmonisation of European regional statistics. Datasets which are important to this work are available on NUTS 1 level and the spatial resolution proved to be sufficient for the regionalisation of agricultural residue potentials (Thorenz et al., 2018). Thorenz et al. (2018) applied a methodology for the calculation of the theoretical, technical and bioeconomic potential of agroforestry residues, which provided the basis for this work. The work at hand extended the approach with an annual forecast of the potentials until 2030. In fact, regional crop production, and as a consequence the available agricultural residues, depend on several factors such as market development and weather extremes or pandemics which often lead to a high volatility in the regional annual production volumes. The results of this work display regional forecasts on the assumption that crop yields, crop areas and other factors follow an average trend. A distinction is made between the three different levels, *theoretical potential*, *technical potential*, as well as the *bioeconomic potential*, which are described as follows (Thorenz et al., 2018):

1. The theoretical potential (ThP) of agricultural residues is a function of the cultivated area of primary crop, yield of a primary crop and the residue to crop ratio of the specific crop.

$$ThP_{c,r,t} = Yield_{c,r,t} * Area_{c,r,t} * R : C\ ratio_c \tag{1}$$

$Yield_{c,r,t}$ denotes the yield in t/ha for the crop c in region r in the year t. The *Area* (in ha) has the same indices and the $R : C\ ratio_c$ is assumed to be variable for different crops but is supposed to be constant within the considered time frame and regions.

2. The technical potential (TP) of agricultural residues considers that only certain shares of residues can be recovered due to technical, legislative and sustainability criteria. These criteria are combined in the factor Sustainable Removal Rate (SRR), which reduces the theoretical potential.

$$TP_{c,r,t} = SRR_c * ThP_{c,r,t} \tag{2}$$

SRR_c denotes the Sustainable Removal Rate for crop species c.

3. The bioeconomic potential (BP) calculates by the consideration of competing applications. The most important competing application of straw is the bedding of animals (cattle, horse, pig, etc.) but also other agricultural uses like horticulture and mushroom cultivation (Supplementary Material, Table 5).

$$BP_{c,r,t} = TP_{c,r,t} - CA_{c,r,t} \tag{3}$$

$CA_{r,c,t}$ denotes competing applications for crop species c, region r and year t.

These three potentials provide the independent variables *area, yield, residue to crop ratio, sustainable removal rate (SRR)* and *competing applications.* Equations (1)–(3) describe the mathematical relation of the independent variables and the potentials. To perform forecasts on a dependent variable, the independent variables need to be forecasted. The three different residue potentials were the forecasting subject in this study.

2.1. Forecasting approach

This section deals with the analysis and explanation of the independent variables and the applied time series models. Thorenz et al. (2018) identified the crop yield, the cultivated area, the residue to crop ratio, the sustainable removal rate and competing applications as independent variables determining the different potentials. Each variable shows specific peculiarities, which necessitates a careful selection of applied time series models. Historic time series of the analysed independent variables showed patterns like a linear trend, no trend, a logistic trend or exponential decay. For each time series, different appropriate time series models were fitted with a final selection of the most suitable model according to quality measures, which are further described in the following section.

2.1.1. Cultivated crop area

Regional forecasts on the **cultivated crop area** of different species are rarely found in literature. The EU Agricultural Outlook annually projects the most important values in context of agriculture production in the European Union, including projections on cultivated crop area (European Commission, 2017b). The outlook is based on the Aglink-Cosimo Model, which is a comprehensive partial equilibrium model for global agriculture (OECD and FAO, 2015). A large set of macro-economic assumptions takes into account several developments such as population change, oil price, EU inflation and currency exchange rates. For specific species, external factors like changing consumption patterns, biofuel policy and land use changes are considered (European Commission, 2017b). On the downside, the outlook differentiates only in EU-15, the EU member states before 2004, and EU-N13, EU members that joined in 2004 or later (more information in Supplementary Material, Table 7).

The cultivated crop area is subject to a complex nexus of afore mentioned factors such as population change, oil prices, changing consumption patterns, agro-policies and others, whereby the outlook's projections provided the basis for the independent variable *cultivated crop area*. Simply disaggregating the outlook's area projections to regional level would bias the regional prognosis. As the last observed value is the basis for future predictions, regional extremes of the last observed value would be strongly bias the prediction. To address this inaccuracy, statistical time series models were applied to smooth the first year (in this case the year 2017). Historic time series for the cultivated crop area of each species are available on NUTS 1 level (Eurostat, 2017). For data without trend, simple exponential smoothing (ES1) and for data with linear trend, Holt's linear trend method (ES2) was applied (Hyndman and Athanasopoulos, 2013). As data was investigated on an annual basis, seasonal variations were ruled out and seasonal time series models were excluded. All models were parametrised by optimisation of Theil's inequality coefficient (U). Theil's inequality coefficient compares the quality of a prognosis to the quality of the naïve prognosis, and the optimal U minimises the forecasting error e_t (Theil, 1966). If the optimised U is larger than 1, the quality of a forecast is worse than the naïve prognosis which leads to a rejection of the model (see eq. (4)).

$$U = \sqrt{\frac{\frac{1}{K}\sum_t^K e_t^2}{\frac{1}{K}\sum_t^K (y_t - y_{t-1})^2}} \tag{4}$$

The Tracking Signal indicates systematic errors in case the model systematically under- or overestimates data. The tracking signal calculates as the sum of all errors divided by the Mean Average Error (MAE). A model is only applied in case the Tracking Signal ranges between $-0.5 < TS < 0.5$ (Thonemann, 2010) (see formula (5)).

$$TS = \frac{\sum e_i}{MAE} \tag{5}$$

In the case of simple exponential smoothing for data without trend, the area forecast $\hat{y}_{t+1}$ depends on the smoothing parameter α. It can take values between 0.05 and 1 with low values giving more weight to old area observations, depicted by $\hat{y}_{t-1}$, and high values giving more weight to the last observed crop area y_t.

$$\hat{y}_{t+1} = \alpha * y_t + (1-\alpha) * \hat{y}_{t-1} \tag{6}$$

For each time series, α is selected by minimising the quality measure U (Theil's inequality coefficient). For time series with trend, the tracking signal of simple exponential smoothing is larger than 0.5, respectively smaller than -0.5. In the case of time series with linear trend, Holt's linear trend method applies. The forecast $\hat{y}_{t+h|t}$ is made of one smoothing equation for the level l_t and one for the trend b_t (Hyndman and Athanasopoulos, 2013).

$$\hat{y}_{t+h|t} = l_t + hb_t \tag{7}$$

$$l_t = \alpha y_t + (1-\alpha)(l_{t-1} + b_{t-1}) \tag{8}$$

$$b_t = \beta^*(l_t - l_{t-1}) + (1-\beta^*)b_{t-1} \tag{9}$$

The smoothing parameters α and β range from 0.05 to 1 with small parameters giving more weight to old area observations, and large parameters giving more weight to recent data (Schlittgen and Streitberg, 2001). The parameter h is the h-step-ahead forecast, which linearly multiplies the last estimated trend variable. In case none of the introduced models fitted the investigated data accurately, naïve prognosis was applied. Fig. 1 plots the historically cultivated wheat grain area (solid lines) and time series models (dashed lines) of some NUTS 1 regions. Bassin Parisien (NUTS 1 region of France) is exemplarily highlighted for regions without measurable trend (Bassin Parisien's quality measures of ES1: $TS = -0.08$ and $U = 0.81$). Sachsen-Anhalt (Germany) is exemplarily depicted for the group of regions with measurable trend. The forecast for the year 2017 bases on the time series models and from 2018 to 2030, the annual percentage change of the cultivated area was adopted from the EU Agricultural Outlook (European Commission, 2017b).

2.1.2. Grain yield

The agricultural database of Eurostat (2017) provides historic time series of the annual **grain yield** of each species on NUTS 1 level. Grain yields are limited by an agro-economic saturation, which arises from plant specific biophysical properties and the limited provision of the crops with key resources like nutrients, sunlight, water and the space to grow. Table 1 shows the saturation levels for agricultural crop yields (European Commission, 2016).

Fig. 2 shows a log-log plot of all available historic wheat grain production values and corresponding cultivated areas (98 NUTS 1 regions and 16 historic years). The red line represents the average yield saturation of 7.0 t/ha that was assumed for wheat grain. The blue lines constitute historic average wheat yields of the whole EU (in 2000, 4.89 t/ha and in 2015, 5.73 t/ha) as well as the highest historically observed wheat grain yield (10.66 t/ha, Ireland in 2015). The historically achieved yield maximum of 10.66 t/ha is distinctively higher than the expected agro-economic yield saturation. Ireland benefits from stable and good rainfall and a lack of extreme weather events like cold winters or hot summers. Combined with an expensive disease control, Ireland is the world leader in wheat

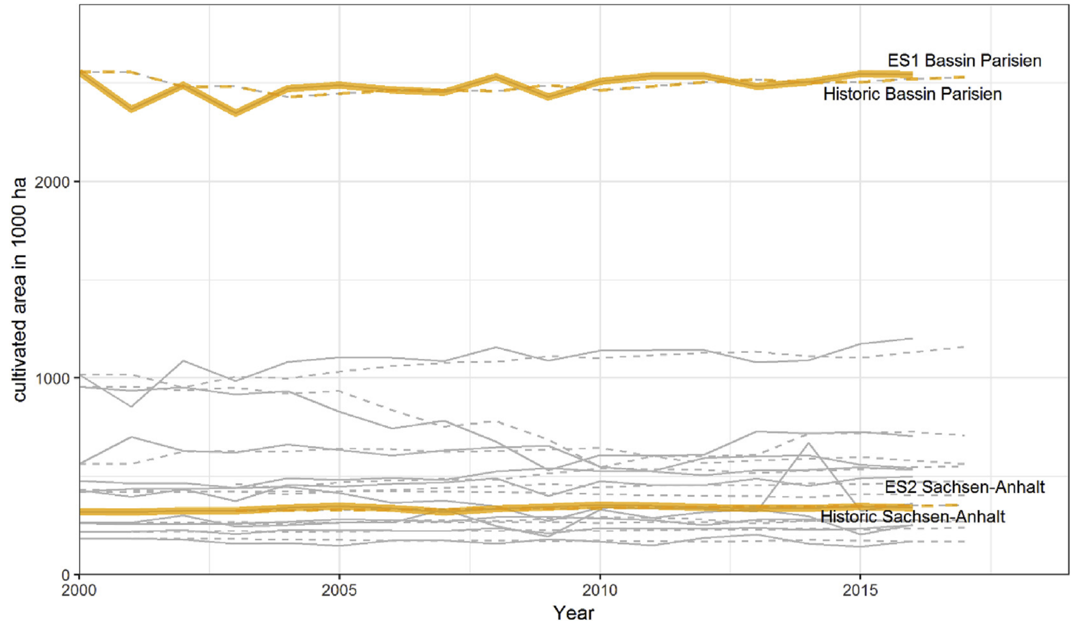

Fig. 1. Plot of the cultivated area of wheat grain. The solid lines represent historically cultivated areas; the dashed lines depict the results of the applied time series model. Bassin Parisien (France) is highlighted exemplarily for regions where simple exponential smoothing (ES1) applies and Sachsen-Anhalt (Germany) is highlighted for regions where Holt's linear trend method (ES2) applies.

Table 1
Agro-economic yield saturation of relevant crops.

Agricultural products	Agro-economic yield saturation (in t/ha)	Residue-to-Crop ratio	Sustainable Removal Rate
Wheat grain	7.0	1.00	40%
Corn grain	10.4	1.13	50%
Barley grain	5.3	0.93	40%
Rapeseed	3.9	1.70	50%

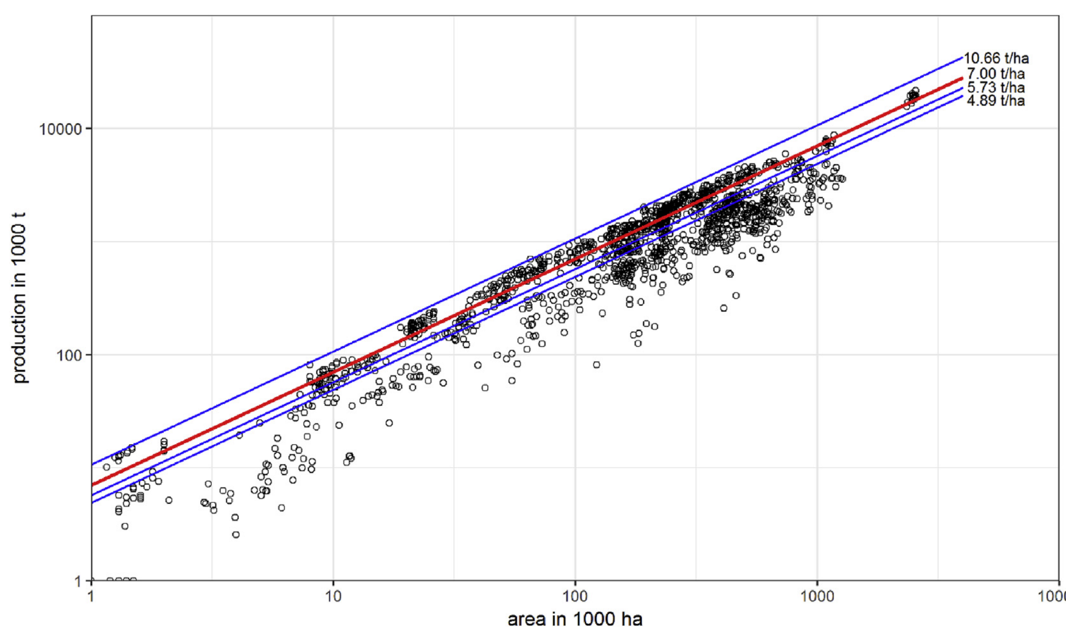

Fig. 2. Log-log plot of wheat grain production and cultivated area with equi-yield lines. The red line represents the assumed agro-economic yield saturation of wheat grain. The upper blue line represents the highest historically achieved wheat yield (10.66 t/ha, Ireland in 2015). The 5.73 t/ha yield line corresponds to the average wheat grain yield in 2015 and the 4.89 t/ha yield line correspondes to the average wheat grain yield in 2000. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

yields (Jones, 2015). The average yield increased in the last 15 years by nearly one ton per hectare.

Logistic growth models apply very well to the case of limited resources (Rye et al., 2013). Therefore, future yields were forecasted with logistic growth models including region-specific parameters. Eq. (10) shows the logistic growth function with $\hat{y}_t$ being the prognosis in period t. The yield asymptotically approaches the saturation level, which implies decreasing growth rates. Estimates for the starting value y_0, the saturation level S and the growth factor k can be retrieved from literature or acquired by parametric rating.

$$\hat{y}_t = \frac{S}{1 + \left(\frac{S}{y_0} - 1\right) * e^{-k*S*t}} \tag{10}$$

In principle, a saturation value for agricultural crops exists in the form of the agro-economic yield saturation. The parameters k and y_0 were estimated by a linearisation of eq. (10). The slope *m* and the y-intercept *b* in eq. (11) were derived from the linearised model by the least squares method (linear regression).

$$f(t) = \ln\left(\frac{S}{y(t)} - 1\right) = \ln\left(\frac{S}{y_0}\right) - kSt = b + mt \tag{11}$$

The missing parameters *k* and y_0 of the original nonlinear model were then calculated by inverse transformation shown in eq. (12) and eq. (13).

$$k = -\frac{m}{S} \tag{12}$$

$$y_0 = \frac{S}{1 + e^b} \tag{13}$$

For each of the 98 NUTS 1 regions, the saturation S of the logistic growth model corresponds to the yield saturation. The growth factor k as well as the initial value y_0 were calculated from historic data (2000–2016). Time series with strong growth in the past have a higher growth factor and regions with slow or no growth were parametrised with lower growth factors leading to almost stable future yields. Due to advantageous conditions like deep rich soils, good rainfall, very few extreme weather events or expensive disease control (Jones, 2015), some regions exceeded this assumed saturation, whereby the saturation level of those regions were adjusted to their respective historic maximum. In case of constant historic yields, the logistic growth model did not project the data properly, wherefore in this case, simple exponential smoothing performed well. This was especially true for regions with already very advanced agriculture and thus high yields. In case, no model fitted the data naïve prognosis was applied.

Fig. 3 shows the historic and forecasted wheat grain yields of selected 28 EU countries. The region Niedersachsen in Germany belongs to the regions with already very high grain yields where the results indicate no significant increase in the future whereby simple exponential smoothing had better forecasting quality. Romania, on the contrary, substantially increased its grain yield in the last years. The logistic growth model was parametrised with this data, which led to a high growth factor k resulting in fast approximation towards the saturation level.

2.1.3. Residue to crop ratio and sustainable removal rate

The **residue to crop ratio** as well as the **sustainable removal rate** were assumed to be constant over time and region. According to Foulkes et al. (2011), the harvesting index and thereby the residue to crop ratio of cereal plants has been constant since the early 1990s. Thorenz et al. (2018) reviewed several studies on residue-to-crop ratios and the results are displayed in Table 1. Sustainable removal rates of harvesting residues ensure the incorporation of nutrients to sustain the humus quality. The rate depends on various factors like the kind of soil, farming patterns, soil fertilisation, water supply and other factors making it difficult to give region-specific rates (Scarlat et al., 2010). For reasons of simplicity, in this work the sustainable removal rate was supposed to stay constant over time and region.

2.1.4. Competing applications

The demand of **competing applications** is the last factor required for the calculation of bioeconomic potential. According to Thorenz et al. (2018), competing applications consume nearly 30 Mt residual straw annually. The most important competing applications for straw are the bedding of animals like cattle bedding with a share of about 41 per cent of the straw consumed by competing applications, pig bedding with about 12 per cent, sheep bedding with about 11 per cent and horse bedding with about 6 per cent. Apart from animal bedding, surface-mulching accounts for about 12 per cent of the demand, the production of compost for mushroom cultivation accounts for 10 per cent of the straw demand from competing application, the energy production in combined heat and power plants (CHP) accounts for 6 per cent and the covering of strawberries for about 2 per cent. Calculation specifications for the straw demand of competing application were based on Scarlat et al. (2010) and Thorenz et al. (2018). In this work it was assumed that the calculation specifications will remain constant in the period under review. As for the variables introduced before, the forecasting of the straw demand from competing applications is based on historic time series. For data without trend, simple exponential smoothing was applied with stable future demand, for data with a positive trend, Holt's linear trend method was applied with increasing future demand. For time series with negative trend, Holt's linear trend method was applied to the logarithmical demand to address the circumstance that demand cannot become negative.

Fig. 4 shows the historic and future straw demand of selected competing applications in Poland. The future demand of cattle bedding and mushroom cultivation was forecasted by Holt's linear trend method. Strawberry covering strongly fluctuated in the past around a stable level, wherefore simple exponential smoothing was selected. Pig bedding distinctively decreased in the past 15 years, wherefore Holt's linear trend method was applied to the logarithmical straw demand of pig bedding. The forecasting results for every NUTS 1 region can be found in Supplementary Material, Table 5.

2.2. Data preparation

Eurostat provides historical data of cultivated crop area, crop yields and agricultural crop production on NUTS 1 level with some data gaps from 2000 to 2016. Where necessary, data gaps were filled by appropriate methods. Country data (NUTS 0) is available on Eurostat without gaps, wherefore in the case of missing NUTS 1 level data, country data is used to calculate the missing NUTS 1 data. Data gaps were filled by multiplying the historic average NUTS 1 shares with the country data of the missing year. In-data tests indicated a good performance of this method.

Historical data for the calculation of competing demand were obtained from Eurostat for a number of cattle, pig and sheep on NUTS 1 level (Eurostat, 2017). For strawberry and mushroom production as well as for a number of horses, data was obtained from FAO Stat with the disadvantage that figures are only available on NUTS 0 level (FAO, 2017). To disaggregate country data of those applications, the area share of each NUTS 1 region within the country is used as disaggregation proxy.

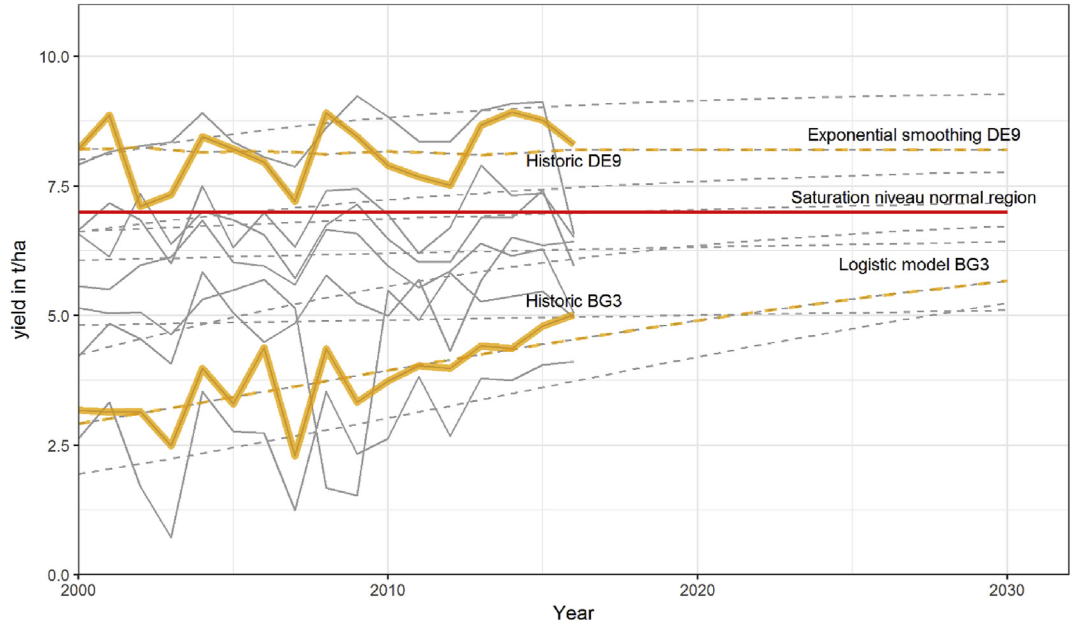

Fig. 3. Historic and future wheat grain yields by NUTS 1 regions. The solid lines represent documented historic yields of NUTS 1 regions with an emphasis of DE9 (Niedersachsen) and BG3 (Severna I Yugoiztochna Bulgaria). The dashed lines depict the forecasting until 2030 with an emphasis of DE9 (simple exponential smoothing) and BG3 (logistic model).

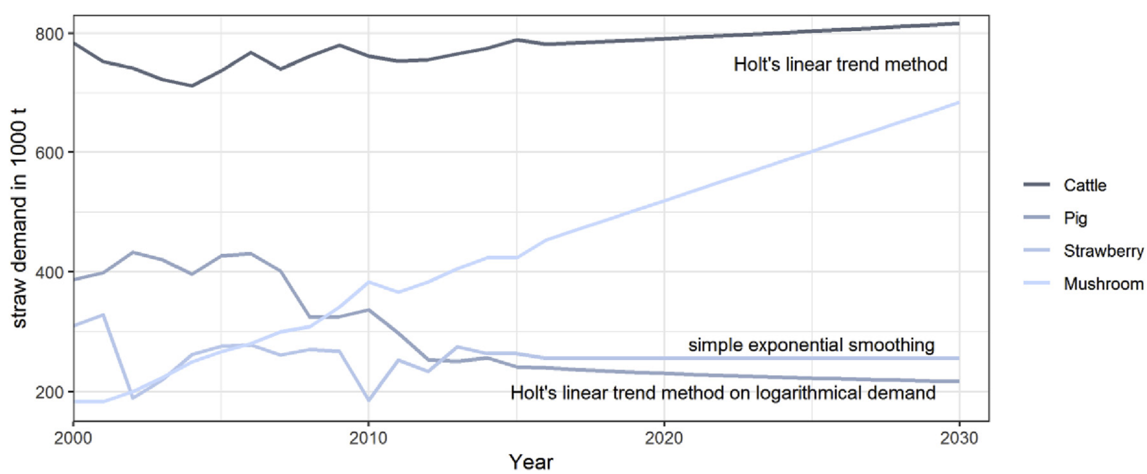

Fig. 4. Historic and future straw demand of cattle bedding, pig bedding, strawberry covering and mushroom cultivation in Poland.

3. Results

Harvesting residues of wheat grain (common wheat and durum wheat), corn grain, barley grain and rapeseed represent about three quarters of the annually accumulated lignocellulose residues from EU's fields. Results of each feedstock type are discussed in detail in the following sections. All forecasts and results were calculated on NUTS 1 level. For a comprehensible depiction of the results, most of the diagrams and tables are displayed on aggregated level (EU28 or country level). Detailed forecasting results on NUTS 1 level of theoretical, technical and bioeconomic potentials until 2030 are found on annual basis in the data sheets of Supplementary Material, Table 1, Table 2, and Table 3.

Fig. 5 displays aggregated values of the historic and forecasted bioeconomic potential for the EU28. Results indicate that the most important agricultural residue wheat straw further increases in the future. Also corn straw is likely to continue its positive trend in the next years. This is mainly due to their competitiveness on the world market and comes at the expense of crops like oats and also rapeseed (European Commission, 2017b, 2016). The cultivated area of barley is expected to stay rather stable. Together with only marginal increases in barley yields, the theoretical potential of barley straw increases marginally. The strong growth rates of rapeseed production, mainly due to expansions in the cultivated area, seem to reach a plateau with rather decreasing production volumes in the years to come.

The results indicated that the overall theoretical potential of the considered agricultural residues rises from 326.8 Mt in 2017 to approximately 360.6 Mt in the year 2030, which corresponds to an increase of about 10.3 per cent. The bioeconomic potential calculates at 113.0 Mt in 2017 and is supposed to rise to approximately 127.0 Mt in 2030. This increase is mainly due to increasing yields in central eastern European countries. Especially for common wheat, increases in the cultivated area could come at the expense of other cereals (European Commission, 2017b). Results show a rather stable demand of competing applications for agricultural residues of

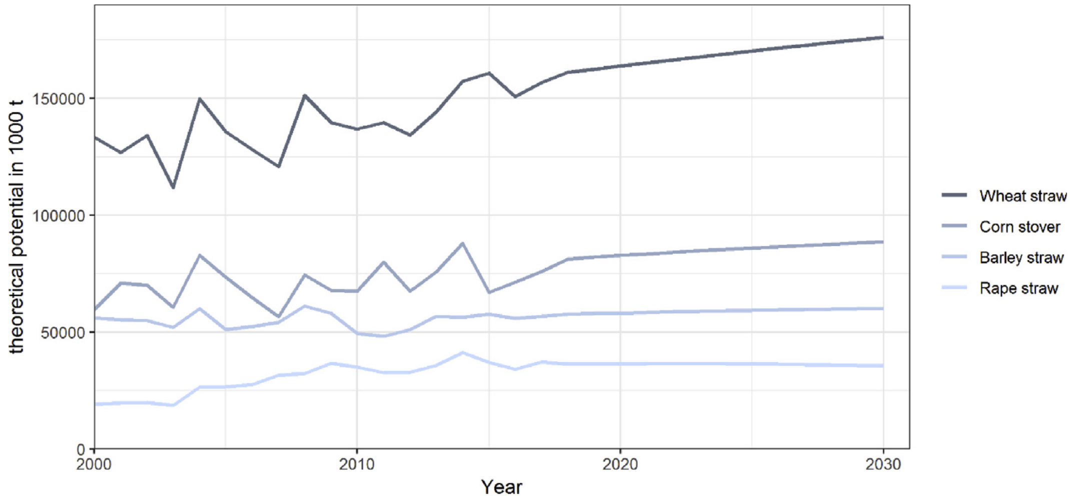

Fig. 5. Aggregated historic and forecasted theoretical potential of four assessed lignocellulose feedstock types.

about 30 Mt. For the years ahead, the results do not show significant changes in demand of the largest straw consumer cattle bedding, pig bedding and sheep bedding (Supplementary Material, Table 5).

Table 2 is an aggregated summary that compares the 2017 potentials with the forecasted potentials in 2030. According to the results, the overall bioeconomic potential of corn stover will increase by nearly 20 per cent. In the same time, the amount of rapeseed straw is supposed to decrease slightly (spatially explicit data is found in Supplementary Material, Table 3).

Fig. 6 (a) shows a map of the EU with the aggregated bioeconomic potential of the considered residues (without the oversee regions). Central Europe, Western Europe and parts of Southeast Europe show the largest residue potentials. 45 of the 98 NUTS 1 regions show large supply potentials of more than 1.0 Mt. The region around Paris (Bassin Parisien) has by far the largest potentials with more than 14.0 Mt. Regions exposed to more extreme weather tend to have lower potentials. This holds true for the south of Spain, Italy and France, most parts of Greece and Cyprus. Also, northern regions like Ireland, the Netherlands or western parts of the United Kingdom show an undersupply in straw. Regions with more extreme weather (like heat waves or long and cold periods) show less stable supply. Fig. 6 (b) shows the forecasted percentage change in the residue availability for each NUTS 1 region. Results show especially for central eastern European regions increases in harvesting residue volumes by 2030. In some regions, overall volumes are likely to grow by about 30 per cent or more during the coming decade. This is mainly due to advancing farming practices which lead to increasing crop yields. Region specific nexus are analysed in the following sections.

3.1. Wheat straw

According to the results, wheat straw from common and durum wheat remains the most important agricultural lignocellulose residue in the European Union. The growth rate of the cultivated area is expected to stay rather small with an average annual growth of around 0.1 per cent (European Commission, 2017b) (Supplementary Material, Table 7). In countries with a long EU membership, yields tend to be on average higher than in countries with more recent EU accession. On the contrary, this implies in many cases that yields are already around the agro-economic saturation with little or no potentials for further increasing yields. In countries like Belgium, Denmark, France, Germany or the Netherlands, the models predict growth rates between 0 per cent and well below 3 to 4 per cent over the whole period under observation, which implies nearly constant yields. Central and Eastern European Countries with more recent EU accession like Bulgaria, Estonia, Poland and Romania show yield growth rates up to 30 per cent between 2017 and 2030. Those countries currently undergo advances in farming technology and attain a more efficient resource management (European Commission, 2017b).

3.2. Corn stover

Like wheat, corn production is also likely to expand further in the coming decade. Fig. 7 shows the EU map with the bioeconomic potential of corn stover in 2017 (a) and in 2030 (b) (without the oversee regions). The main driver for the increase in corn stover potentials are the increasing crop yields. Similar to wheat, most noticeably Bulgaria, Romania and Slovakia are catching up with farming techniques leading to increasing crop yields between 1.5 t/ha and 2.3 t/ha resulting in yields of up to 7–9 t/ha. Those countries are likely to register distinctly larger residue potential growths of up to 25–30 per cent compared to most other regions. According to the recently published Agricultural Outlook, from 2020 onward, the cultivated corn grain area is expected to slightly decrease by 0.1–0.2 per cent per year (European Commission, 2017b). In countries with stagnating yield growth rates like France or Italy, this means stable or even slightly falling production volumes.

Table 2
Comparison of the average 2017 data with forecasted 2030 data.

Agricultural harvesting residues	2017 Theoretical potential (1000 t)	2017 Bioeconomic potential (1000 t)	2030 Theoretical potential (1000 t)	2030 Bioeconomic potential (1000 t)	Change Theoretical Potential	Change Bioeconomic potential
Wheat straw	156,880	50,097	176,144	57,227	12.3%	14.2%
Grain corn stover	75,961	30,429	88,642	36,503	16.7%	20.0%
Barley straw	56,664	16,666	60,251	18,098	6.3%	8.6%
Rapeseed straw	37,281	15,807	35,584	15,205	−4.6%	−3.8%

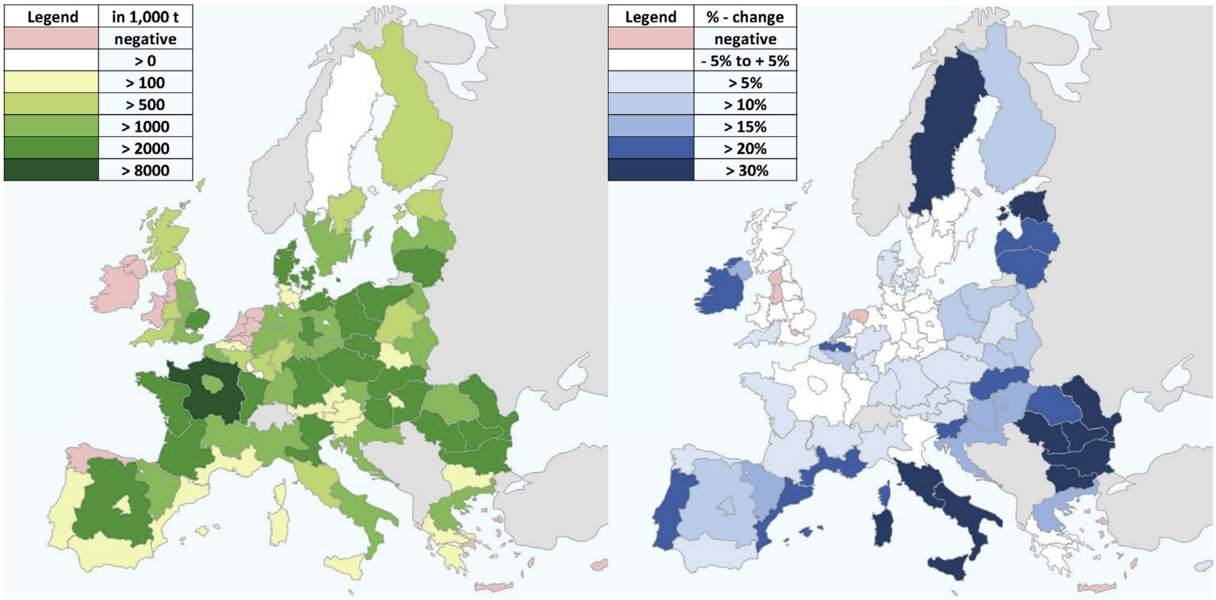

Fig. 6. (a) Total bioeconomic potential of the four considered agricultural residues wheat straw, corn stover, barley straw and rapeseed straw in the year 2030. (b) Shows the forecasted percentage change in the residue availability.

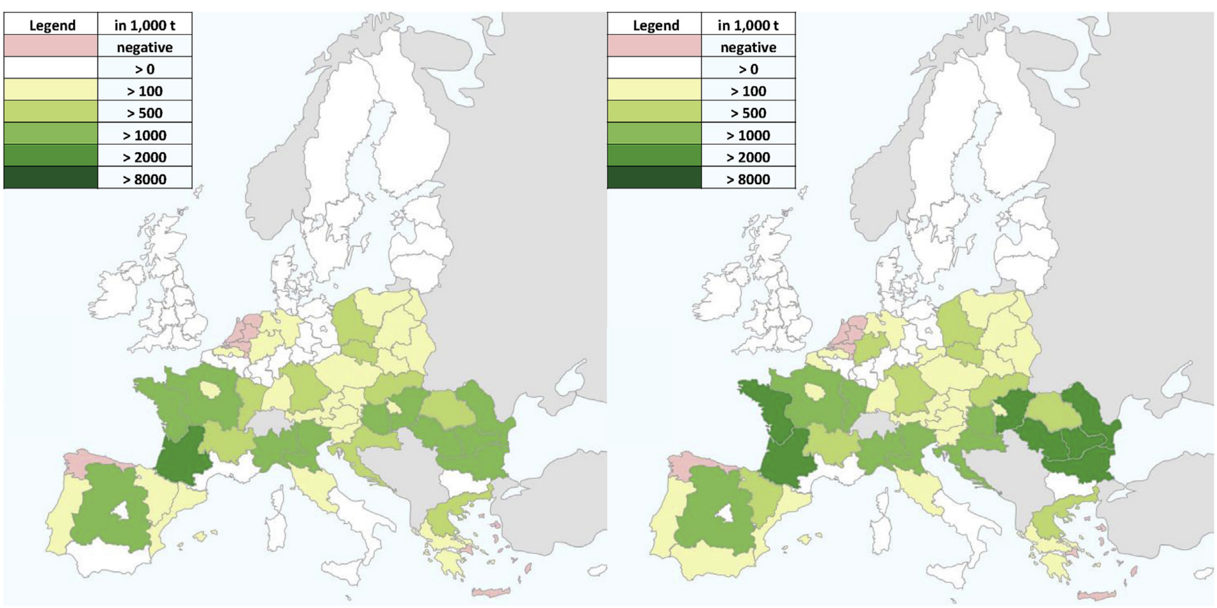

Fig. 7. (a) Bioeconomic potential of corn stover 2017 and (b) bioeconomic potential of corn stover 2030.

Romania, which is already the second largest producer of corn, could catch up with France by 2030 as the largest producer. Even though the cultivated corn grain area could slightly decrease in the decade after 2020, the overall production volumes are expected to increase until the year 2030.

3.3. Barley straw

It is predicted that the barley straw potential will have the most stable supply in the coming years. Already in the historic period under consideration, in nearly all regions of the EU, barley production stayed rather constant or had a slightly negative trend. According to the European Commission (2017b), the annual changes in the cultivated area are expected to fluctuate around 0 per cent (Supplementary Material, Table 7). In EU regions with a more recent EU accession, the models predict yield increases. As those countries only produce minor volumes of barley, the increase in yield carries little weight for the overall production volumes. To sum up, in the EU28, theoretical barley straw potentials are expected to increase by about 6 per cent until the year 2030.

3.4. Rapeseed straw

Compared to the results of the other investigated feedstocks, rapeseed straw volumes will decrease in the next ten years in most regions. According to the, European Commission (2017b), the total rapeseed area in the EU will decrease by about 0.5–0.9 per cent annually. The contraction is driven by the decrease in demand for vegetable oil and a decreasing demand for first generation biofuels. Additionally, a shift from rapeseed towards imported soybean can be observed at the moment (European Commission, 2016). The decreasing cultivated land share of rapeseed has especially strong effects on production volumes in countries with already high grain yields like France or Germany. In countries that currently undergo advances in farming practices, the expected area decrease is compensated by growing grain yields (like Romania or the Czech Republic). Fig. 8 plots the theoretical potential of rapeseed straw for each EU country with an emphasis on France and Romania. France includes the regions that already reached the yield saturation and Romania represents regions that still face strong increases in the achievable yield. For the whole EU28, the theoretical potential of rapeseed straw in 2030 is supposed to drop by 4.6 per cent and the bioeconomic potential by 3.8 per cent compared to the year 2017.

Detailed results for each species as well as each NUTS 1 region are found in the excel sheet of (Supplementary Material, Table 1).

4. Discussion

This work forecasted agricultural residue potentials of lignocellulose matter until the year 2030. Wheat (common and durum), corn, barley and rapeseed are the crops with the largest production volumes in the EU also yielding the highest amounts of harvesting residues. Up to 80 per cent of lignocellulose residues from agricultural harvesting (cereals and oil crops) arise from those species (Thorenz et al., 2018). Based on historic data (2000–2016), the cultivated area of the year 2017 was forecasted with fitted time series models. From 2018 to 2030, annual percentage change in the cultivated area was adopted from the EU Agricultural Outlook. This approach was chosen, as exogenous macro-economic factors that affect the cultivated area are not taken into account by applying time series-based models only. To prove the robustness of model assumptions, the cultivated area forecasted by the EU Agricultural Outlook was compared to a time series-based forecast of the cultivated area (Supplementary Material, Tables 6 and 7). For wheat straw and corn stover, the results hardly differ. In the time series-based area forecast, residue potentials of barley straw are expected to rather decrease in the next decade. In many regions, barley area contracted in the last years and time series-based models predict that this will continue. Conversely, rapeseed area developed positively between 2000 and 2016 which results in increasing area forecasts. The sensitivity analysis regarding the cultivated area development confirm that time series-based forecasts do not include exogenous information, although they strongly effect the future.

Forecasts of crop yields are based solely on fitted models and especially in regions with more recent EU membership, the logistic model fitted very well and identified a positive development of yields in the observed years. In regions where the yield fluctuated around a stable level in past years, simple exponential smoothing applied better (see chapter 2.1.2). To proof the results of this study, they were compared with the EU Outlook's predictions. The regionalised yield forecasts of this study were aggregated to the EU-15 and EU-N13 level, based on the production share of a region. For wheat and corn, the results show a good comparability (difference in the 2030 yield forecast well below 3 to 4 per cent). While barley yields on EU-N13 level are similar, yields on EU-15 level differ by nearly 15 per cent. The reason for this difference are the historic barley yields, which already differ by around 15 per cent between the EU Agricultural Outlook and the Eurostat data used in this work. For EU-15 countries, rapeseed yield forecasts are almost similar, whereas for the EU-N13 aggregation, this studies yield forecast is more positive and in 2030 the prediction exceeds the Outlook's prediction by 15 per cent (further information on the comparison is found in the Supplementary Material, Tables 4 and 7).

The residue to crop ratio as well as the sustainable removal rate were assumed to stay constant during the period under consideration. This assumption is a limitation of the study, as the residue to crop ratio as well as the sustainable removal rate depend on regional and terrain specific features. The sustainable removal rate is an important factor for the humus quality and thereby for a sustainable and long-term-oriented agriculture. In Germany, the Association of German Agricultural Assessment and Research Organisations provides a methodology for the calculation of field specific humus balance which provides a basis for the calculation of regionalised sustainable removal rates (VDLUFA, 2014). However,

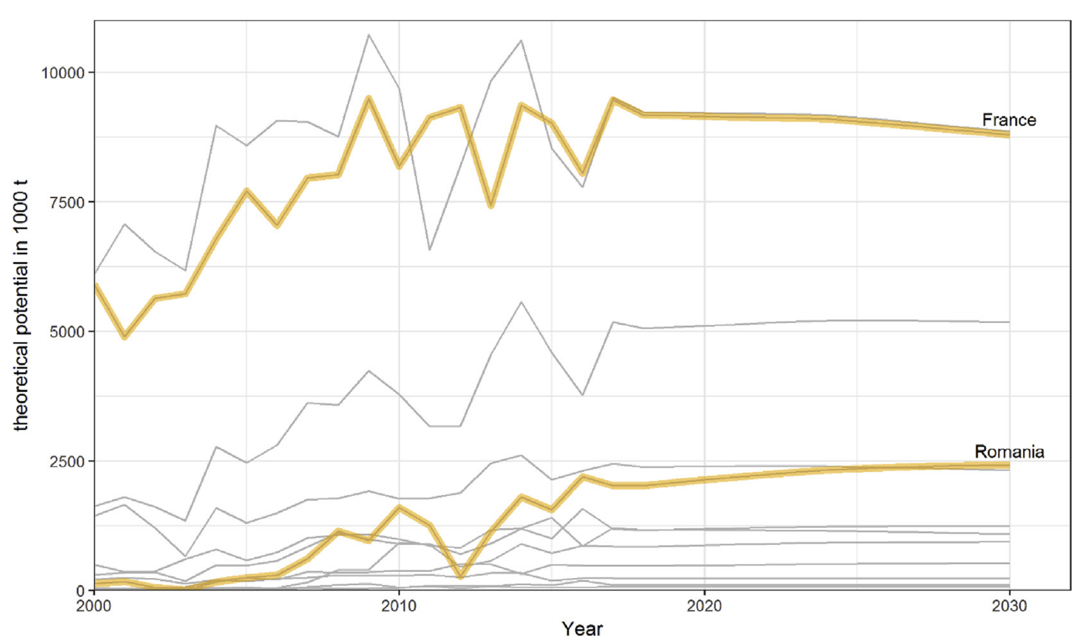

Fig. 8. Development of theoretical potentials of rapeseed straw from 2016 to 2030 (selected countries).

the methodology requires specified information, which is difficult to acquire in assessments on macro level, therefore this study used a sufficiently high average sustainable removal rate (Scarlat et al., 2010).

To verify the robustness of presented results, this study completes with an out-of-sample test for the year 2017, where forecasted residue volumes were compared with actually recorded values of 2017. Beginning of the year 2018, first datasets on 2017 crop production were published on NUTS 0 level (EU28 countries) by EUROSTAT (Eurostat, 2018). Accordingly, the forecasted theoretical potentials were compared to the actual potentials of the year 2017. While the forecasted theoretical potential of wheat straw in the EU28 summed up to 156.9 Mt, the actual wheat straw potential was 152.7 Mt, which corresponds to a deviation of 2.7 per cent. Corn stover deviates by 2.5 per cent (Forecast: 76.0 Mt, actual volume: 74.1 Mt). Barley straw was forecasted with 56.7 Mt and the actual volume summed up to 55.1 Mt, which corresponds to a deviation of 2.8 per cent. The same small deviation holds true for rapeseed straw with a forecast of 37.3 Mt and a actual volume of 37.0 Mt (deviation of 0.6 per cent). As a result of the out-of-sample test on aggregated EU level for the year 2017, it may be noted that the time series models show a high prognosis accuracy. However, it is noticeable that the forecast overestimated the observed production in 2017.

On country level, larger deviations between forecasts and actual volumes were registered (see Fig. 9). For wheat straw, deviations between forecasted and actual potentials are small for all large producers. Romania, the fifth biggest wheat straw producer in the EU, showed the largest deviation with about a 20 per cent higher theoretical potential than forecasted. The exemplary development in 2017 was due to favourable weather, government subsidies, proper fertiliser management and disease prevention (Dobrescu, 2017). Due to poor weather conditions during the growing campaign in 2017, the largest wheat crop producer, France, stayed about 3.5 per cent behind the forecasted volumes (Houghton, 2018). Again for corn stover the actual 2017 vol in Romania strongly exceeded the forecast (about 25 per cent), which made Romania the second largest corn stover producer in the EU in 2017. The results indicate that Romania's production catches up with France as the biggest producer in the year 2030. However, also for corn the development in Romania in the year 2017 was exceptionally positive (Dobrescu, 2017). Other important corn producing countries like France, Italy or Spain significantly produced less than forecasted.

For barley straw, the 2017 forecast of the largest producers is fairly accurate (deviation in Germany: 2.7 per cent, France: 0.7 per cent, UK: 0.8 per cent). In Spain, the fourth largest producer, the forecast exceeded the actual production by about 21 per cent. A severe drought hit Spain leading to distinctively smaller barley grain yields (Rehman, 2017). While for rapeseed straw on NUTS 0 level the difference of the forecast and the actual values is close to zero, on NUTS 1 level large differences are noted (see Fig. 10). Especially the largest producers, France and Germany, showed remarkable differences between forecast and actual volumes. While rapeseed straw volumes in 2017 in Germany were about 25 per cent less than forecasted, in France the actual volumes exceeded the forecasted potentials by about 12 per cent, which partly counterbalanced the sum. The German rapeseed production suffered from negative temperatures after sowing, heat waves during the growth phase, and very wet phases during the harvest which all together led to the remarkable drop (Krauβ, 2017). In France, rapeseed yields in 2017 reached a record level-high due to optimal growing conditions leading to higher than forecasted straw potentials (Trompiz, 2017).

On EU28 aggregation, the out-of-sample test reveals robust forecasting results as regional anomalies are compensated. At

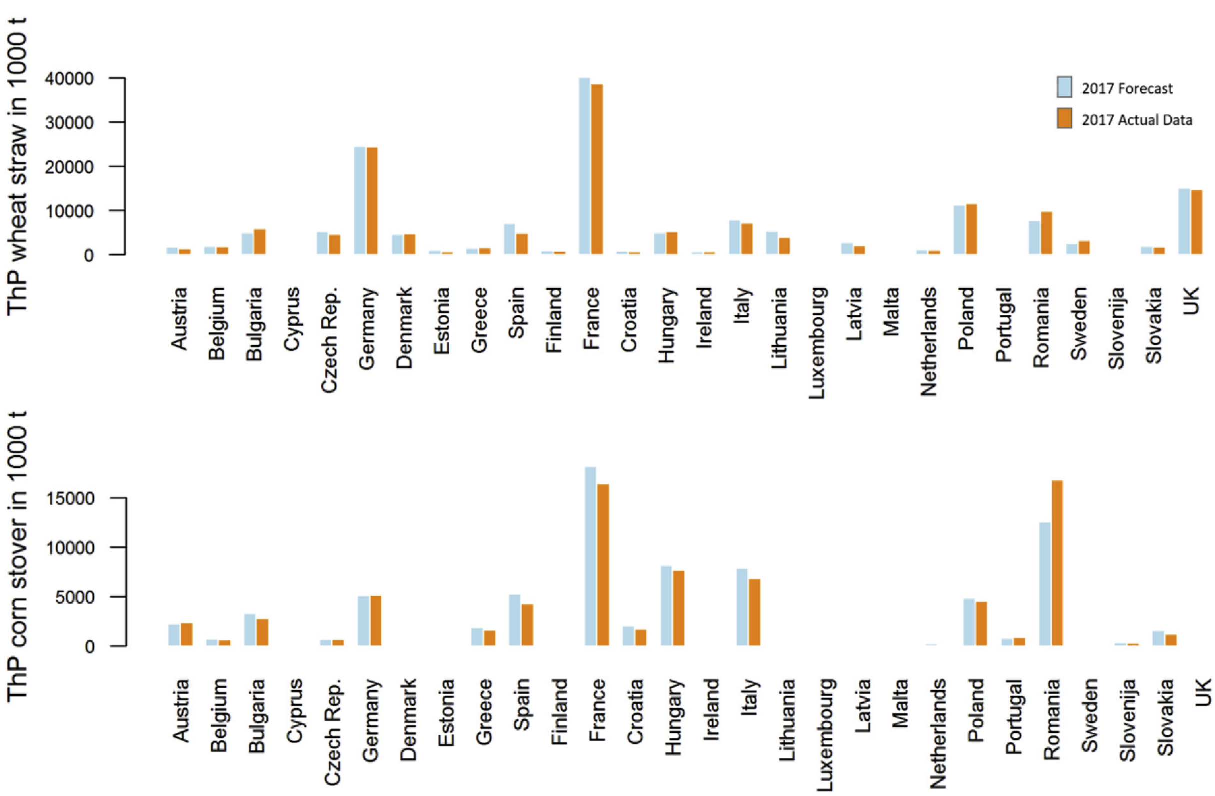

Fig. 9. Theoretical potential of wheat straw and corn stover forecasts and actual 2017 data.

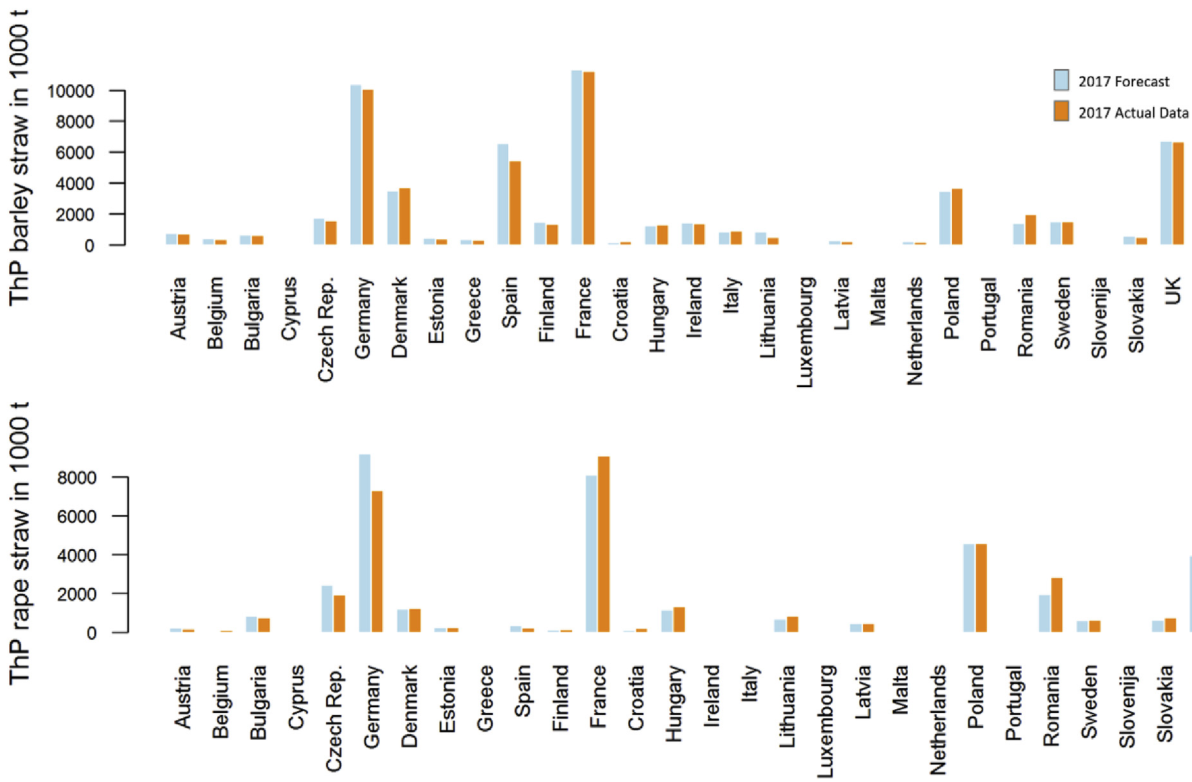

Fig. 10. Theoretical potential of barley straw and rapeseed straw forecasts and actual 2017 data.

regional level, larger deviations between the forecast and actual production were observed. These deviations are mainly driven by annual weather events, that strongly influence crop yields (Lesk et al., 2016). Weather events appeal from very small-to large-scale, whereby they are not confined to a given political region or a country. In 2003, almost the whole EU faced extremely unfavourable weather conditions with heatwaves and droughts in many regions leading to a severe drop in the agricultural productivity (Ciais et al., 2005). Likewise, precipitation can strongly impact grain volumes, as seen in 2016 in Northern France. Wheat and corn grain production collapsed by about 35 per cent due to extreme precipitation during the growth phase (Agrifrance, 2017). However, extreme weather events do not show long term effects on agricultural crops and production returns to normal in the year after the event (Lesk et al., 2016).

Annual regional variations due to weather are difficult to anticipate. The more spatially detailed forecasts are the stronger are impacts of such events. The latest report by the Intergovernmental Panel on Climate Change (IPCC) leave little doubt for an accumulation of climate anomalies in the coming years. Events with negative effects on crop yields like heatwaves, droughts or extreme precipitation during the growth phase are likely to occur more frequently and more intensely (IPCC, 2014). Lesk et al. (2016) points out that the intensified agriculture of high-income countries with yield-maximising strategies are more susceptible to extreme weather events than less developed regions that tend to use risk-minimising strategies. That supports the inference that future weather anomalies could have strong impacts on annual regional residue potentials, especially in high-income countries.

5. Conclusion

Lignocellulose materials from agricultural harvesting residues are expected to become an important renewable resource for materials and biofuel of the post-petrol era. There are still many issues that have to be addressed before lignocellulose can be applied on a large scale. On the one hand, technical issues like the resistant nature of lignocellulose or the large variety of sugars derived from hemicellulose and cellulose have to be addressed (Balat, 2011). On the other hand, economic questions have to be answered. Currently, neither a transparent market nor a transparent price for agricultural harvesting residues exists in the EU. The question about sustainably available feedstock potentials is also still an object of discussion (Hennig et al., 2016). This work contributes to a future perspective on the available potentials in the EU. Before investments in large-scale biorefineries take place, decision makers from politics and business need to know where to expect the largest as well as most stable feedstock supply. The variety of feasible lignocellulose materials is much broader and covers for example grasses like miscanthus, pruning residues, forest thinning residues and others. By adapting the assessed feedstock, the introduced methodology can also be applied to a broader range of resources.

As the out-of-sample test shows, the 2017 forecast of the theoretical potential of agricultural residues proved to be adequate at the EU28 level. However, annual fluctuations on regional level are difficult to address. Future studies may focus on the determination of the impacts of weather events on agricultural production, respectively on agricultural residue potentials. Simulated future daily weather data that is derived from climate change scenarios could for example be considered. Duveiller et al. (2017) for example recently published, simulated near (2020) and medium term (2030) daily weather data that is ready to be applied to crop modelling studies. This work broadens the knowledge about feedstock potentials from agricultural residue potentials that are available for the transition towards a bioeconomy. As biomass supply chains seem to be more effective on regional scale, the aim of this work is the prediction of potentials on regional basis.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jclepro.2018.11.072.

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