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Geospatial supply-demand modeling of lignocellulosic biomass for electricity and biofuels in the European Union

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ABSTRACT

Bioenergy can contribute to achieving European Union (EU) climate targets while mitigating impacts from current agricultural land use. A GIS-based modeling framework (1000 m resolution) is employed to match biomass supply (forest and agricultural residues, complemented by lignocellulosic energy crops where needed) with biomass demand for either electricity or bio-oil production on sites currently used for coal power in the EU-28, Norway, and Switzerland. The framework matches supply and demand based on minimizing the field-to-gate costs and is used to provide geographically explicit information on (i) plant-gate supply cost; (ii) CO_2 savings; and (iii) potential mitigation opportunities for soil erosion, flooding, and eutrophication resulting from the introduction of energy crops on cropland.

Converting all suitable coal power plants to biomass and assuming that biomass is sourced within a transport distance of 300 km, would produce an estimated 150 TW h biomass-derived electricity, using 1365 PJ biomass, including biomass from energy crops grown on 6 Mha. Using all existing coal power sites for bio-oil production in 100-MW pyrolysis units could produce 820 PJ of bio-oil, using 1260 PJ biomass, including biomass from energy crops grown on 1.8 Mha. Using biomass to generate electricity would correspond to an emissions reduction of 135 $MtCO_2$, while using biomass to produce bio-oil to substitute for crude oil would correspond to a reduction of 59 $MtCO_2$. In addition, energy crops can have a positive effect on soil organic carbon in most of the analyzed countries. The mitigation opportunities investigated range from marginal to high depending on location.

1. Introduction

In November 2018, the European Commission presented its strategic long-term vision for a prosperous, modern, competitive and climate-neutral economy by 2050 – i.e., an economy with net-zero greenhouse gas emissions [1]. In December 2018, the EU adopted Directive 2018/2001/EU on the promotion of the use of energy from renewable sources [2]. The new regulatory framework includes a binding renewable energy target for the EU for 2030 of 32% with an upward revision clause by 2023. In 2018, renewable energy represented almost 18% of energy consumed in the EU, of which about 60% was bioenergy[2] [3,4]. Most of the demand is met with domestically produced biomass (about 96% in 2016 [4]).

Bioenergy systems can be associated with a range of positive and negative environmental, social and economic effects, which are context specific and depend on a multitude of factors including soil and climate conditions, type of biomass production system, scale of deployment, and prior land use [5,6]. Bioenergy deployment can cause food price increases and food security impacts if food and feed crops are diverted to biofuel production, or lands previously used for food become used for energy crop production [7–12]. However, the outcome depends critically on feedstock type and context conditions (e.g., quality of governance, legal principles concerning land ownership and dependency on subsistence agriculture) and studies have demonstrated that bioenergy can be synergistic rather than competing with food production [13–15].

Organic waste and residues in the agriculture and forestry sectors represent a significant source of biomass [16] but also dedicated cultivation of energy crops will be needed if biomass demand grows towards

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the scale indicated in many scenarios meeting ambitious climate targets [17,18]. Lignocellulosic crops, such as miscanthus, switchgrass, willow, and poplar, currently cover a very small share of EU croplands, but may grow in importance as EU adopts more ambitious policies to cut emissions and foster development towards climate neutrality [19]. Impacts of expanding such crops depend on the type of land converted as well as the type of cultivation systems put in place. Suitable lignocellulosic crops can be cultivated on marginal lands, i.e., areas with limited agronomic and economic potential for food production [20,21]. Such areas can include abandoned [22] and/or degraded [23] cropland, or lands designated as wastelands [24]. If lignocellulosic crops are cultivated on such marginal lands competition with food production can be lower [21]. It can also provide job opportunities in rural areas [25] and improve agronomic conditions [26], thus increasing the total area of productive agricultural land. In addition, appropriate selection, siting, and management of lignocellulosic crops in intensively managed and productive agricultural landscapes can improve conditions for biodiversity and reduce environmental impacts associated with current agriculture, e.g., reduce flooding risk, erosion, eutrophication, and pesticide use, and promote soil productivity and carbon storage [24,27–38]. Such solutions for mitigating environmental impacts from current agriculture practices ensure that agricultural landscapes maintain their productivity, thus limiting negative economic effects for the farmer, as well as the need to expand agricultural production elsewhere to meet increasing biomass demand [25].

Biomass use in existing fossil infrastructure (e.g., power plants, refineries) represents an important short- and medium-term opportunity for facilitating bioenergy deployment [39–42]. Biomass co-firing in existing conversion infrastructure (e.g., coal-fired boilers) can help reduce greenhouse gas (GHG) emissions at low cost, constituting a stepping-stone for developing biomass supply infrastructure as well as conversion technologies entirely based on biomass [39,40]. This is especially important when carbon pricing is weak [39]. Biomass use for energy in the existing fossil fuel infrastructure takes advantage of existing process knowledge, associated services, and markets. In this regard, the production of so-called biocrudes, and the integration of biofuel production with oil refineries is gaining attention. Important benefits include reduced petroleum dependency in refineries and lower biofuel production costs [43,44]. Bio-oil derived from fast pyrolysis of lignocellulosic materials is among the most inexpensive biocrude that can be produced today and upgraded to a product compatible with refinery streams [45].

Prospects for bioenergy implementation depend on a range of factors, including resource availability, cost of harvesting/collecting, capacity of conversion plants, and biomass transport cost [46–48]. Several studies have estimated the availability of lignocellulosic resources for the EU and individual member states, considering bio-physical and environmental constraints at different spatial resolutions [49–52]. To get a better understanding of how biomass-based demand can be met and to estimate the associated cost, high-resolution assessments are needed [53]. Studies have addressed the siting of biomass conversion plants based on the spatial distribution of biomass resources and logistical conditions (e.g., de Jong, Hoefnagels [47] at a resolution of half a degree, or Monforti, Lugato [46], Monforti, Bódis [48] at 1000 m). Supply-demand matching has also been performed based on information about biomass demand by location. Nivala, Anttila [54] (at 1 ha resolution) considered biomass availability under certain constraints within certain distances from existing power plants in Finland. Di Fulvio, Forsell [55] calculated the cost of supplying roundwood and logging residues to industry gates in the EU, including transport cost at a resolution of half degree; and Cintas, Berndes [40] estimated the cost of supplying biomass for co-firing in existing coal power plants in the EU at 1000 m resolution. However, the higher-resolution analyses found in the literature did not consider multiple biomass supply sources and did not take into account that farmers may change their land use to cultivating more lignocellulosic crops if bioenergy demand increases in their vicinity.

A GIS-based 1000 m resolution analytical framework is employed, which is based on and updated from the previous analytical framework [40], to further quantify and match selected biomass demand and supply sources in the EU-28, Norway and Switzerland (designated EU28+). The purpose of using this methodology framework is to derive geographically explicit information about the possible build-out of biomass supply chains to meet localized biomass demand, including the assessment of the pressure driving land-use change and possible environmental consequences of mobilizing biomass supply for energy. In this paper, the focus is on supply-demand patterns on relatively short scales and on greening the existing fossil infrastructure. The biomass demand side includes existing petroleum refineries and coal-fired power plants, and the supply side includes forest and agricultural residues, and lignocellulosic crops on current cropland. The resulting CO_2 emissions reduction and the associated costs are calculated. An indicative assessment is made of the mitigating effects that integrating dedicated biomass plantations in agricultural landscapes could have on specific negative environmental impacts of current agriculture. For simplicity, time dynamics are not investigated in this study as it would add a layer of complexity while not changing the outcome of the supply-demand matching and potential associated environmental mitigation benefits (unless there are significant differences between countries).

2. Method and scenarios

2.1. Analytical framework

Fig. 1 shows the analytical framework, which is an updated version of the framework presented in Cintas, Berndes [40], covering EU28+. The framework consists of (i) a biomass demand module, which here includes existing coal-fired power plants and petroleum refineries; (ii) a biomass supply module, which includes forest and agricultural residues and biomass from dedicated cultivation of lignocellulosic crops on cropland (*energy crops*, for short); and (iii) an integration module that matches biomass supply with biomass demand based on minimizing the cost of transporting biomass from harvest sites to plant gates and on staying below a specified maximum transport cost that for the EU on average corresponds to transport distances of approximately 100, 200, and 300 km.

2.1.1. Biomass demand module

Bioenergy production and associated biomass demand are calculated for two scenarios representing separate bioenergy development pathways. Both scenarios rely on the existing coal power plant infrastructure as a basis for new bioenergy supply chains, either converting the power plants to 100% biomass-firing plants or using the sites of the power plants to establish pyrolysis units for producing a raw bio-oil to be transported to petroleum refineries (Fig. 2). Power-plant data is obtained from the Chalmers Power Plant Database for Europe (CPPD) [56], which is continuously updated. The calculation of avoided CO_2 emissions uses emission factors that are representative for the fossil fuel displacement in the scenarios (coal-based electricity and crude oil). Biogenic carbon balances are not considered in the calculations, but we stress that these can significantly influence the net carbon balance over time, see Berndes, Ahlgren [57], Cintas, Berndes [58], Cintas, Berndes [59], and the section below describing the biomass supply module.

Scenario 1 assumes that all existing co-firing power plants, and the coal-fired power plants identified as suitable for co-firing in Cintas, Berndes [40], have been retro-fitted to allow biomass fuel shares to reach 100%, provided biomass is available (Fig. 2a). Power plants transitioning toward bio-electricity have figured in the United Kingdom (UK), for instance, where three coal plants co-fired biomass while they were converted to dedicated biomass-fired plants [61]. Coal-fired power plants identified as not suitable are assumed to be demolished or used for other purposes than the biomass conversion investigated here. Already existing biomass power plants are not included in the analysis.

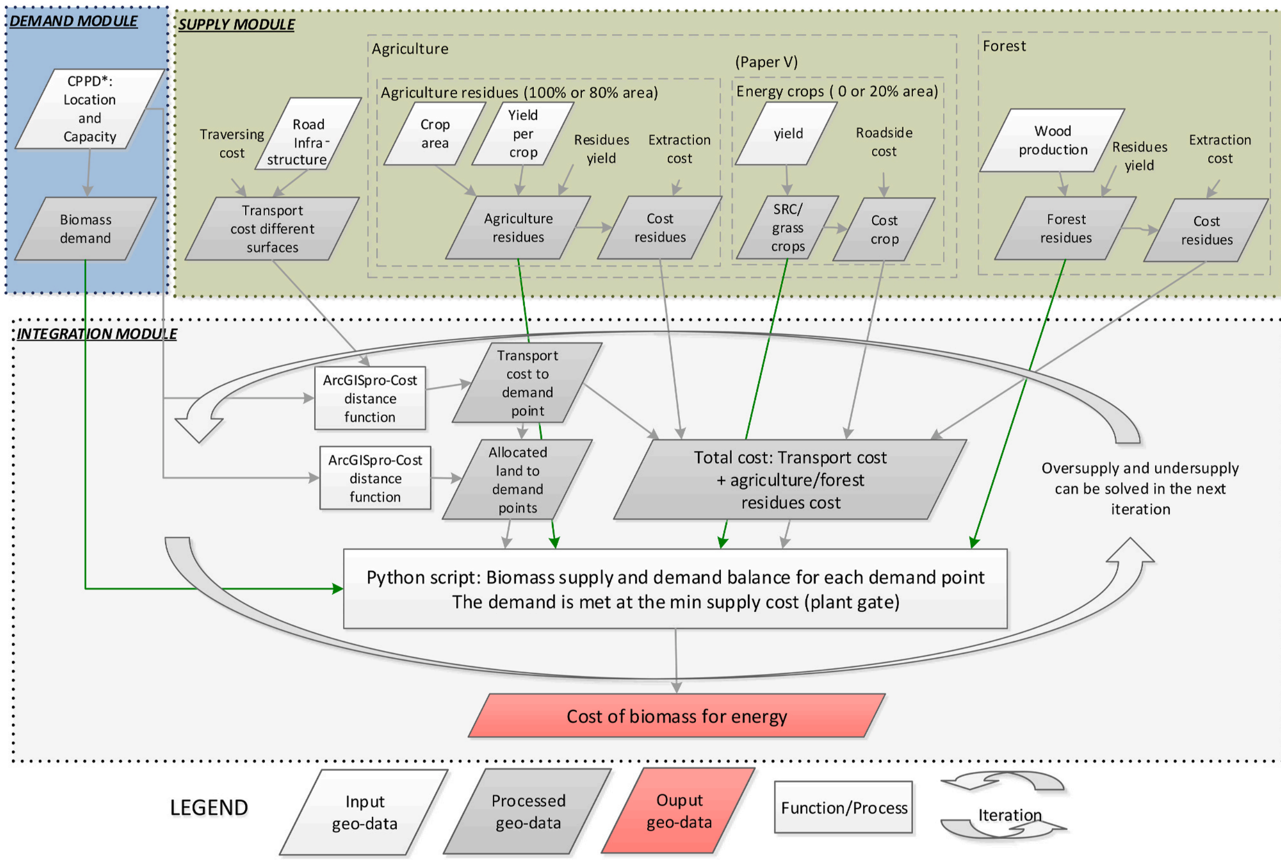

Fig. 1. Modeling framework updated from Cintas, Berndes [40] to include all existing coal power plants in the demand module and lignocellulosic energy crops in the supply module.

These plants mainly use other types of domestic and imported biomass fuels, such as pellets, demolition wood and organic consumer waste [62], but represent a potential source of competing biomass demand.

The biomass demand of each boiler is estimated based on: (1) the installed coal power capacity (as per the CPPD); (2) load factors, based on the national electricity generation by fuel [63] and the national installed capacity (CPPD) (see Supplementary Information, SI); and (3) the electrical efficiency (extracted from the CPPD when available, otherwise calculated based on Hansson, Berndes [42] and the age of the boilers). The efficiency of the biomass-fired power plants is assumed to be the same as reported for the current coal power plants, assuming that new state-of-the-art biomass plants reach similar efficiencies as older coal power plants. Emission factors are set to 0.0959 tCO_2/GJ and 0.101 tCO_2/GJ for hard coal and lignite, respectively, based on IPCC [64]. Due to boiler specific requirements, only woody biomass (forest residues and short rotation coppice, SRC) is assumed to be suitable for combustion in biomass-dedicated plants (since its relatively low alkali content makes it less likely to cause corrosion problems). Some of the existing coal plants used in the analysis are combined heat and power (CHP) plants, but heat production is not considered since the modelling concerns electricity output.

In Scenario 2, existing refineries with hydrocrackers (according to Johansson, Rootzén [60] and representing about 37% of the total capacity) are assumed to shift from petroleum to bio-based oil, which is produced in pyrolysis units built on current coal power plant sites. All coal power plants available in the CPPD are assumed to represent suitable sites for bio-oil production (Fig. 2b). The capacity of each pyrolysis unit is set to 100 MW bio-oil, corresponding to the planned size of the so-called GoBiGas phase two project (100 MW bio-methane) [65]. A fast pyrolysis process that can reach a conversion efficiency of 65% is assumed (see Mohan, Pittman [66] and Rogers and Brammer [67], reporting efficiencies of 50–75%). Some of the by-products, i.e., char and pyrolysis gases, are burnt to provide heat for the pyrolysis process with some excess available for sale [67]; however, for simplicity, the latter is assumed to be negligible and not included in the assessment. The bio-oil produced is assumed to replace crude oil in the closest refinery. The emission factor for crude oil is set to 0.0733 tCO_2/GJ, based on IPCC [64]. All types of biomass are assumed to be suitable for pyrolysis. Scenarios for SRC and for grass biomass are modeled separately.

2.1.2. Biomass supply module

In this study, the biomass supply includes: agricultural residues (residues from wheat, rye, barley, maize, sugar beets, rapeseed, and sunflower); forest residues (tops and branches from forest thinning and final felling); and lignocellulosic energy crops (short rotation coppice and grass crops).

The amounts of forest and agricultural residues available for energy after considering competing uses ("residue supply potential") are estimated along with the roadside supply cost, which includes the costs of extraction, collection, treatment, and transport to the roadside. The agricultural residue supply potential is estimated using crop-specific residue generation rates and geographically varying extraction rates, considering two alternative uses of the residues, namely, soil quality management and straw for bedding. For forest residues, a constant harvest rate (28%, based on de Jong, Akselsson [68]) is used for all countries due to the lack of consistent geographical data. This harvest rate reflects the share of stands in the landscape subject to residue harvest and the residue harvest rate in those stands. The roadside supply costs are calculated at the country level using country-specific factors based on labor costs and price indices. These costs include the cost of harvest, in-field transport, storage, and treatment. See Cintas, Berndes [40] for more information about the calculation of residue supply

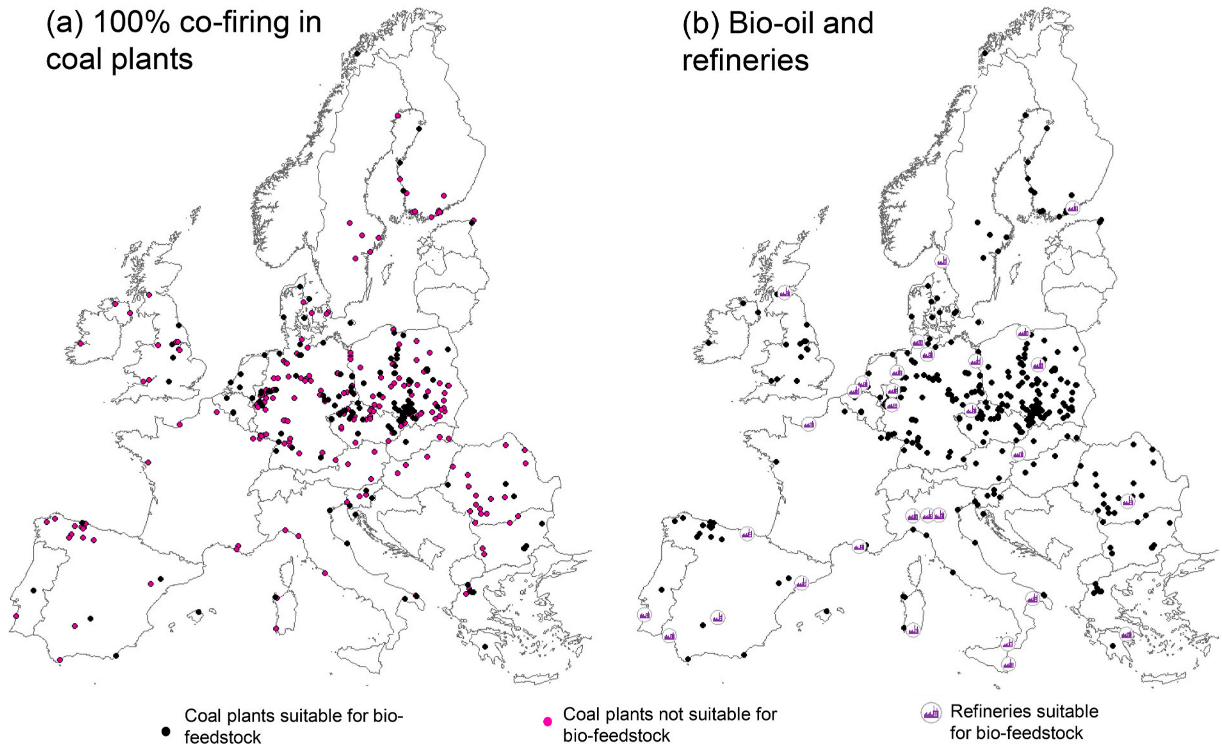

Fig. 2. Demand points corresponding to coal-fired power plants included in the Chalmers Power Plant Database for Europe (CPPD) and refineries with hydrocrackers, corresponding to type three and four in Johansson, Rootzén [60]. (a) Scenario 1: Black dots represent the plants identified in Cintas, Berndes [40] for which retrofitting for biomass co-firing was considered economically feasible (constructed after 1990 [42]) or those that have already been retrofitted for co-firing. Purple dots: Plants that are constructed before 1991 (i.e., assumed not to be available for retrofitting). (b) Scenario 2: black dots represent all the existing coal power plant sites that are assumed suitable for construction of bio-oil units to feed bio-refineries. Industrial icons represent refineries identified as suitable for bio-based feedstock. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

potentials and associated roadside costs.

Two different types of energy crops are considered: (i) a generic short rotation coppice (SRC) crop, based on willow and poplar data; and (ii) a generic grass crop, based on switchgrass and miscanthus data. Yield and roadside cost data correspond to a medium input management level; irrigation is only applied in the establishment phase for certain dedicated crops. The yield level is set to the lowest value of either the water-limited potential or 90% of the full potential [69]. It is assumed that energy crops can be established on up to 20% of agriculture area, corresponding to CORINE Land Cover 2012 classes "12: Non-irrigated arable land," "13: Permanently irrigated land," "19: Annual crops associated with permanent crops," "20: Complex cultivation patterns," and "21: Land principally occupied by agriculture with significant areas of natural vegetation." Total biomass supply from energy crops is calculated with Eq. (1) and the Raster calculator tool in ArcGIS Pro:

$$Biomass\ \ supply\left[\frac{GJ}{year}\right] = A[ha] \times 0.2 \times Cy\left[\frac{t}{ha}\right] \times LHV\left[\frac{GJ}{t}\right] \qquad \text{(Eq. 1)}$$

- *A*: Cropland area according to the CORINE Land Cover classification (defined above).
- 0.2: 20% of the total cropland area is assumed to be available for energy crops.
- *Cy*: Crop yields at the NUTS3 level [70]. Each generic crop yield is obtained by selecting the yield associated with the lowest roadside cost (i.e., willow/poplar and switchgrass/miscanthus). This is done with the Raster calculator. To create a raster, the table with data on crop yields is joined with the attribute table for the NUTS3 polygons [71] (using "Add join" with "NUTS ID" as the join field); thereafter, the "Feature to Raster" tool is used to create a raster map with the yield for each crop.
- *LHV*: Low heating values, dry basis, are assumed to be 17.5 MJ/kg for willow and poplar at 50% moisture [72] and 17.3 MJ/kg for switchgrass [73] and miscanthus [74] at 15% moisture.

Roadside cost for energy crops at the NUTS 3 level are obtained from Ramirez-Almeyda, Elbersen [69] assuming a plantation lifetime of 12 years for willow and poplar and 15 years for perennial grasses. Roadside costs include crop establishment, fertilizing, crop protection, harvesting/cutting, uprooting, baling, shredding, chipping, crushing, collecting, and/or densifying at the point of harvest, and in-field transport to the road side collection point. The cost of land is neglected as energy crops are assumed to be mostly grown on marginal land without alternative economic use [75]. The transport cost consists of variable costs (estimated as a function of the distance traveled) and fixed costs for loading and unloading. The variable transport costs for SRC biomass are set to be the same as for forest residues, i.e., 0.16 €/km Mg DM (this is set as the value for Sweden and is then adapted for each country), while the transport costs for grass crops are set to be the same as for agricultural residues, i.e., 25% higher than for forest residues. Only road transport (by truck) is considered as transport distances are considered too short for making rail and ship transport economically interesting, see Cintas, Berndes [40] for a detailed description of the transport cost calculations.

GHG emissions associated with the supply of energy crops are included. Conversion of cropland to perennial energy crops can increase carbon storage in soils, whereas conversion of pasture land can either decrease or increase soil carbon storage [76–79]. GHG emissions in the cultivation phase are mainly associated with the use of fertilizers [28]. The emission factor for energy crops is set to 0.5 tCO_2eq/ha, which corresponds to average numbers in Whitaker, Field [76] and is slightly above the recommendation for grass crops in JRC [80]. The emission factor is doubled in the sensitivity analysis.

2.1.3. Integration module

In the integration module, biomass demand and supply are matched in an iterative process that compares the biomass demand in a given power plant with the biomass supply within the area allocated to that plant. The comparison is made for one power plant at a time and is repeated for all power plants. If the demand cannot be met with the biomass within a plant's allocated area, unused biomass from other areas surrounding other plants can be drawn on in the next iteration. This process is iterated so long as there is unutilized biomass supply and there are power plants with unmet demand. The transport cost is optimized in each iteration, see Cintas, Berndes [40] for a description of the steps included in the demand-supply matching. The integration module is updated to source biomass within specified transport distances and prioritize the use of residues over cultivated bioenergy feedstock, which can be planted on 20% of any given cropland cell. Thus, energy crops are planted as a complement if residues do not suffice to meet the demand within the set maximum transport distance. In this study, the maximum transport distances were set to 100, 200, and 300 km. Nivala, Anttila [54] used 200 km as the maximum distance from which biomass could be supplied at a reasonable cost, based on practical experience in Finland. The limit on transport distance reflects both transport cost constraints and possible competing biomass uses in the surrounding area.

2.2. Mitigation of current negative land-use impacts

We investigate the prospects for mitigating selected environmental impacts by introducing perennial lignocellulosic bioenergy plantations in agricultural landscapes. Where energy crops are needed to complement residues to meet the demand for biomass, the cropland location, as determined by the biomass demand-supply matching, is combined with GIS-based mapping of (i) the share of the vegetated area in the landscape that is used for cultivation of annual crops (annual crop density); and (ii) the severity of current environmental impacts associated with the cultivation of annual crops. The data on annual crop density is combined with environmental impact indicators to produce four levels of expected effectiveness in mitigating the negative environmental impacts of introducing perennial lignocellulosic bioenergy plantations, thus taking into account both the degree of environmental impacts and the density of annual crops. The following impact categories are considered: (i) soil loss due to water and wind erosion; (ii) diffuse nitrogen emissions to water; (iii) declining soil organic matter (soil organic carbon, SOC, status); and (iv) impacts associated with recurring floods, see Englund, Börjesson [81].

3. Results

3.1. Scenario 1: all existing coal-fired power plants suitable for biomass co-firing use 100% biomass

All power plants suitable for biomass co-firing with coal are converted to use only biomass, producing 241 TW h bio-electricity and using about 2133 PJ biomass. Germany is the largest producer of bio-electricity (107 TW h), followed by Poland (45 TW h). CO_2 emissions in the electricity sector are reduced by 211 Mt CO_2, a figure that takes into account agricultural emissions associated with growing energy crops (contributing to reduce total emissions savings by roughly 4%).

At the EU28+ level, forest residues and SRC biomass sourced within a distance of 100 km, 200 km, and 300 km, can meet 22%, 50%, and 64% of the total biomass demand, respectively, see Fig. 3, which shows the outcome of the demand-supply matching in Scenario 1 for the countries with demand for biomass for bio-electricity. All but six countries can meet the biomass demand when the maximum transport distance is set to 200 km. Norway cannot meet the demand, Poland can meet 84% of the demand, Germany 22%, the Netherlands 25%, Spain 53%, and Italy 25%. When the maximum transport distance is increased to 300 km, Poland can meet its full demand. Spain, Italy, and Norway cannot meet the demand at this transport distance because resources are relatively small and scattered. Germany and the Netherlands have large coal power plants, which means that biomass demand is concentrated within small areas and cannot fully be met within a 300-km transport distance (long-distance imports are considered in the Discussion).

In the three transport distance limit cases, residues and SRC biomass are provided from 20, 48.5, and 60.5 Mha (for a limit of 100 km, 200 km, and 300 km, respectively). In each case, residues are collected on about 90% of the area, while SRC cultivation occurs on the remaining 10%. Fig. 4 shows the distribution of forest residue collection and SRC biomass cultivation to meet the biomass demand in Scenario 1. Note that in this figure, the cells highlighted as subject to SRC cultivation only have 20% of their area cultivated with SRC. Fig. 5 shows the amount of land subject to residue extraction or SRC cultivation in each country.

Countries with relatively low biomass demand for biomass co-firing (Finland, Estonia, Romania, and Slovakia) can meet all, or almost all, the demand with forest residues. The remaining countries need to use both forest residues and SRC biomass. Germany and Poland have the largest areas subject to residue harvest or SRC cultivation: 10–17% of the

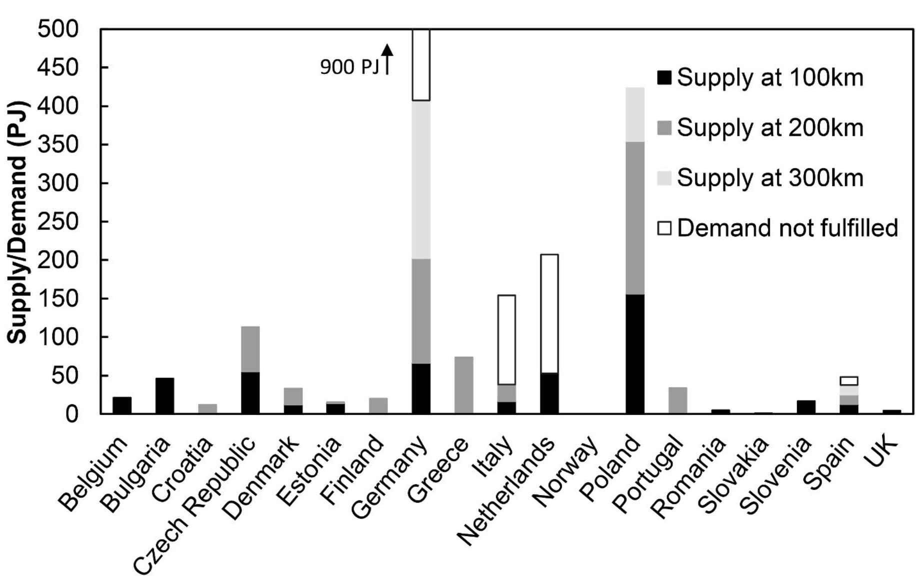

Fig. 3. Scenario 1 results: Biomass demand that can be met when sourcing biomass over transport distances less than 100 km, 200 km, and 300 km. The unshaded segments represent demand that cannot be met with supply sourced from within a 300 km distance. Note that, although it is not visible, the demand is not met in Norway (0.4 PJ), but it is met in Slovakia (0.9 PJ). Only countries with coal power plants suitable for conversion are included, i.e., power plants that already use biomass are not considered.

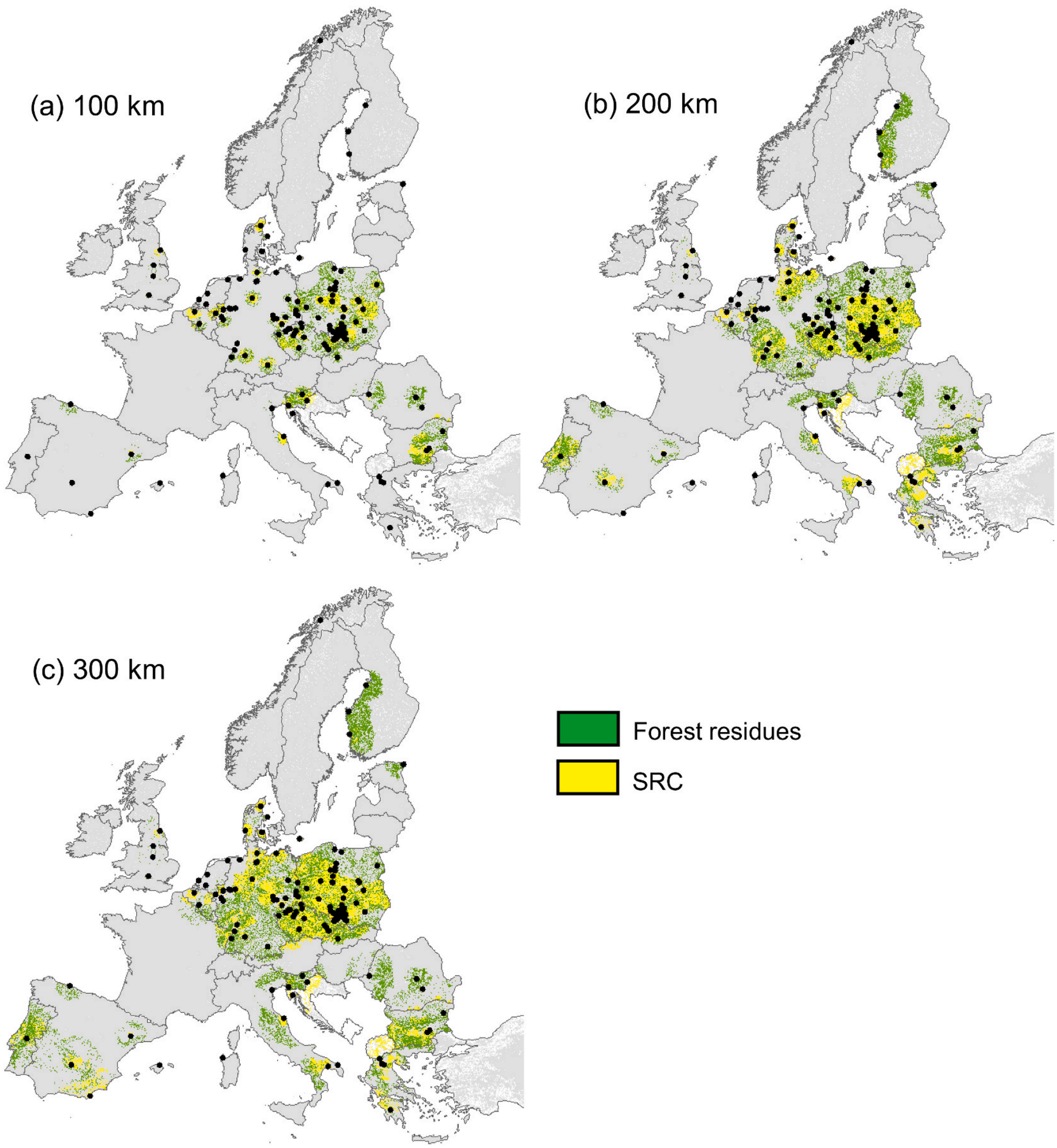

Fig. 4. Feedstock used to meet the demand for Scenario 1 with transport distance limited to 100 km, 200 km, and 300 km. Note that the cells highlighted as subject to SRC cultivation only have 20% of their area cultivated with SRC.

affected area is used for SRC cultivation (1.9–2.1 Mha). Denmark, the Netherlands (in all three distance cases), Greece and Croatia (only in the 200 km and 300 km cases) need to cultivate SRC on more than 25% of the affected area. In the 300 km case, the largest SRC cultivation areas (besides Poland and Germany) are found in Greece, Czechia, Bulgaria, Italy, and Spain (0.2–0.5 Mha).

SRC plantations have the potential to mitigate specific environmental impacts of current cropland use. Fig. 6 gives an indication of how effective that mitigation could be for selected impacts (with max. transport distance set to 300 km). For soil erosion, the estimated effectiveness ranges from low to medium in Germany, Poland (medium in the south of both countries where SRC can be introduced in areas having higher risks of water erosion), Greece, Spain, Bulgaria, and Czechia. The effectiveness is estimated to be medium to high for a significant part of the SRC-planted areas in Denmark (in areas subject to higher risk of wind erosion) and Italy (areas with higher risk of water erosion). For diffuse nitrogen emissions due to agriculture, the mitigation effectiveness of SRC plantations is estimated to range from high and very high in Denmark and the UK; low to medium in Germany and half of the SRC area in Poland and Czechia; marginal to low in Bulgaria; and marginal in Spain, Greece, Portugal, and Finland. Concerning SOC, the expected effectiveness in improving SOC status is high in Poland, Denmark, Czechia, Bulgaria, and Germany (on more than half of the land), and low to high in Greece and Spain. Finally, the expected effectiveness of mitigating flooding ranges from low to high to low for more than half of the SRC area in Germany, Poland, Belgium, and Bulgaria, while it is low in Denmark and marginal in Spain, Portugal, and Greece.

The costs of biomass for bio-electricity for the given transport distance limits are shown in Fig. 7. When the transport distance is limited to at most 100 km, 68% of the demand that can be met (i.e., of the 22%, see section above) can be supplied at costs below 3 €/GJ, an additional 19% can be supplied, for a combined 87%, at costs below 4 €/GJ, and another 13%, for a total of 100%, at costs below 10 €/GJ. For a limit of 200 km, 60%, 75%, and 100% of the demand that can be met can be supplied at costs below 3, 4, and 10 €/GJ, respectively. For 300 km, the corresponding numbers are 52%, 74%, and 100%. Countries that could meet their biomass demands at rather low costs are Poland, Czechia, Romania, and Slovakia. Higher costs are associated with a larger need for SRC as a complement to forest residues in countries with high labor costs and price index, i.e., Denmark, Germany, the Netherlands, and the

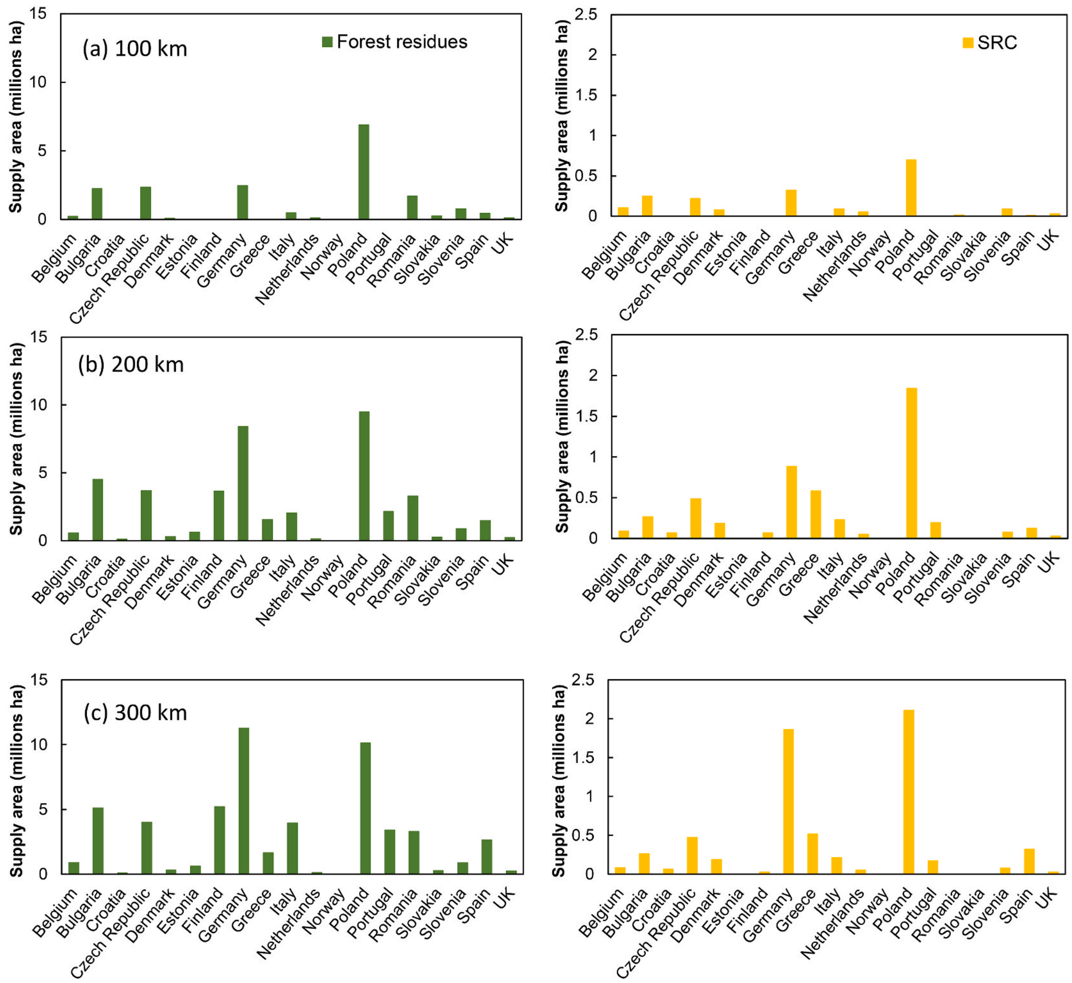

Fig. 5. Scenario 1 results: Land area subject to forest residue harvest (left) and SRC cultivation (right) at the country level.

Mediterranean countries, Italy, Greece, and Spain. In Finland and Germany, high costs are partially a result of forest residues being transported over long distances (300 km).

3.2. Scenario 2: bio-oil and refineries

Bio-oil plants (each 100 MW) are built on all the existing coal power plant sites, producing 970 PJ of bio-oil and using about 1493 PJ biomass. The largest bio-oil producers are naturally the countries with the most coal power plants, i.e., Poland (97 units), Germany (93), Czechia (43), Spain (20), Romania (17), Italy (15), and the UK (14). The total reduction in CO_2 emissions from displacing crude oil with bio-oil amounts to about 70 Mt CO_2. Emissions associated with the cultivation of energy crops reduce these CO_2 emission savings by about four percent.

About 63%, 77%, and 84% of the biomass demand can be met within biomass transport distances of 100 km, 200 km and 300 km, respectively, see Fig. 8, which shows the outcome of the demand-supply matching in Scenario 2. If grass crops are used instead of SRC, less demand can be met due to lower yields and higher transportation costs. In general, countries with greater demand for biomass for bio-oil production have higher residue supply potentials. France is an exception, with the largest residue supply potential but with only three coal power plant sites to convert to bio-oil production.

Fig. 9 shows where residues are collected and SRC biomass cultivated to meet the biomass demand in Scenario 2 (for grass crops, see SI). Again, the cells highlighted as subject to SRC cultivation have a maximum of 20% of their area cultivated with SRC. Fig. 10 shows the areas that are subject to residue extraction and/or SRC cultivation in each country. The use of agricultural residues is prioritized over energy crops; due to larger residue availability, the total area planted with energy crops is lower in Scenario 2 than in Scenario 1. In total, about 66, 107, and 134 Mha are subject to residue extraction or energy crop production in the three transport distance cases, respectively (to meet roughly 63%, 77%, and 84% of the total demand). The total area required for energy crop cultivation is rather similar (1.8 Mha) for the different transport distances, so the share of area with energy crops is smaller when biomass is transported over longer distances. The relative need to establish energy crops decreases as residues are allowed to be sourced from longer distances. With the 300 km supply distance, Poland, Germany, Spain, Czechia, and Italy have a substantial area planted with energy crops (0.2–0.7 Mha). The area required for energy crops, besides being quite constant, is located very consistently throughout the three transport distance cases (see orange and yellow areas in Fig. 9).

Fig. 11 shows the expected effectiveness of SRC in mitigating the selected environmental problems in Scenario 2, assuming a maximum transport distance of 300 km. The expected mitigation of soil erosion ranges from low to medium in Germany and Poland (medium in the middle and south of both countries, as energy crops are introduced on land with medium risk of erosion by water); while it can have a low to high effect in a significant part of the area in Spain, Italy, and Czechia (on land subject to water erosion problems). The expected mitigation of diffuse nitrogen loads from agricultural activity could range from low to high in Germany and Czechia; marginal to low in Poland and Spain; and fairly marginal in Italy. For improving soil organic carbon (SOC), the expected effectiveness is high in Poland, Spain, and Italy (more than half

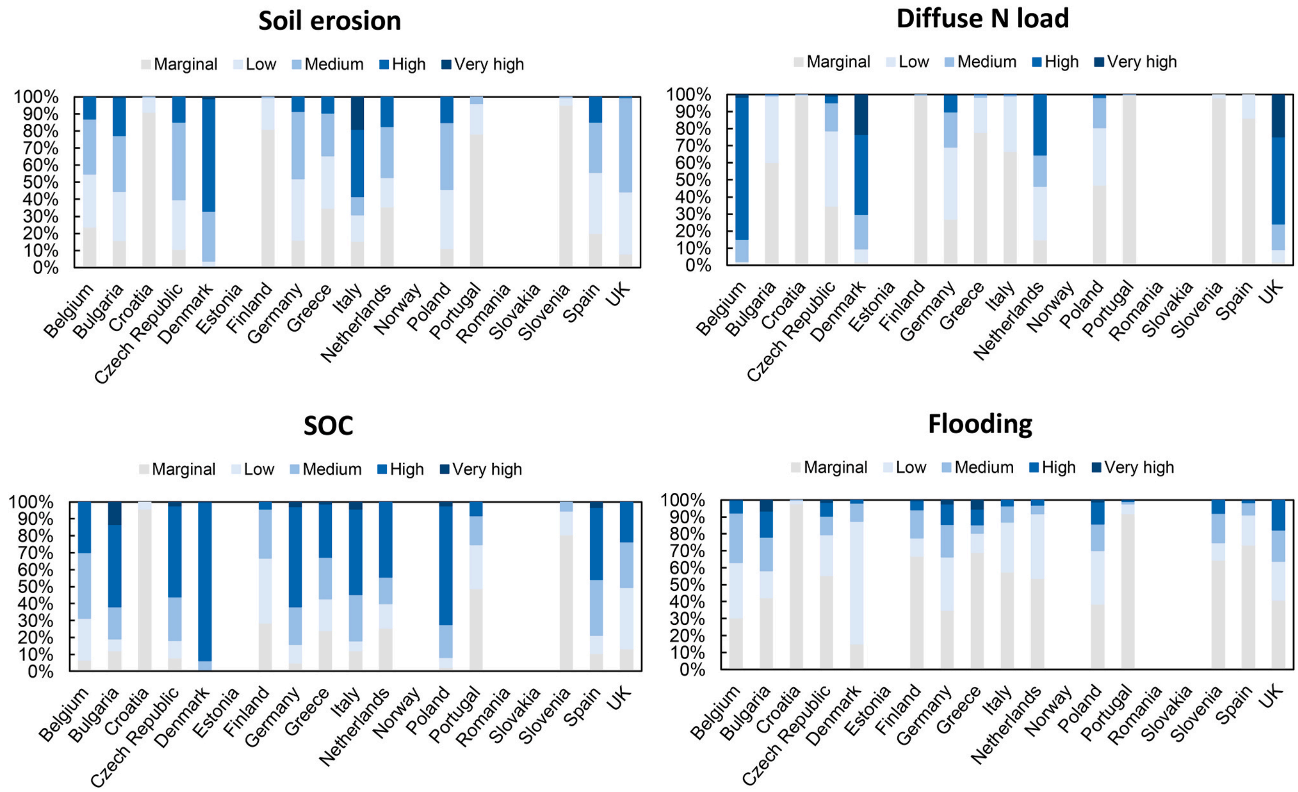

Fig. 6. Indication of effectiveness in mitigating selected environmental impacts in the case that allows SRC to be sourced up to 300 km from the point of biomass demand (Scenario 1).

the land); and from low to high in Germany and Czechia. The expected effectiveness in mitigating flooding in Germany, Poland, Spain, and Czechia ranges from low to high in more than half the area used for energy crops, while in Italy it is rather marginal.

Fig. 12 illustrates the cost of biomass for bio-oil for the assumed transport distances. In general, SRC crops are associated with lower costs than grass crops (see the corresponding figures for grass crops in the SI). For the 100 km transport limit case, 76% of the demand that can be met (i.e., of the 63%, see section above) can be supplied at costs below 3 €/GJ, 86% at costs below 4 €/GJ, and 100% at costs below 10 €/GJ. In the 200 km case, 67%, 89%, and 100% of the demand that can be met can be supplied at costs below 3, 4, and 10 €/GJ, respectively. For 300 km, the corresponding numbers are 59%, 86%, and 100%. Countries that could meet their demand at rather low costs are Poland, Romania, and Slovakia; Czechia could meet a major part. In contrast, Germany, the Netherlands, Italy, Greece, Spain, Croatia, and France are associated with higher costs due to the introduction of energy crops. High costs in Germany, Denmark, the UK, Finland, and Sweden are also associated with residues transported over long distances, i.e., 300 km.

3.3. Sensitivity analysis of biomass supply potential and land availability for energy crops

Fig. 13 shows the sensitivity of the results to assumptions on (i) biomass quality requirement (whether both forest and agricultural residues are permitted, which is only relevant for Scenario 1); (ii) energy crop yields; (iii) availability of pasture land for energy crops; and (iv) capacity of pyrolysis units (50 MW bio-oil and 200 MW bio-oil, in Scenario 2). In general, results for Scenario 1 are more sensitive to assumptions that affect the potential supply from energy crops, i.e., yields and availability of pasture land. SRC is more important in this scenario since agricultural residues cannot be used. If agricultural residues are not prioritized in Scenario 2, cropland cells are set to use 80% of the area for food crops and 20% for energy crops. Without this constraint, bio-oil production is slightly higher, and less area is subject to biomass mobilization since energy crops provide more biomass per unit land than agricultural residues do.

Scenario 2 results are obviously sensitive to the size of the assumed pyrolysis units. If capacity is reduced by 50% (50 MW bio-oil), production of biofuels is reduced by 40%. More units could have their demand met (327 out of 385 units), but supply is still limiting where units are rather close to each other (Poland, Germany, and Spain). If the capacity is instead doubled (200 MW bio-oil), the bio-oil production also doubles, but unmet demand becomes more common (Poland, Germany, Czechia, and Spain). If there is no restriction on bio-oil capacity or transport distance, about 4.9 EJ bio-oil is produced using 5.1 EJ of biomass from energy crops grown on 20% of total cropland and 2.4 EJ of residues [40]. An additional 1 EJ of bio-oil could be produced if 20% of pasture land were also available.

Results in Scenario 1 are also sensitive to the assumed biomass quality requirements (possibility to use both agricultural and forest residues). If boilers can use agricultural residues, and their use is prioritized over energy crops, slightly less of the demand will be met (due to the lower biomass supply per unit land), and the area used for energy crops will be reduced by more than 50%.

When the assumed GHG emission factors associated with cultivating energy crops (see *Biomass supply module*) are doubled, the total emission savings in Scenarios 1 and 2 are reduced by 6% and 4%, respectively.

4. Discussion

The total biomass supply considered in this study amounts to 7.5 EJ (primary energy), which—given the adopted conversion efficiencies—corresponds to about 25% of EU electricity generation (in 2018 [82]) or 15% of the crude oil used in EU refineries (in 2018 [83]), and could roughly support biofuel production equivalent to 28% of road transport fuels use in the EU [84].

Bentsen and Felby [85] reviewed studies of European bioenergy

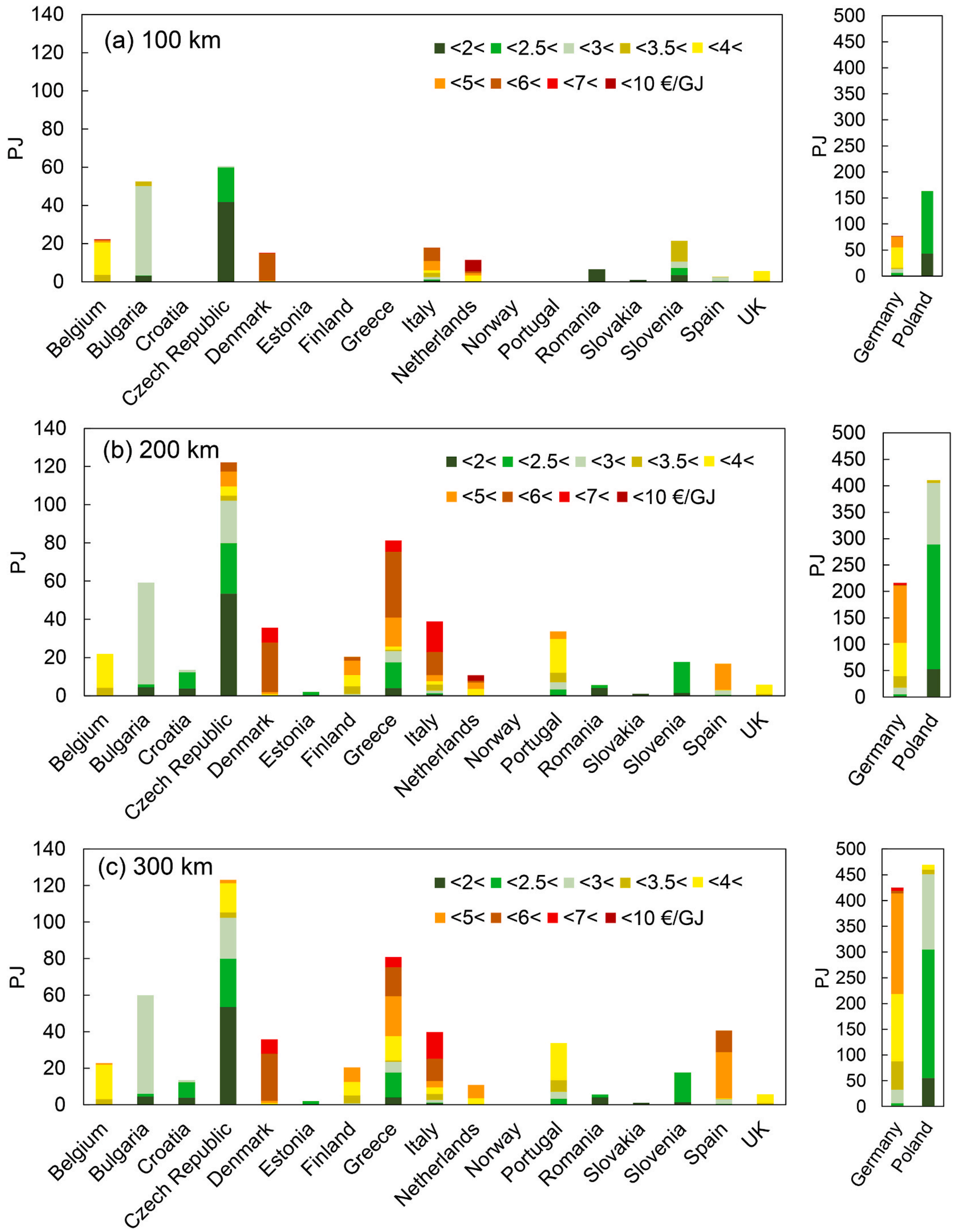

Fig. 7. Biomass supply for bio-electricity at different cost intervals (€/GJ) in Scenario 1.

resources and found significant variations due to differences in both methodology and parameter assumptions. Yet, the supply potentials used in our modeling are within the range found in Bentsen and Felby [85] (e.g., results for 2030: 4.3–6.0 EJ/yr energy crops, 0.9–3.1 EJ/yr agriculture residues, 0.8–6.0 EJ/yr forest biomass). Among other studies focusing on energy crops, Schueler, Weddige [86] estimated that 1.6–3.9 EJ of biomass could be produced in 2030 using some 15–17 Mha of land. Fischer, Prieler [51] estimated that some 44–53 Mha of cropland and 19 Mha of pasture could be available for bioenergy feedstock production by 2030, mainly in Eastern Europe which has greater opportunities for productivity improvements that reduce the amount of land needed for food production. Whether and how farmers introduce bioenergy crops on their lands depend on many factors, including profitability, alternative land use, and tradition [87,88]. In this study, 20% of agriculture lands can be used for bioenergy crops, corresponding to a maximum area of 25 Mha for the EU28+. This area is below the average from Schueler, Weddige [86] and Fischer, Prieler [51].

Restrictions on the biomass transport distance and capacity of electricity/bio-oil plants limit access to biomass resources and consequently electricity/bio-oil production. When bio-oil is produced in 100 MW pyrolysis units using biomass sourced within a 300-km transport distance, the bio-oil output corresponds to about 7% of the crude oil use in suitable EU refineries (i.e., refineries equipped with hydrocrackers), and 17% of the total biomass resource would be used, including 1.8 Mha of energy crop cultivations. When the biomass power plants are assigned the same capacity as current coal power plants, the electricity output

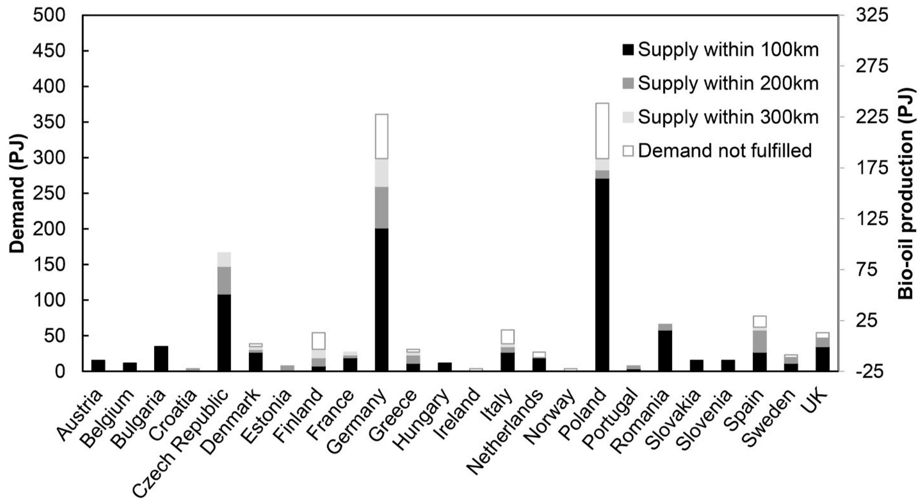

Fig. 8. Scenario 2 results: Biomass demand that can be met when sourcing biomass over transport distances less than 100 km, 200 km, and 300 km (left axis), and the corresponding bio-oil production (right axis). Only countries with coal power plants sites are included.

corresponds to about 4.5% of EU electricity generation (in 2018), and 18% of the total biomass resource would be used, including 6 Mha of energy crops.

Considering the part of the biomass demand that was met in the scenarios, more than 74% (electricity) and 86% (bio-oil) can be supplied at a gate-cost below 4 €/GJ biomass, which is in the lower end of the cost range for collectable residues reported by Brown et al. [44]. As a price comparison, the wood chip price[3] (district heating and industry) mostly stayed within the range 2.8–5.5 €/GJ in Sweden during the recent 20 years [89]. Chip price for district heating in Finland increased from about 4 €/GJ in 2008 to 5.5 €/GJ in 2013 and has varied between 5.5 and 6 €/GJ since then [90]. Biomass costs and market prices in different countries and for specific feedstocks are uncertain and volatile, and it is challenging to derive comparable data from the literature due to underdeveloped markets and lack of a uniform format for reporting prices [91]. Profitability for biomass producers will depend on many factors, including price and taxation of competing fuels, electricity prices, emission allowances, and other policy instruments, discussed further below.

Localization of power/bio-oil plants on additional sites (greenfield sites, forest industries, and other industrial sites) facilitates access to more biomass resources while keeping transport distances within set limits (see, e.g., Gonzales and Searcy [92] and de Jong, Hoefnagels [47]). Larger plant capacity would also make it possible to use a greater share of biomass resources, and other transportation modes would make biomass supply over longer distances economically viable, notably railway or shipping in addition to road transport [49,72,93–97]. Cintas, Berndes [40] showed that most coal power plants (hard coal) in the EU are relatively close to ports and use imported coal, which means that the long-distance supply infrastructure for solid fuels already exists. Bio-oil can also be imported using existing port infrastructure as the refineries already import crude oil. Thus, in many cases long-distance biomass imports can complement resources in the areas surrounding the plants.

The modeling in this work assumes that agricultural residues are prioritized over energy crops. In reality, land-use decisions will vary depending on preferences and local conditions. As noted, cultivating lignocellulosic crops can be a welcome opportunity for landowners who seek to make economic use of marginal lands and/or address land-use impacts such as soil erosion, soil compaction, salinization, sedimentation, and eutrophication of surface waters due to fertilizer runoff. Indications that lignocellulosic crops may affect selected environmental aspects warrant further analyses at higher resolution that consider additional aspects, including biodiversity effects. Such analyses can preferably adopt a more sophisticated approach to crop selection, which in this study was based only on economics. For instance, Ramirez-Almeyda, Elbersen [69] found grass crops to be cheaper than SRC when climate and soil conditions are considered. Grass crops are more drought tolerant than SRC, and switchgrass requires less water [69], making it a more likely candidate in Mediterranean countries.

The motivation behind the selected scenarios is to investigate options to displace fossil fuels and decrease CO_2 emissions while using the existing fossil infrastructure. The options can contribute towards EU and national renewable energy targets if they meet sustainability and GHG emission criteria in the RED II [2]. The generated bioelectricity counts as renewable according to the RED II, and can comply with the GHG criteria, as feedstock is sourced from less than 500 km and used in new state-of-the-art biomass plants reaching similar electric efficiencies as the former coal power plants (>36%) [40,42]. As noted, many of the power plants also produce heat which improves the total energy efficiency significantly. Biofuels derived from the produced bio-oil will be categorized as advanced biofuels, since produced from feedstock listed in Part A of Annex IX [2], and can therefore be counted towards the transport sub-target.

Residues in the forest and agriculture sectors are eligible feedstocks according to the RED II if not associated with unsustainable land use practices. The adopted extraction rates (see Section 2.1.2 *Biomass supply module*) reflect significant research as well as practical experiences in residue management aligned with sustainability requirements. Concerning lignocellulosic crops, the proposed targeting of marginal land reduces land competition with food and feed crops, which aligns with intentions in RED II as well as the Commission Delegated Regulation (EU) 2019/807 complementing the RED II. At the same time, RED II may complicate measures to reduce environmental impacts of current agriculture practices, if these involve some degree of displacement of annual food and feed crops with lignocellulosic crops providing feedstock for energy.

Bio-electricity already contributes significantly to the electricity supply in several EU nations (e.g., Germany, Finland, Sweden, and Austria), and it is incentivized in most of the EU via feed-in tariffs (a feed-in premium) or quota obligations [98]. Biofuels represent around 5.5% of the total fuel use for road transport in the EU [99], and the use is incentivized via national targets with quota obligations and often also with tax exemptions. Market and policy developments will determine whether existing coal power sites will be converted to support further

[3] Wood fuel and peat gate prices, excl taxes. Current prices in SEK, converted to € based on exchange rate 1€ = 10 SEK.

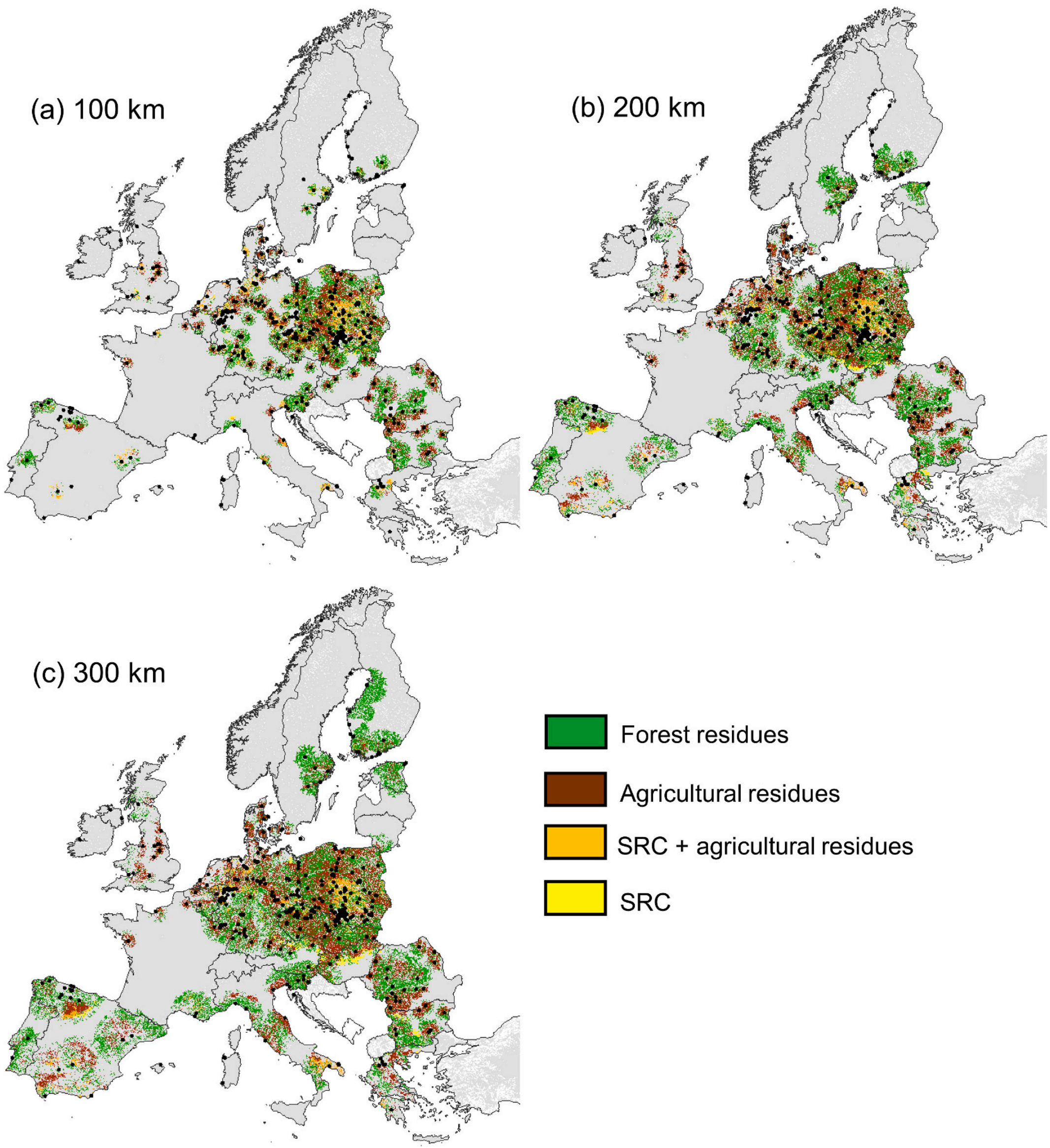

Fig. 9. Feedstock used to meet the demand in Scenario 2 with transport distance limited to 100 km, 200 km, and 300 km. Each cell representing cropland can provide both agricultural residues and energy crops (SRC or miscanthus/switchgrass) because we assume that energy crops can be established on 20% of a cropland cell. SRC is set to have the same transport cost as forest residues and can therefore be transported over longer distances than agricultural residues, which leads to SRC-only cells. In the case of grass crops (miscanthus/switchgrass), the transport cost is the same as for agricultural residues so there is no land providing only grass energy crops.

bioenergy growth. Beyond specific markets created by policies, the economic viability of bioenergy options will depend on the cost of fossil CO_2 emissions. Studies have shown that rising CO_2 prices can make it attractive to cultivate lignocellulosic crops for bioenergy, and scenarios that meet ambitious climate targets commonly include an order of magnitude more biomass from plantations than the current level [100]. The EU agriculture policy and rural development programs, as well as climate change and the shaping of adaptation measures, will have a large influence on how landowners and other actors view alternative land uses and risks associated with investments into biomass feedstock production [101–104].

Nevertheless, supply side limitations may necessitate prioritizing the use of biomass for energy [105]. Drawing conclusions about the best use of limited biomass resources is not within the scope of this study. Rather, the purpose is to understand how using biomass in the existing fossil infrastructure could transform the energy sectors. Analyses using techno-economic models provide important complementary information in this respect. One conclusion from such analyses is that liquid and gaseous biofuels may be needed (along with electrification and improvements in vehicle energy efficiency) to achieve rapid and deep reductions in the use of fossil fuels in the transport sector [106]. Moreover, biofuels are currently the only practical alternative to fossil fuels for aviation, marine shipping, and heavy freight transport. On the other hand, studies indicate that so-called “negative emissions” might be needed to reach the Paris Agreement aim to hold the increase in the global average temperature well below 2 °C above pre-industrial levels and pursue efforts to limit the temperature increase to 1.5 °C above pre-industrial levels. The use of biomass in applications that employ carbon capture and storage (BECCS) may thus be considered more desirable in the long term than the use of biomass in applications that are difficult to combine with CCS, such as biofuels for transport.

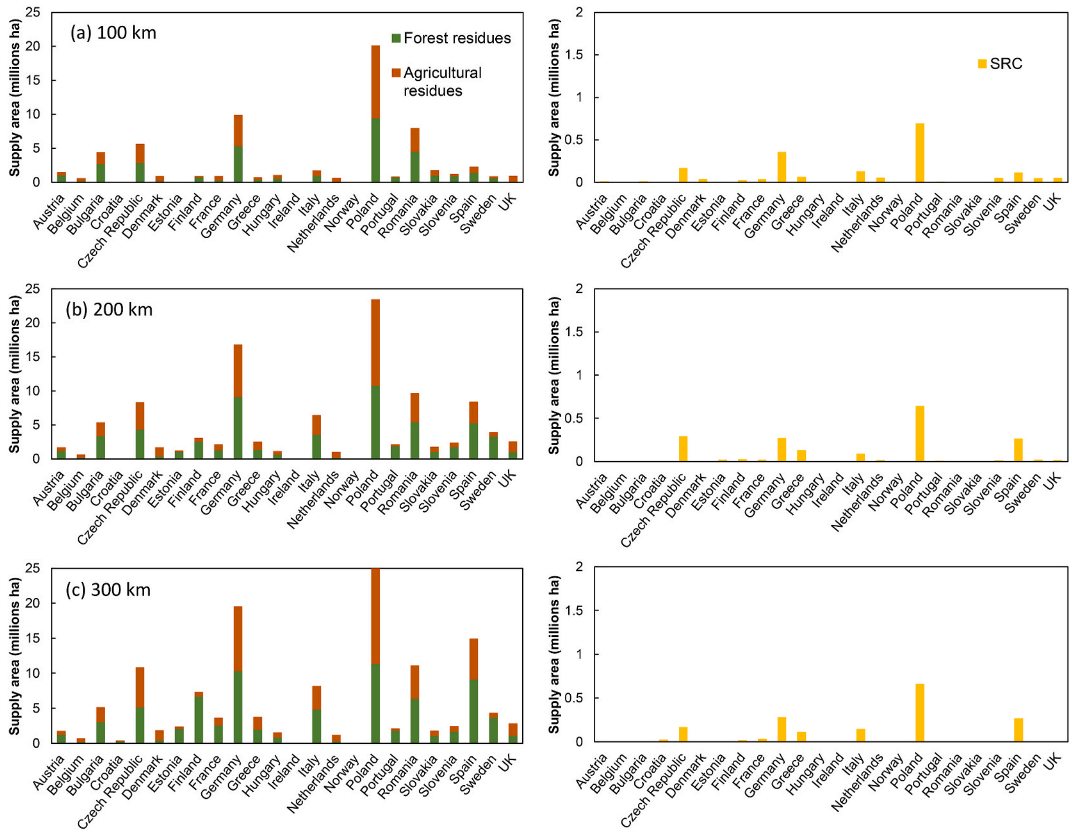

Fig. 10. Scenario 2 results: Land area subject to forest and agricultural residue harvest (left) and SRC cultivation (right) at the country level.

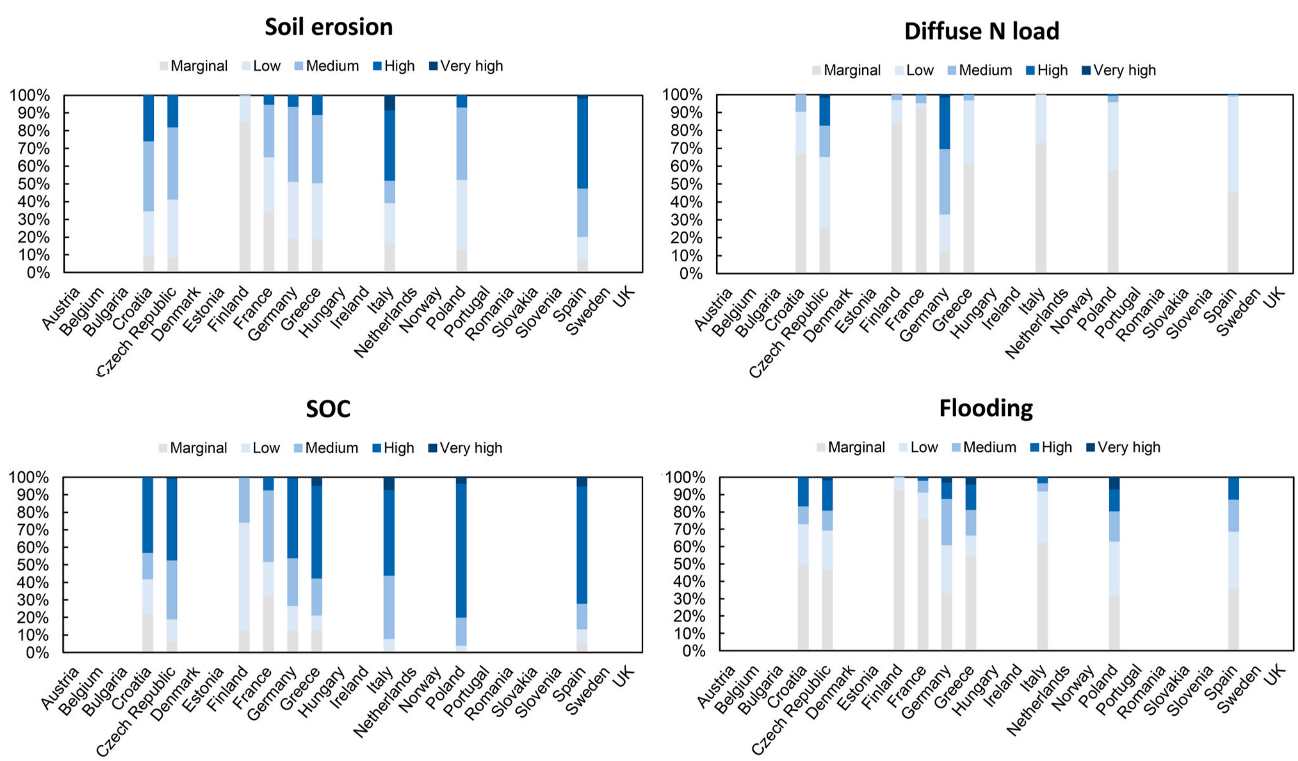

Fig. 11. Indication of effectiveness in mitigating selected environmental impacts in the case that allows SRC to be sourced up to 300 km from the point of biomass demand (Scenario 2).

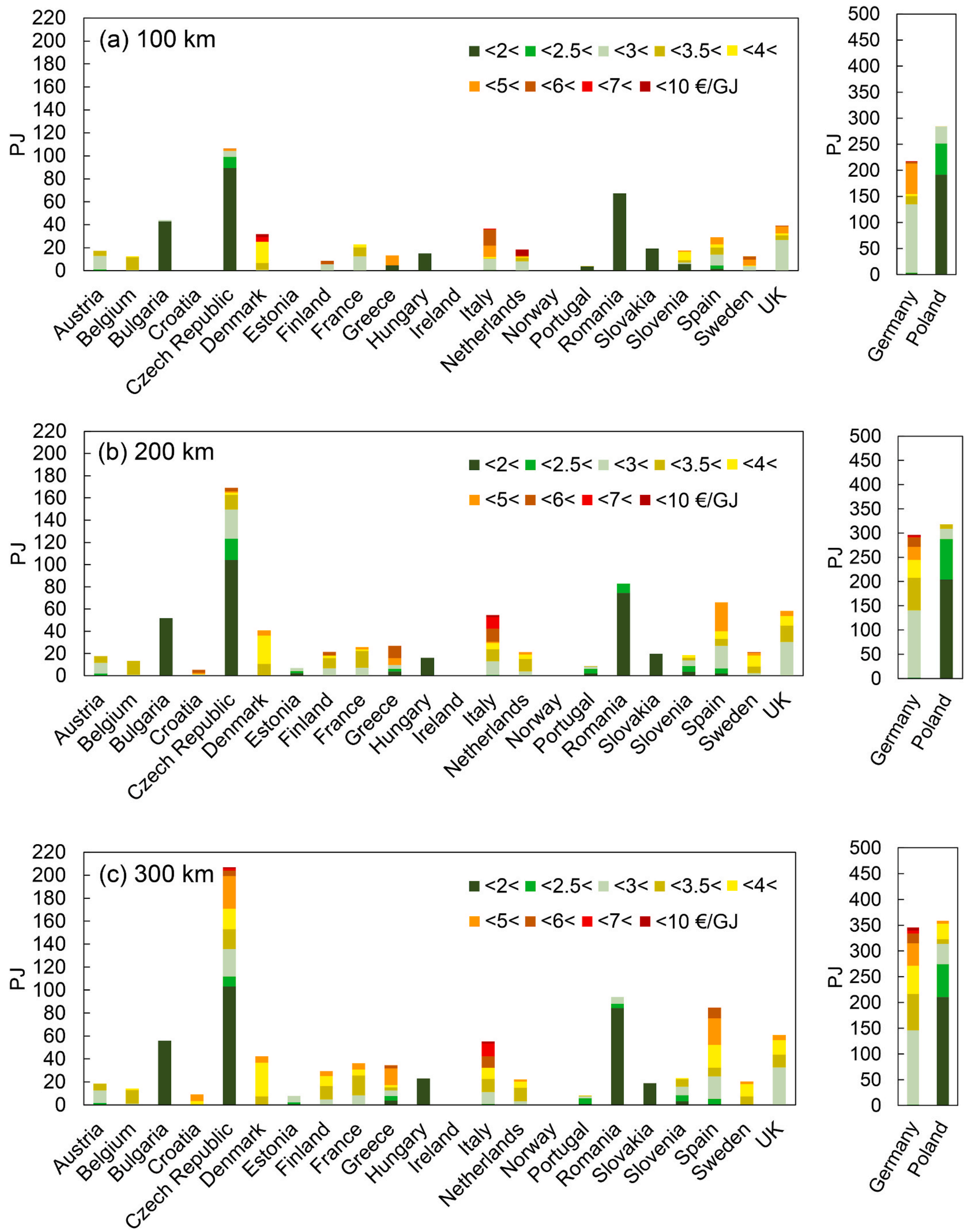

Fig. 12. Biomass supply for bio-oil production at different cost intervals (€/GJ) in Scenario 2.

5. Conclusions

We employ a GIS modeling framework to match biomass supply (residues and energy crops) with biomass demand for either electricity or bio-oil production on sites currently used for coal power.

Converting all suitable coal power plants to biomass energy plants would produce an estimated 50–150 TW h of biomass-derived electricity (1.5–4.5% of the electricity consumed in the EU28+), assuming unchanged capacity and conversion efficiency. Using all existing coal power sites for bio-oil production in 100 MW pyrolysis units could produce 610–820 PJ of bio-oil, corresponding to 5–7% of the crude oil use in EU refineries. Most of the coal power plants are located in Germany, Poland, and Czechia, which means that the biomass demand is concentrated in these countries.

A significant part of the biomass resources in the EU28+ was inaccessible in the modeling due to constraints on the sourcing distance. More of the domestic biomass resources can be made available if bioenergy plants are not confined to coal power sites. Long-distance imports of biomass (that meet the sustainability and GHG emissions criteria in RED II) can complement domestic biomass supply since many coal power plants and refineries already have an established infrastructure for long-distance sea transport.

The results of the demand-supply matching include residue harvest over extensive forest and agriculture areas. Governance will be important to prevent unsustainable extraction rates, especially close to those bioenergy plants where the willingness to pay for biomass is the greatest. Energy crop cultivation represents an important complement to residue harvest. Appropriate siting, design, and management of bioenergy

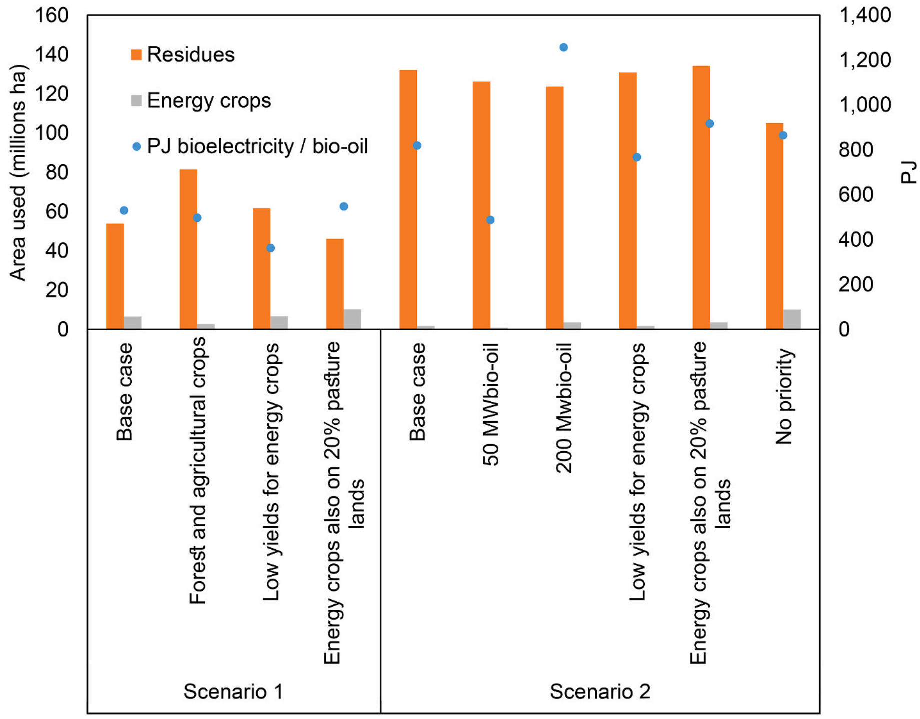

Fig. 13. Sensitivity analysis for the two scenarios investigated in this work.

plantations may help address environmental impacts associated with current agricultural practices.

The results of the analysis underline the relevance of a wide-ranging evaluation of bioenergy systems, considering both constraints and opportunities. In this study, effects on SOC status stood out, with indications of possible positive effects in most of the countries analyzed. In addition to improving soil productivity, carbon sequestration in soils would enhance the climate benefits of biomass displacing fossil fuels. Concerning soil erosion, flooding, and eutrophication, mitigation opportunities range from marginal to high depending on the location. In addition to more careful analyses of possible environmental effects, studies of the kind reported in Busch [107] can inform the development of stakeholder processes and land-use decisions balancing social, economic, and environmental aspects.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.biombioe.2020.105870.

References

[1] Ec, The Commission calls for a climate neutral Europe by 2050*, Press Release 28 November 2018, https://ec.europa.eu/commission/presscorner/detail/en/IP_18_6543. Accessed November 2019.
[2] Ec, Directive (EU) 2018/2001 of the European Parliament and of the Council of 11 December 2018 on the promotion of the use of energy from renewable sources (recast). https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32018L2001&from=EN. (Accessed 6 December 2019).
[3] Eurostat, Renewable Energy in the EU in 2018: Share of Renewable Energy in the EU up to 18.0%, 2020. Eurostat news release.
[4] Ec. European Commission's Knowledge Centre for Bioeconomy, Brief on biomass for energy in the European Union. https://publications.jrc.ec.europa.eu/repository/bitstream/JRC109354/biomass_4_energy_brief_online_1.pdf, 2019. (Accessed 6 December 2019).
[5] IPCC, in: P.R. Shukla, et al. (Eds.), Climate Change and Land. an IPCC Special Report on Climate Change, Desertification, Land Degradation, Sustainable Land Management, Food Security, and Greenhouse Gas Fluxes in Terrestrial Ecosystems, 2019.
[6] C. Robledo-Abad, H.J. Althaus, G. Berndes, S. Bolwig, E. Corbera, F. Creutzig, et al., Bioenergy production and sustainable development: science base for policymaking remains limited, GCB Bioenergy 9 (2017) 541–556, https://doi.org/10.1111/gcbb.12338.
[7] Y. Yamagata, N. Hanasaki, A. Ito, T. Kinoshita, D. Murakami, Q. Zhou, Estimating water–food–ecosystem trade-offs for the global negative emission scenario (IPCC-RCP2. 6), Sustainability Science 13 (2) (2018) 301–313.
[8] M.C. Rulli, D. Bellomi, A. Cazzoli, G. De Carolis, P. D'Odorico, The water-land-food nexus of first-generation biofuels, Sci. Rep. 6 (1) (2016) 1–10.
[9] C. Pahl-Wostl, Governance of the water-energy-food security nexus: a multi-level coordination challenge, Environ. Sci. Pol. 92 (2019) 356–367.
[10] R. Bailey, The "food versus fuel" nexus, The handbook of global energy policy 8 (2) (2013) 265–281.
[11] N. Condon, H. Klemick, A. Wolverton, Impacts of ethanol policy on corn prices: a review and meta-analysis of recent evidence, Food Pol. 51 (2015) 63–73.
[12] U.M. Persson, The impact of biofuel demand on agricultural commodity prices: a systematic review, Wiley Interdisciplinary Reviews: Energy Environ. 4 (5) (2015) 410–428.
[13] K.L. Kline, S. Msangi, V.H. Dale, J. Woods, G.M. Souza, P. Osseweijer, et al., Reconciling food security and bioenergy: priorities for action, GCB Bioenergy 9 (3) (2017) 557–576.
[14] F. Rosillo-Calle, A review of biomass energy–shortcomings and concerns, J. Chem. Technol. Biotechnol. 91 (7) (2016) 1933–1945.
[15] O. Englund, G. Berndes, The roles of public and private governance in promoting sustainable bioenergy, in: The Law and Policy of Biofuels, Edward Elgar Publishing, 2016.
[16] S.V. Hanssen, V. Daioglou, Z.J. Steinmann, S. Frank, A. Popp, et al., Biomass residues as twenty-first century bioenergy feedstock—a comparison of eight integrated assessment models, Climatic Change (2019) 1–18.
[17] V. Daioglou, J.C. Doelman, B. Wicke, A. Faaij, D.P. van Vuuren, Integrated assessment of biomass supply and demand in climate change mitigation scenarios, Global Environ. Change 54 (2019) 88–101.
[18] IPCC, in: V. Masson-Delmotte, P. Zhai, H.-O. Pörtner, D. Roberts, J. Skea, P. R. Shukla, et al. (Eds.), Global Warming of 1.5C. An IPCC Special Report on the Impacts of Global Warming of 1.5C above Pre-industrial Levels and Related Global Greenhouse Gas Emission Pathways in the Context of Strengthening the Global Response to the Threat of Climate Change, Sustainable Development, and Efforts to Eradicate Poverty, World Meteorological Organization, Geneva, Switzerland, 2018, p. 32.

[19] EC European Commission, EU climate action and the European Green Deal. https://ec.europa.eu/clima/policies/eu-climate-action_en, 2020. (Accessed 7 October 2020).
[20] P. Schröder, B. Beckers, S. Daniels, F. Gnädinger, E. Maestri, N. Marmiroli, et al., Intensify production, transform biomass to energy and novel goods and protect soils in Europe—a vision how to mobilize marginal lands, Sci. Total Environ. 616 (2018) 1101–1123.
[21] F. Pancaldi, L.M. Trindade, Marginal lands to grow novel bio-based crops: a plant breeding perspective, Front. Plant Sci. 11 (2020) 227.
[22] J.E. Campbell, D.B. Lobell, R.C. Genova, C.B. Field, The global potential of bioenergy on abandoned agriculture lands, Environ. Sci. Technol. 42 (15) (2008) 5791–5794.
[23] J. Dauber, M.B. Jones, J.C. Stout, The impact of biomass crop cultivation on temperate biodiversity, Gcb Bioenergy 2 (6) (2010) 289–309.
[24] X. Cai, X. Zhang, D. Wang, Land availability for biofuel production, Environ. Sci. Technol. 45 (1) (2011) 334–339.
[25] O. Englund, I. Dimitriou, V.H. Dale, K.L. Kline, B. Mola-Yudego, et al., Multifunctional perennial production systems for bioenergy: performance and progress, Wiley Interdisciplinary Reviews: Energy Environ. 9 (2020) e375.
[26] B.G. Peter, L.M. Mungai, J.P. Messina, S.S. Snapp, Nature-based agricultural solutions: scaling perennial grains across Africa, Environ. Res. 159 (2017) 283–290.
[27] B. Jankauskas, G. Jankauskiene, Erosion-preventive crop rotations for landscape ecological stability in upland regions of Lithuania, Agric. Ecosyst. Environ. 95 (1) (2003) 129–142.
[28] E.M.W. Smeets, I.M. Lewandowski, A.P.C. Faaij, The economical and environmental performance of miscanthus and switchgrass production and supply chains in a European setting, Renew. Sustain. Energy Rev. 13 (6) (2009) 1230–1245.
[29] G. Berndes, F. Fredrikson, P. Börjesson, Cadmium accumulation and Salix-based phytoextraction on arable land in Sweden, Agric. Ecosyst. Environ. 103 (1) (2004) 207–223.
[30] G. Berndes, P. Börjesson, M. Ostwald, M. Palm, Multifunctional biomass production systems–an overview with presentation of specific applications in India and Sweden, Biofuels, Bioproducts and Biorefining 2 (1) (2008) 16–25.
[31] P. Börjesson, G. Berndes, The prospects for willow plantations for wastewater treatment in Sweden, Biomass Bioenergy 30 (5) (2006) 428–438.
[32] W. Stephens, T.M. Hess, J.W. Knox, Review of the Effects of Energy Crops on Hydrology, 2001.
[33] I. Dimitriou, C. Baum, S. Baum, G. Busch, U. Schulz, J. Köhn, et al., The impact of short rotation coppice (SRC) cultivation on the environment, Landbauforschung–vTI Agriculture and Forestry Research 59 (3) (2009) 159–162.
[34] R. Holland, F. Eigenbrod, A. Muggeridge, G. Brown, D. Clarke, G. Taylor, A synthesis of the ecosystem services impact of second generation bioenergy crop production, Renew. Sustain. Energy Rev. 46 (2015) 30–40.
[35] P. Manning, G. Taylor, M. E Hanley, Bioenergy, food production and biodiversity–an unlikely alliance? Gcb Bioenergy 7 (4) (2015) 570–576.
[36] L.M. Verdade, C.I. Piña, L.M. Rosalino, Biofuels and biodiversity: challenges and opportunities, Environmental Development 15 (2015) 64–78.
[37] C. Emmerling, R. Pude, Introducing miscanthus to the greening measures of the EU common agricultural policy, Gcb Bioenergy 9 (2) (2017) 274–279.
[38] S. Baum, A. Bolte, M. Weih, Short rotation coppice (SRC) plantations provide additional habitats for vascular plant species in agricultural mosaic landscapes, BioEnergy Research 5 (3) (2012) 573–583.
[39] L. Cutz, G. Berndes, F. Johnsson, A techno-economic assessment of biomass co-firing in Czech Republic, France, Germany and Poland, Biofuels, Bioproducts and Biorefining 13 (5) (2019) 1289–1305.
[40] O. Cintas, G. Berndes, O. Englund, L. Cutz, F. Johnsson, Geospatial supply–demand modeling of biomass residues for co-firing in European coal power plants, GCB Bioenergy 10 (11) (2018) 786–803.
[41] G. Berndes, J. Hansson, A. Egeskog, F. Johnsson, Strategies for 2nd generation biofuels in EU – Co-firing to stimulate feedstock supply development and process integration to improve energy efficiency and economic competitiveness, Biomass Bioenergy, A roadmap for biofuels in Europe 34 (2010) 227–236, https://doi.org/10.1016/j.biombioe.2009.07.007.
[42] J. Hansson, G. Berndes, F. Johnsson, J. Kjärstad, Co-firing biomass with coal for electricity generation—an assessment of the potential in EU27, Energy Pol. 37 (4) (2009) 1444–1455.
[43] S. van Dyk, J. Su, J.D. Mcmillan, J. Saddler, Potential synergies of drop-in biofuel production with further co-processing at oil refineries, Biofuels, Bioproducts and Biorefining 13 (3) (2019) 760–775.
[44] A. Brown, L. Waldheim, I. Landälv, J. Saddler, M. Ebadian, et al., Advanced biofuels–potential for cost reduction, IEA Bioenergy, Report (2020). Task 41: 2020:01.
[45] A.P. Pinheiro Pires, J. Arauzo, I. Fonts, M.E. Domine, A. Fernández Arroyo, et al., Challenges and opportunities for bio-oil refining: a review, Energy Fuels 33 (6) (2019) 4683–4720.
[46] F. Monforti, E. Lugato, V. Motola, K. Bodis, N. Scarlat, J.-F. Dallemand, Optimal energy use of agricultural crop residues preserving soil organic carbon stocks in Europe, Renew. Sustain. Energy Rev. 44 (2015) 519–529.
[47] S. de Jong, R. Hoefnagels, E. Wetterlund, K. Pettersson, A. Faaij, M. Junginger, Cost optimization of biofuel production–The impact of scale, integration, transport and supply chain configurations, Appl. Energy 195 (2017) 1055–1070.
[48] F. Monforti, K. Bódis, N. Scarlat, J.-F. Dallemand, The possible contribution of agricultural crop residues to renewable energy targets in Europe: a spatially explicit study, Renew. Sustain. Energy Rev. 19 (2013) 666–677.
[49] R. Hoefnagels, G. Resch, M. Junginger, A. Faaij, International and domestic uses of solid biofuels under different renewable energy support scenarios in the European Union, Appl. Energy 131 (2014) 139–157.
[50] I. Kluts, B. Wicke, R. Leemans, A. Faaij, Sustainability constraints in determining European bioenergy potential: a review of existing studies and steps forward, Renew. Sustain. Energy Rev. 69 (2017) 719–734.
[51] G. Fischer, S. Prieler, H. van Velthuizen, G. Berndes, A. Faaij, M. Londo, et al., Biofuel production potentials in Europe: sustainable use of cultivated land and pastures, Part II: land use scenarios, Biomass Bioenergy 34 (2) (2010) 173–187.
[52] J. Hansson, G. Berndes, O. Englund, F.L. De Freitas, G. Sparovek, How is biodiversity protection influencing the potential for bioenergy feedstock production on grasslands? Gcb Bioenergy 11 (3) (2019) 517–538.
[53] D. Thrän, A. Cowie, G. Berndes (Eds.), Roles of Bioenergy in Energy System Pathways towards a "Well-Below-2-Degrees-Celsius (WB2)" World. Workshop Report and Synthesis of Presented Studies, IEA Bioenergy: ExCo, 2020. July 2020.
[54] M. Nivala, P. Anttila, J. Laitila, O. Salminen, M. Flyktman, A GIS-based methodology to estimate the regional balance of potential and demand of forest chips, J. Geogr. Inf. Syst. 8 (2016) 633, 05.
[55] F. Di Fulvio, N. Forsell, O. Lindroos, A. Korosuo, M. Gusti, Spatially explicit assessment of roundwood and logging residues availability and costs for the EU28, Scand. J. For. Res. 31 (7) (2016) 691–707.
[56] J. Kjärstad, F. Johnsson, The European power plant infrastructure—presentation of the Chalmers energy infrastructure database with applications, Energy Pol. 35 (7) (2007) 3643–3664.
[57] G. Berndes, S. Ahlgren, P. Börjesson, A.L. Cowie, Bioenergy and land use change—state of the art, Wiley Interdisciplinary Reviews: Energy Environ. 2 (3) (2013) 282–303.
[58] O. Cintas, G. Berndes, A.L. Cowie, G. Egnell, H. Holmström, G. Marland, et al., Carbon balances of bioenergy systems using biomass from forests managed with long rotations: bridging the gap between stand and landscape assessments, GCB Bioenergy 9 (7) (2017) 1238–1251.
[59] O. Cintas, G. Berndes, A.L. Cowie, G. Egnell, H. Holmström, G.I. Ågren, The climate effect of increased forest bioenergy use in Sweden: evaluation at different spatial and temporal scales. Wiley Interdisciplinary Reviews: Energy Environ. 5 (3) (2016) 351–369.
[60] D. Johansson, J. Rootzén, T. Berntsson, F. Johnsson, Assessment of strategies for CO2 abatement in the European petroleum refining industry, Energy 42 (1) (2012) 375–386.
[61] M.S. Roni, S. Chowdhury, S. Mamun, M. Marufuzzaman, W. Lein, S. Johnson, Biomass co-firing technology with policies, challenges, and opportunities: a global review, Renew. Sustain. Energy Rev. 78 (2017) 1089–1101.
[62] IEA Bioenergy, The Status of Large Scale Biomass Firing - the Milling and Combustion of Biomass Materials in Large Pulverised Coal Boilers, IEA Bioenergy: Task 32: Biomass Combustion and Cofiring, 2016.
[63] Eurostat, Eurostat: energy statistics, Accessed July 2017, https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Energy_statistics_introduced, 2016.
[64] IPCC, Refinement with the 2006 IPCC Guidelines. For National Greenhouse Gas Inventories: Volume 2: Energy, Chapter 2: Stationary Combustion, Intergovernmental Panel on Climate Change, 2019.
[65] A. Alamia, A. Larsson, C. Breitholtz, H. Thunman, Performance of large-scale biomass gasifiers in a biorefinery, a state-of-the-art reference, Int. J. Energy Res. 41 (14) (2017) 2001–2019.
[66] D. Mohan, C.U. Pittman, P.H. Steele, Pyrolysis of wood/biomass for bio-oil: a critical review, Energy Fuels 20 (3) (2006) 848–889.
[67] J. Rogers, J. Brammer, Estimation of the production cost of fast pyrolysis bio-oil, Biomass Bioenergy 36 (2012) 208–217.
[68] J. de Jong, C. Akselsson, G. Egnell, S. Löfgren, B.A. Olsson, Realizing the energy potential of forest biomass in Sweden–How much is environmentally sustainable? For. Ecol. Manag. 383 (2017) 3–16.
[69] J. Ramirez-Almeyda, B. Elbersen, A. Monti, I. Staritsky, C. Panoutsou, E. Alexopoulou, et al., Chapter 9: assessing the potentials for nonfood crops, in: C. Panoutsou (Ed.), Modeling and Optimization of Biomass Supply Chains. Centre for Environmental Policy, Imperial College London, Academic Press, London, United Kingdom, 2017.
[70] S2BIOM, 2017.
[71] Eurostat GISCO NUTS 2013 dataset, Accessed December 2016, https://ec.europa.eu/eurostat/web/gisco/geodata/reference-data/administrative-units-statistical-units/nuts, 2013.
[72] N. Krajnc, Wood Fuels Handbook, Food and Agriculture Organization for the United Nations, 2015.
[73] A. Monti, Switchgrass: A Valuable Biomass Crop for Energy, Springer Science & Business Media, 2012.
[74] N. Brosse, A. Dufour, X. Meng, Q. Sun, A. Ragauskas, Miscanthus: a fast-growing crop for biofuels and chemicals production, Biofuels, Bioproducts and Biorefining 6 (5) (2012) 580–598.
[75] M. Dees, B. Elbersen, J. Fitzgerald, M. Vis, P. Anttila, N. Forsell, et al., A Spatial Data Base on Sustainable Biomass Cost-Supply of Lignocellulosic Biomass in Europe-Methods & Data Sources, Institute of Forest Sciences, University of Freiburg, 2017, p. 174. Grant Agreement no 608622 Chair of Remote Sensing and Landscape Information Systems.
[76] J. Whitaker, J.L. Field, C.J. Bernacchi, C.E. Cerri, R. Ceulemans, C.A. Davies, et al., Consensus, uncertainties and challenges for perennial bioenergy crops and land use, GCB Bioenergy 10 (3) (2018) 150–164.
[77] Z. Qin, J.B. Dunn, H. Kwon, S. Mueller, M.M. Wander, Soil carbon sequestration and land use change associated with biofuel production: empirical evidence, Gcb Bioenergy 8 (1) (2016) 66–80.

[78] A. Nocentini, J. Field, A. Monti, K. Paustian, Biofuel production and soil GHG emissions after land-use change to switchgrass and giant reed in the US Southeast, Food and Energy Security 7 (1) (2018), e00125.
[79] Z.M. Harris, G. Alberti, M. Viger, J.R. Jenkins, R. Rowe, N.P. McNamara, et al., Land-use change to bioenergy: grassland to short rotation coppice willow has an improved carbon balance, Gcb Bioenergy 9 (2) (2017) 469–484.
[80] JRC, Assessing GHG Default Emissions from Biofuels in EU Legislation. JRC Scientific and Policy Reports, Ispra (Italia): European Comission, 2013.
[81] O. Englund, P. Börjesson, G. Berndes, N. Scarlat, J.-F. Dallemand, B. Grizzetti, I. Dimitriou, B. Mola, F. Fahl, Beneficial land use change: strategic expansion of new biomass plantations can reduce environmental impacts from EU agriculture, Global Environ. Change 60 (January 2020) 1011990, https://doi.org/10.1016/j.gloenvcha.2019.101990script.
[82] Eurostat, Eurostat: renewable energy statistics, SHARES summary results 2018, https://ec.europa.eu/eurostat/web/energy/data/shares, 2019. (Accessed 20 January 2020).
[83] E.C. European Commission, Oil refining. https://ec.europa.eu/energy/topics/oil-gas-and-coal/oil-refining_en, 2020. (Accessed 7 October 2020).
[84] Eurostat, Final energy consumption in road transport by type of fuel. https://ec.europa.eu/eurostat/web/products-datasets/-/ten00127, 2020. (Accessed 7 October 2020).
[85] N.S. Bentsen, C. Felby, Biomass for energy in the European Union-a review of bioenergy resource assessments, Biotechnol. Biofuels 5 (1) (2012) 25.
[86] V. Schueler, U. Weddige, T. Beringer, L. Gamba, P. Lamers, Global biomass potentials under sustainability restrictions defined by the European Renewable Energy Directive 2009/28/EC, Gcb Bioenergy 5 (6) (2013) 652–663.
[87] C. Parra-López, M. Holley, K. Lindegaard, S. Sayadi, G. Esteban-López, V. H. Durán-Zuazo, et al., Strengthening the development of the short-rotation plantations bioenergy sector: policy insights from six European countries, Renew. Energy 114 (2017) 781–793.
[88] I. Dimitriou, H. Rosenqvist, G. Berndes, Slow expansion and low yields of willow short rotation coppice in Sweden; implications for future strategies, Biomass Bioenergy 35 (11) (2011) 4613–4618.
[89] Swedish Energy Agency statistical database, Wood fuel- and peat prices. http://pxexternal.energimyndigheten.se/pxweb/en/Tr%c3%a4dbr%c3%a4nsle-%20och%20torvpriser/. (Accessed 25 October 2020).
[90] Statistics: Energy Prices [e-Publication], Statistics Finland, Helsinki, 2020. ISSN=1799-800X, http://www.stat.fi/til/ehi/tau_en.html. (Accessed 25 October 2020).
[91] C.P. Witzel, R. Finger, Economic evaluation of Miscanthus production–A review, Renew. Sustain. Energy Rev. 53 (2016) 681–696.
[92] D.S. Gonzales, S.W. Searcy, GIS-based allocation of herbaceous biomass in biorefineries and depots, Biomass Bioenergy 97 (2017) 1–10.
[93] C.N. Hamelinck, R.A. Suurs, A.P. Faaij, International bioenergy transport costs and energy balance, Biomass Bioenergy 29 (2) (2005) 114–134.
[94] O. Englund, G. Berndes, U.M. Persson, G. Sparovek, Oil palm for biodiesel in Brazil—risks and opportunities, Environ. Res. Lett. 10 (4) (2015), 044002.
[95] P. Lamers, R. Hoefnagels, M. Junginger, C. Hamelinck, A. Faaij, Global solid biomass trade for energy by 2020: an assessment of potential import streams and supply costs to North-West Europe under different sustainability constraints, GCB Bioenergy 7 (4) (2014) 618–634.
[96] V.H. Dale, K.L. Kline, E.S. Parish, A.L. Cowie, R. Emory, R.W. Malmsheimer, et al., Status and prospects for renewable energy using wood pellets from the southeastern United States, Gcb Bioenergy 9 (8) (2017) 1296–1305.
[97] D. Thraen, D. Peetz, K. Schaubach, S. Backéus, L. Benedetti, L. Bruce, Global Wood Pellet Industry and Trade Study 2017, IEA Bioenergy, Paris, France, 2017, p. 243.
[98] G. Erbach, Promotion of Renewable Energy Sources in the EU. EU Policies and Member State Approaches, 2016.
[99] Eurostat, Eurostat: energy balances. Complete energy balances. https://ec.europa.eu/eurostat/web/energy/data/database, 2020. (Accessed 20 January 2020).
[100] IPCC, Summary for policymakers, in: O. Edenhofer, R. Pichs-Madruga, Y. Sokona, E. Farahani, S. Kadner, K. Seyboth, A. Adler, I. Baum, S. Brunner, P. Eickemeier, B. Kriemann, J. Savolainen, S. Schlömer, C. von Stechow, T. Zwickel, J.C. Minx (Eds.), Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change, Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 2014.
[101] J. Hristov, A. Toreti, I. Pérez Domínguez, F. Dentener, T. Fellmann, C. Elleby, et al., Analysis of Climate Change Impacts on EU Agriculture by 2050, EUR 30078EN, Publications Office of the European Union, Luxembourg, 2020, ISBN 978-92-76-10617-3, https://doi.org/10.2760/121115. JRC119632.
[102] EC-DG Agriculture and Rural development, Modernising and Simplifying the CAP. Background Document, Economic Challenges Facing EU Agriculture, 2017.
[103] EC-DG Agriculture and Rural development, Modernising and Simplifying the CAP. Background Document, Climate and Environmental Challenges Facing EU Agriculture and Rural Areas, 2017.
[104] EC-DG Agriculture and Rural development, Modernising and Simplifying the CAP. Background Document, Socio-Economic Challenges Facing EU Agriculture and Rural Areas, 2017.
[105] N. Scarlat, J.-F. Dallemand, F. Monforti-Ferrario, M. Banja, V. Motola, Renewable energy policy framework and bioenergy contribution in the European union–an overview from national renewable energy action plans and progress reports, Renew. Sustain. Energy Rev. 51 (2015) 969–985.
[106] IEA, Energy Technology Perspectives 2017 - Catalysing Energy Technology Transformations, International Energy Agency, Paris, 2017, 6 June.
[107] G. Busch, A spatial explicit scenario method to support participative regional land-use decisions regarding economic and ecological options of short rotation coppice (SRC) for renewable energy production on arable land: case study application for the Göttingen district, Germany, Energy, Sustainability and Society 7 (1) (2017) 2.