

Sustainability constraints in determining European bioenergy potential: A review of existing studies and steps forward



Ingeborg Kluts^{a,b,*}, Birka Wicke^a, Rik Leemans^b, André Faaij^c

^a Copernicus Institute of Sustainable Development, Energy & Resources Group, P.O. Box 80.115, 3508 TC Utrecht, The Netherlands

^b Environmental Systems Analysis Group, Wageningen University, P.O. Box 47, 6700 AA Wageningen, The Netherlands

^c Energy and Sustainability Research Institute, University of Groningen, P.O. Box 72, 9700 AB Groningen, The Netherlands

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ABSTRACT

This paper reviews European land and bioenergy potential studies to 1) identify shortcomings related to how they account for agricultural intensification and its associated environmental effects, and sustainability constraints, and 2) provide suggestions on how these shortcomings can be improved in future assessments. The key shortcomings are:

The environmental impacts of intensification are nearly always ignored in the reviewed studies, while these impacts should be accounted for if intensification is required to make land available for energy cropping.

Future productivity developments of crops and livestock, and the associated land-use and environmental effects are currently limited to conventional intensification measures whereby the proportion between inputs and outputs is fixed. Sustainable intensification measures, which increase land productivity with similar or lower inputs, are ignored in the reviewed studies.

Livestock productivity developments, livestock specific intensification measures and their environmental effects are poorly or not at all covered in the reviewed studies.

Most studies neglect sustainability constraints other than GHG emissions in the selection of energy crops. This includes limitations to rainfed energy crop cultivation, a minimum number of crop species, the structural diversity within cropping areas and the integration of energy crops in existing or new crop rotations, while simultaneously considering the effects on subsequent crops.

These shortcomings suggest that the identification of sustainable pathways for European bioenergy production requires a more integrative approach combining land demand for food, feed and energy crop production, including different intensification pathways, and the consequent direct and indirect environmental impacts. A better inclusion of management practices into such approach will improve the assessment of intensification, its environmental consequences and the sustainable bioenergy potential from agricultural feedstocks.

1. Introduction

Land is a finite and increasingly scarce resource. Competition for land will increase to meet future food and fibre demand of a growing population [1,2]. The expected increase in the use of bioenergy as a renewable energy source requires an additional increase in total agricultural output and thereby further increasing the competition for land [1]. Producing additional agricultural output for bioenergy feedstock can be achieved by extending cropland and pastures into new areas, thereby replacing natural ecosystems (i.e. expansion), and/or by improving productivity of existing cultivated land through the increased or more efficient use of inputs, improvement of agronomic

practices and crop varieties and other innovations (i.e. intensification) [3,4]. Both options have positive and negative environmental effects. Several studies suggest that increasing productivity rather than clearing additional land is preferred to meet the expected increase in demand for agricultural products [3–7]. If intensification is needed to make land available for bioenergy feedstock production, its environmental effects should be accounted for when quantifying the sustainability of bioenergy [8]. The environmental effects of intensification depend on geographic conditions and on how agriculture is organised and managed. Sustainable intensification measures include precision agriculture, multiple cropping systems using crop rotations, intercropping or agroforestry systems, zero or reduced tillage systems and the

* Corresponding author at: Copernicus Institute of Sustainable Development, Energy & Resources Group, P.O. Box 80.115, 3508 TC Utrecht, The Netherlands.
E-mail addresses: ingeborgkluts@gmail.com (I. Kluts), b.wicke@uu.nl (B. Wicke), rik.leemans@wur.nl (R. Leemans), a.p.c.faaij@rug.nl (A. Faaij).

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Table 1
General characteristics of the studies included in the review ^a.

| Study label ^b | Main ref. | Objective of study | Spatial coverage ^c | Spatial resolution | Timeframe | Approach - methodology | Model(s) used | Biomass categories | | | Type of potential |
|--------------------------|-----------|---|-------------------------------|---|---------------------------------|--|---------------------------------------|---------------------|-----------------|-----------------------|--|
| | | | | | | | | Annual arable crops | Perennial crops | Agricultural residues | |
| Allen14 | [23] | Estimation of additional production of perennial energy crops within Europe. | EU-28 | EU-28 | Current (2000–2012) | Resource focused – statistical | n.a. | ✓ | | | Technical |
| Bentsen14 | [24] | Estimation of agricultural residues potentially available through agricultural intensification. | Global | World regions (North, South, West Europe ^d) | 2006–2008 | Resource focused – statistical | n.a. | | | ✓ | Theoretical |
| Böttcher10 | [25] | Estimation of bioenergy potentials and demonstration of harmonised approaches developed within the Biomass Energy Europe (BEE) project. | EU-27 | Member State, EU-27 | 2010, 2020, 2030 | Resource focused – statistical, spatially explicit and modelling | EPIC, EUFASOM | ✓ | ✓ | ✓ | Theoretical, technical, economic, implementation |
| Böttcher13 | [26,27] | Transformation of technical potentials from Elbersen13 into economic potentials. | Global | Global, EU-27 | 2000, 2010, 2020, 2030 | Demand driven – cost supply | GLOBIOM | ✓ | ✓ | | Economic |
| Daiglou16 | [28] | Estimation of residues availability for energy and material uses considering ecological and current uses. | Global | World regions (West, Central Europe ^e) | 1971–2100 | Integrated assessment | IMAGE | | | ✓ | Theoretical, ecologically sustainable |
| deWit10 | [29] | Estimation of technical and cost and supply potential for biomass resources. | EU-27 +CH+NO | NUTS-2 | 2010, 2020, 2030 | Resource focused – spatially explicit | n.a. | ✓ | ✓ | ✓ | Technical, economic |
| EEA13 | [8,11] | Review of the implications of resource efficiency principles for developing EU bioenergy production. | EU-27 | EU-27 | 2020 | Demand driven – cost supply | CAPRI, MITERRA, PRIMES, AGLINK-COSIMO | ✓ | ✓ | ✓ | Economic |
| Elbersen13 | [30,31] | Quantification of technically constrained biomass potentials for different scenarios assumptions. | EU-27 | NUTS-2 | Current (2006–2008), 2020, 2030 | Demand driven – modelling | CAPRI, MITERRA, GLOBIOM, GEMIS | ✓ | ✓ | ✓ | Ecologically sustainable |
| Fischer10 | [32] | Estimation of available land for bioenergy production for different scenarios assumptions. | EU-27 +CH+NO | NUTS-2 | 2010, 2020, 2030 | Resource focused – spatially explicit | n.a. | | | ✓ | Technical land potential, ecologically sustainable |
| Krasuska10 | [33] | Estimation of surplus agricultural land theoretically available for non-food crops. | EU-27 | NUTS-2 | Current (2003–2007), 2020, 2030 | Resource focused – spatially explicit | RENEW land allocation model | | | | Theoretical land potential |
| Monforti13 | [34] | Geographical assessment of potential bioenergy production from | EU-27 | NUTS-2 | 2000–2009 | Resource focused – spatially explicit | n.a. | | | ✓ | Ecologically sustainable |

(continued on next page)

Table 1 (continued)

| Study label ^b | Main ref. | Objective of study | Spatial coverage ^c | Spatial resolution | Timeframe | Approach - methodology | Model(s) used | Biomass categories | | Type of potential |
|--------------------------|-----------|---|--|---|------------------|---------------------------------------|---------------|--------------------|---|---------------------------------------|
| Monforti15 | [35] | agricultural residues. Estimation of available agricultural residues obtainable without impacting the EU SOC stock. | EU-27 | Member State, 1×1 km | Current (2012) | Resource focused – spatially explicit | n.a. | ✓ | | Ecologically sustainable |
| Pudelko13 | [36] | Estimation of biomass potentials from agricultural and forestry residues and municipal waste. | EU-27 +CH | NUTS-3 | 2008–2011 | Resource focused – statistical | n.a. | ✓ | | Theoretical, ecologically sustainable |
| Scarlat10 | [37] | Resource-based assessment of the available agricultural crop residues for bioenergy production. | EU-27 | Member State | 1998–2007 | Resource focused – statistical | n.a. | ✓ | | Ecologically sustainable |
| Scarlat13 | [38] | Quantification of land use impacts of EU's 2020 bioenergy targets based on NREAP projections. | EU-27 | Member State | 2020 | Demand driven – statistical | n.a. | | | Technical land potential |
| Schueler13 | [39] | Quantification of the effect of EU RED sustainability criteria on the theoretical biomass potential. | Global | World regions (OECD Europe ^f) | 2000 | Resource focused – spatially explicit | LPJmL | ✓ | ✓ | Ecologically sustainable |
| Searle13 | [40] | Estimation of sustainable availability of cellulosic wastes and residues. | EU-27 | EU-27 | 2011, 2020, 2030 | Statistical | n.a. | ✓ | | Ecologically sustainable |
| Spöttle13 | [41] | Assessment of agricultural residues potential with low ILUC risk. | DK, DE, ES, FR, HU, IT, NL, PL, RO, UK | Country | 2002–2011 | Resource focused – statistical | n.a. | ✓ | | Ecologically sustainable |

^a A detailed characterisation of the studies is provided in the Online Supplementary Information.

^b Study labels consist of first author's last name and year of publication.

^c CH=Switzerland, DK=Denmark, DE=Germany, ES=Spain, FR=France, HU=Hungary, IT=Italy, NL=the Netherlands, NO=Norway, PL=Poland, RO=Romania, UK=United Kingdom.

^d North, South and West Europe in Bentsen14 include EU-15+ Albania, Andorra, Bosnia and Herzegovina, Croatia, Estonia, Faeroe Islands, Gibraltar, Iceland, Latvia, Liechtenstein, Lithuania, Macedonia FYR, Malta, Monaco, Montenegro, Norway, San Marino, Serbia, Slovenia, Switzerland.

^e West and Central Europe in IMAGE include EU-27+ Albania, Andorra, Bosnia and Herzegovina, Croatia, Faeroe Islands, Gibraltar, Iceland, Liechtenstein, Macedonia FYR, Monaco, Montenegro, Norway, San Marino, Serbia, Switzerland, Vatican City State.

^f OECD Europe include Austria, Belgium, Czech Republic, Denmark, Estonia, Finland, France, Germany, Greece, Hungary, Iceland, Ireland, Italy, Luxembourg, the Netherlands, Norway, Poland, Portugal, Slovak Republic, Slovenia, Spain, Sweden, Switzerland, Turkey and United Kingdom.

improvement of animal feeding practices [4,9]. The effects of these measures on productivity and the environment are complex and not completely understood yet [4].

Sustainable agricultural intensification is an important prerequisite to increase agricultural feedstock production for energy purposes without converting high carbon-stock land [8]. Many studies assess the potentials and impacts of energy crop cultivation and primary agricultural residues for bioenergy [e.g. 9–13]. These studies consider a limited number of sustainability constraints (e.g. exclusion of high biodiverse areas and land for food production). In addition, most studies exclude the effects of agricultural intensification on the environmental profile of bioenergy. Only a few studies took a more integrated approach on bioenergy, agricultural intensification and environmental impacts [14–17]. However, their coverage is limited to a single province [14] or country [15], or aggregated for Europe [16] or the world [17]. De Wit et al. [16] and Melillo et al. [17] assess the net

greenhouse gas (GHG) emissions of agricultural intensification to release land for energy crop production and bioenergy production. Both studies ignore intensification of livestock production and only one intensification pathway is considered for crop production.

The overall net impact of bioenergy production is, however, closely related to land use and direct or indirect land-use change. The sustainable bioenergy potential could be constrained through these changes in land use, including both the conversion of natural ecosystems to agricultural land and changes in agricultural management [7]. An integrated approach on both agricultural management and sustainability constraints for bioenergy production is thus necessary to estimate the sustainable land availability for feedstock production and subsequent bioenergy potential. A better understanding of the key factors influencing the potential and impacts of bioenergy production in relation to agricultural intensification is needed to identify pathways for sustainable bioenergy production within Europe.

Given the limitations described above, this paper aims at 1) identifying shortcomings in land and bioenergy potential estimates related to how they account for agricultural intensification, its associated environmental effects and other sustainability constraints, and 2) providing suggestions on how these shortcomings crucial for sustainable biomass production may be improved in future assessments. Our review focuses on European land and bioenergy potential studies given the region's interest in increasing the share of sustainable bioenergy in the total energy mix.

The paper is structured as follows: [Section 2](#) includes an overview of the reviewed land and bioenergy potential studies and models, the criteria on which the studies are reviewed and the bioenergy potential types considered. [Section 3](#) presents and discusses the findings of the review. First, findings in terms of sustainability constraints and intensification measures on the land available for energy crop cultivation are given and discussed ([Section 3.1](#)). Then, the land availability for energy crop cultivation as estimated by the different studies is compared ([Section 3.2](#)). Hereafter, sustainability constraints to determine the agricultural bioenergy potential and the associated environmental impacts are presented and discussed ([Section 3.3](#)), followed by a comparison of bioenergy potentials from agricultural feedstocks ([Section 3.4](#)). These sections also consider the differences in modelling approaches applied in the reviewed studies. Based on our findings, we conclude ([Section 4](#)) on how to assess the environmental and land use effects induced by agricultural biomass production and intensification in Europe in a more integrated manner in future studies.

2. Approach

2.1. Overview of studies and models

The review included studies that cover global (including Europe as a world region) and European land and bioenergy potentials up to 2030 and specifically consider environmental sustainability criteria. Additional criteria for studies to be included in this review are that they are 1) reported in English to ensure accessibility and 2) published between 2009 and 2015. The ISI Web-of-Science and Google Scholar were used to identify studies complying to these criteria. In addition, the bibliographies of the selected studies were examined to find other relevant studies. [Table 1](#) lists the reviewed studies and their general characteristics; a more detailed characterisation of the studies is provided in the Online [Supplementary Information](#). Because this review aimed at identifying the included intensification measures and sustainability constraints, potentials were not standardised on time frame and area coverage.

The selected studies differ on approaches (i.e. refer to a generalized concept followed in an assessment) and methodologies (i.e. translate assumptions and datasets into land and bioenergy potentials) ([Table 1](#)). Batidzirai et al. [18] comprehensively classifies approaches and methodologies. Approaches include demand-driven approaches, resource-focused approaches, integrated assessments, impact and feasibility assessments, and reviews. Methodologies include statistical analysis, spatially explicit analysis, cost supply analysis and energy- or agriculture-system modelling [18]. Most studies included in our review apply a resource-focused approach ([Table 1](#)), estimating the whole resource base as opposed to a demand-driven approach in which the amount of biomass required to meet a certain target is estimated.

Different models are applied in the reviewed studies ([Tables 1, 2](#)). Agro-economic models and integrated assessment models are important approaches to assess the bioenergy potential from agriculture. These models cover agriculture production, including crop (food, feed, fibre and energy crops) and livestock production, the land use and availability for each activity, and the environmental impacts of the projected agricultural activities. Biophysical process models are central approaches to consider the environmental impacts of agricultural land management. A description of the models and differences between the

models is provided in the Online [Supplementary Information](#).

2.2. Sustainability constraints and intensification measures

The biomass potential studies were reviewed on the inclusion of sustainability constraints and intensification measures. The sustainability constraints to land and bioenergy potentials were divided into the following principles (based on [19,20]): 1) secure food, feed and bio-based material production; 2) prevent biodiversity loss; 3) significantly contribute to GHG emission mitigation; and 4) minimise negative impacts on soil, water and air. We evaluated whether constraints and measures are considered in the reviewed studies, how these are included, which assumptions are made and which datasets are used.

The four principles are translated to sustainability constraints to the land potential and subsequently the energy potential. The first sustainability constraint to the land potential is the exclusion of land area needed for food production to ensure food security. Assumptions of future food demand and productivity increases in crop and livestock production were reviewed. In addition, the differences in modelling the impacts of intensification on land use and environment among the reviewed studies were determined. A second constraint to the land availability that is reviewed is the exclusion of high biodiverse areas and high carbon stock areas as defined in the EU's Renewable Energy Directive [21] to prevent biodiversity loss and high GHG emissions.

Three environmental sustainability constraints to the energy crop potential were considered in this review, related to the avoidance of negative impacts on soil, water and air, biodiversity conservation and GHG emissions mitigation. Constraints related to the prevention of negative impacts on soil, water and air include the adaptation of management practices to local biophysical conditions (e.g. appropriate crop selection and crop rotations), the exclusion of highly degraded areas and steep areas for energy cropping, limited or no irrigation of energy crops in certain areas and maximum extraction rates for primary agricultural residues [19]. Biodiversity conservation requires the adaptation of management practices in biodiversity sensitive areas and in areas under agro-environmental support, extensive or organic farming, the implementation of buffer zones in sensitive areas and diversity within the cropping area (e.g. by a minimum number of crop species and varieties and structural diversity) [19]. The amount of GHG emissions of energy crop cultivation and harvesting and the GHG emissions by indirect land use change (ILUC) also constraint the sustainable energy potential.

2.3. Bioenergy potential types

First and second generation feedstocks are often distinguished. First generation agricultural feedstock refers to conventional food crops, including oil, starch and sugar crops. Second generation agricultural feedstock includes crops cultivated for energy purposes, grassy or herbaceous and woody crops, and agricultural residues. The environmental impacts of these two feedstocks differ. Therefore, the bioenergy potential was distinguished by feedstock type where possible.

Five types of biomass potentials (i.e. theoretical, technical, ecologically sustainable, economic and implementation potential) were further distinguished, following Batidzirai et al. [18] and Chum et al. [22]. Sustainability constraints are considered in the technical potential by taking into account spatial restrictions due to competition with land used for food, feed and fibre production. Sustainability constraints related to protection of nature, biodiversity, soil, water and air are considered in the ecologically sustainable potential. Sustainability constraints could also be considered in the economic potential in addition to the criteria of economic profitability. This study reviewed technical, ecologically sustainable, economic and implementation potentials with various sustainability constraints considered.

Table 2
Models used by the studies included in this review.

| Model | Main ref. | Model approach | Principle objective | Spatial coverage and resolution ^a | Time horizon and resolution |
|----------------|-----------|-----------------------------|---|--|--|
| CAPRI | [42] | Partial equilibrium model | Simulation and comparison of impacts from different sets of agricultural and trade policies on EU's agriculture and the environment. | EU-27, NO, WB, TR (NUTS-2) Global agricultural markets (country or country block) Production side: HSMU (138,000 units in EU-27) | 10-year intervals up to 2030 |
| CENTURY | [43] | Biophysical process model | Simulation of carbon, nitrogen, phosphorus and sulphur dynamics in natural and cultivated soils. | Global | Monthly time steps |
| EUFASOM | [44] | Partial equilibrium model | Assessment of the economic and environmental impacts of political, technological and environmental change on European land use. | EU-25 (country) Rest of the World (continental regions) Production side: HRU (> 1,000 units in EU-25) | 5-year intervals up to 2150 |
| GLOBIOM | [45–47] | Partial equilibrium model | Providing policy analysis on global issues concerning land use competition between the forestry and agricultural sector as the major land-based production sectors. | EU-28 (country) Rest of the World (25 regions) Production side: HRU intersected with 0.5×0.5° grid and country boundaries (> 10,000 units worldwide) | 10-year intervals up to 2050 |
| IMAGE | [48] | Integrated assessment model | Analysis of large-scale and long-term human-environment interactions to gain better insight into the processes of global environmental change. | Global Socio-economic processes: 26 regions Land use and LUC: 5×5' grid Land-based processes: 30×30' grid | Annual or 5-year intervals up to 2100 |
| LPJmL | [49,50] | Biophysical process model | Simulation of vegetation composition and distribution, and carbon and water stocks and flows for natural and agricultural ecosystems. | Global (30×30' grid) | Daily, monthly or annual time steps |
| EPIC | [51] | Biophysical process model | Simulation of crop growth under varying natural processes in agricultural land management and the assessment on how land management affects the environment. | Global (HRU) | Daily time steps spanning decades to centuries |
| MITERRA-Europe | [52,53] | Biophysical process model | Assessment of the effects and interactions of agricultural policies and measures on nitrogen and GHG emissions in the EU's agricultural sector. | EU-27 (country, NUTS-2) | Annual time steps |

^a NO=Norway, TR=Turkey, WB=Western Balkan (Croatia, Macedonia, Montenegro, Albania, Bosnia and Herzegovina, Kosovo, Serbia).

3. Results and discussion

3.1. Sustainability constraints to land availability for energy cropping

Constraints related to food security (Section 3.1.1) and biodiversity and GHG emissions (Section 3.1.2) need to be considered in the estimation of the land potential. Table 3 presents these constraints in the reviewed studies.

3.1.1. Exclusion of areas dedicated to food, feed and fibre production

All studies, except the spatially explicit method by Böttcher10,¹ restrict energy crop cultivation to surplus land (i.e. land not needed for other purposes including food production) (Table 3). The amount of land dedicated to food and feed production in Europe depends on 1) the projected food demand, and 2) the projected level of agricultural productivity for crops and livestock products, as further discussed below. In addition, trade in agricultural products and Europe's self-sufficiency ratio are determining factors in the land potential, but not further discussed in this paper as the paper's scope is on agricultural intensification measures and environmental sustainability constraints only.

3.1.1.1. Projected food demand. Projections on future food demand are based on projections on population, gross domestic production and food consumption per capita. Projections by the FAO [54,55] on future food demand are used by Beringer11 and Böttcher13, while EEA13 and Elbersen13 use projections by the Royal Society [9]. Not all studies explicitly mention the land area needed for food production (Table 3). Biomass demand from sectors other than food and fibre (e.g. chemical

sector) is ignored in all the studies. The total land and biomass potential should therefore be considered as the total land and biomass available for both energy and material purposes.

3.1.1.2. Projected agricultural productivity and related environmental impacts

3.1.1.2.1. Crop yield projections. Projections on future crop yields are essential to estimate the future agricultural land dedicated to food and feed crop production. Besides, such projections are also relevant to estimate primary agricultural residue potential as the agricultural residue yield is initially proportional to crop yield and then becomes constant [24].

3.1.1.2.1.1. Crop yield projections in statistical and spatially explicit studies

The reviewed studies applying a statistical or spatially explicit methodology base crop yield changes on historical trends (Fischer10, deWit10 and Krasuska10) or potential crop yields (Bentsen14). Fischer10 and deWit10 extrapolate historical crop yield developments for Western European countries (i.e. the 15 member states (MS) in the EU from January 1995 to April 2004) and assume an annual increase of 0.2–0.5% until 2030, while crop yields in Eastern European countries (i.e. the 12 MS joining the EU in May 2004) are assumed to increase faster (2.1–2.6% p.a.) to gradually close the existing yield gap between the Western and Eastern European countries. Krasuska10 also apply two different yield growth rates for Western (0.25–0.5% per year) and Eastern European MS (0.55–1.1% per year). These rates are based on projections by the European Commission's Directorate-General for Agriculture and Rural Development [56]. Bentsen14 estimate crop yield increases on potential crop yields based on the global agro-ecological zoning approach [57]. They use the FAO/IIASA database [58] which contains estimates of different land suitability classes and associated crop yields for different levels of agronomic

¹ Study labels consist of first author's last name and year of publication, main references are given in Table 1.

Table 3

Incorporation of aspects in the quantification of surplus land in the studies included in the review (✓=included; ✗=not included; n.a.=not applicable because study does not include projections on future potentials).

| Study | Exclusion of areas dedicated to food and feed production | | | Exclusion of highly biodiverse areas |
|---|--|--|---|---|
| | Land area for food production | Projected increase in crop productivity | Projected increase in livestock productivity | |
| Allen14 | ✓- Land needed for food and feed production, arable land in rotation and grassland under agricultural management excluded. | n.a. | n.a. | ✓- Forest, non-forest semi-natural habitats |
| Böttcher10_statistical | ✓- Current land needed for food and feed production excluded based on grain equivalent: 86–100 Mha | n.a. | n.a. | ✓- Permanent meadows and pasture |
| Böttcher10_spatially explicit | ✗ | n.a. | n.a. | ✗ |
| Böttcher10_model | ✓- Land area for food and feed production is not explicitly mentioned | ✓- Crop yields are based on EPIC results. Not specified. | ✗ | ✓- Forest, wetland |
| Böttcher13 | ✓- Land area for food and feed production is not explicitly mentioned | ✓- 0.5% annual crop yield increase plus regional average yield changes are caused by management systems changes and re-allocation of crops to more productive areas. | ✓- Livestock production system transitions | ✓- HNV farmland |
| deWit10 and Fischer10 | ✓- Land needed for food production excluded: 105–107Mha in 2030. | ✓- Distinction between Western European MS (0.2–0.5% p.a.) and Eastern European MS (2.1–2.6% p.a.) | ✓- Livestock feed conversion efficiency increases. Not specified. | ✓- Forest, pasture (for annual arable crops), set-aside farmland |
| EEA13_market first | ✓- Land needed for food and feed production excluded based on CAPRI reference run for 2020: 183 Mha [93] | ✓- CAPRI reference run 2020 and 2030 results. Not specified. | ✓- CAPRI reference run 2020 and 2030 results. Not specified. | ✗ |
| EEA13_climate focus, EEA13_resource efficiency | ✓- Land needed for food and feed production excluded based on CAPRI reference run for 2020: 183 Mha [93] | ✓- CAPRI reference run 2020 and 2030 results. Not specified. | ✓- CAPRI reference run 2020 and 2030 results. Not specified. | ✓- HNV farmland |
| Elbersen13 | ✓- Land needed for food and feed production excluded based on CAPRI reference run 2020 and 2030 results. | ✓- CAPRI reference run 2020 and 2030 results. Not specified. | ✓- CAPRI reference run 2020 and 2030 results. Not specified. | ✓- HNV farmland |
| Krasuska10 | ✓- Land needed for food and feed production excluded. | ✓- Distinction between Western European MS (0.25–0.5% p.a.) and Eastern European MS (0.55–1.1% p.a.) | ✓- Forage-to- grain ratio increases. Not specified. | ✓- Only current (2003–2007) agricultural land considered |
| Schueler13 | ✓- Areas for food, feed and fodder production are excluded based on HYDE grass- and cropland data [94] | n.a. | n.a. | ✓- Nature reserves, wetland, forest, highly biodiverse areas, anthropogenic grassland |

input.

3.1.1.2.1.2. Crop yield projections in agricultural-system modelling studies

The partial equilibrium models used by the studies all apply a combination of exogenous and endogenous crop yield projections. Exogenous projections are based on historical trends in EUFASOM and GLOBIOM, and on historical trends in combination with expert consultation, for example from the AGLINK modelling system, in CAPRI. Exogenous yield projections in IMAGE are based on FAO projections [59] in combination with biophysical yield effects due to climate change and increased CO₂ effects, and changes in agricultural area calculated by the LPJmL model.

Endogenous yield changes could be caused by many different factors, including land or crop prices, climate change and management changes. In EUFASOM and GLOBIOM, endogenous yields are related to management system changes and the crop distribution among the land [60]. EUFASOM defines crop management system alternatives as combinations of three tillage intensities, two irrigation alternatives and different fertilisation levels. GLOBIOM defines four management systems globally, namely subsistence, low input-rainfed, high input-rainfed and high input-irrigated. For the EU, a set of technologies is combined to define management system alternatives, including two levels of fertiliser input, two levels of irrigation, three levels of tillage and many combinations of crop rotations. The input structure for each management system is fixed following a fixed proportions production function (also referred to as Leontief production function) in both

EUFASOM and GLOBIOM. Crop yields, input requirements and environmental impacts for each crop management system alternative and simulation unit are simulated by EPIC. To serve as an input to GLOBIOM, the crop yields derived from EPIC are rescaled to fit FAOSTAT's average regional yields considering management factors not included in EPIC [45]. GLOBIOM calibrates its production cost (i.e. farmer margin and all input costs minus labour costs), for each system using FAOSTAT national producer price data. EUFASOM bases its production costs (i.e. all input costs including labour) for the system alternatives on farm surveys within the Farm Accountancy Data Network. Costs for specific management options are then computed through economic principles and engineering equations [60]. Each management system thus has its own input requirements, production costs and production efficiency. GLOBIOM computes for a given agricultural demand the most cost-efficient production pattern constrained by land availability and the resources costs. This allows for shifts in management system alternatives and changes in the allocation across spatial units with different climatic and soil suitability. The sum of all management systems and locations is used to obtain the regional (NUTS-2) production pattern and average yields [45].

CAPRI determines endogenous yield changes through a hybrid approach combining a fixed proportions production function for variable costs and a non-linear cost function that captures the effects of labour and capital. Two technologies are available for most crop activities: a low and high yielding variant, each covering half of the activities observed in ex-post data. Economic indicators per crop,

including revenues, variable costs and gross-value added, are derived from the crop yields on Homogenous Soil Mapping Units (HSMU) level. Crop yields react to changes in output prices [42]. Certain constraints to yield growth rates, such as an annual minimum yield growth rate of 0.5% and specific upper limits to prevent unrealistic crop yields, are implemented.

3.1.1.2.2. Livestock productivity projections. Projections on livestock productivity are important to estimate surplus land since one-third of total European agricultural land is pastureland [61], and approximately 60% of total European cereal production is used for animal feed [62]. Changes in pasture productivity are only relevant in the studies estimating surplus pastureland considered to be used for woody and grassy energy crop cultivation (Fischer10 and deWit10). However, projections on the amount of feed needed to produce one unit of livestock product are relevant for all studies estimating surplus arable land.

3.1.1.2.2.1. Livestock productivity projections in statistical and spatially explicit studies

Fischer10 distinguish between ruminants (e.g. cattle and sheep) and monogastric animals (e.g. pigs and chicken) in the calculation of feed input. A technological coefficient is used by Fischer10 to measure livestock intensity (i.e. required energy input per unit of livestock output). Feed input allocation is based on energy requirements. Protein requirements are not included. The total energy requirements for ruminants are partitioned into a share derived from feed crops and a share from grazing on pastureland. The area of pastureland required for ruminant production is estimated by applying an estimated energy yield per hectare of grassland based on grassland productivity data calculated with the agro-ecological zones methodology [57].

3.1.1.2.2.2. Livestock productivity projections in agricultural-system modelling studies

Livestock productivity is included differently in the partial equilibrium models. The livestock categories cattle, pigs, poultry, sheep and goats are included in CAPRI and cover different activities for each category. For several livestock activities (e.g. dairy cows, heifer fattening or male adult cattle fattening) high and low yielding variants are grouped similar to CAPRI's crop production systems [42]. EUFASOM classifies livestock production systems based on the Farm Accountancy Data Network classification on economic size and farm specialty, including dairy farms, grazing livestock, pigs and/or poultry, and mixed farms [44]. Livestock production in GLOBIOM is characterised by the number of animals by species, production system and type (i.e. dairy, meat or other) in each Simulation Unit. Eight production systems for ruminants are differentiated and six of these are based on their agro-ecological zone (i.e. arid, humid, temperate) and feed type (i.e. grazing, mixed). The other two are an urban and a remaining system [47]. The spatial distribution and allocation between production systems of ruminants is based on the Gridded Livestock of the World database [63,64]. Two production systems for monogastrics are defined, an industrial and a smallholder system. The spatial distribution of monogastrics is not included in GLOBIOM because monogastrics are not georeferenced to ecosystems like grasslands [47]. Livestock productivity for monogastric animals in GLOBIOM is based on feed conversion efficiencies identified through literature review and for ruminants on the basis of animal feed ratios using the digestibility model RUMINANT. This model ensures consistency between feed inputs and animal products output of the different production systems. European grassland productivity is simulated with EPIC for different fertiliser inputs and off-take rates [47]. Production costs for each production system alternative are based on FAOSTAT producer prices for animal product outputs and grain inputs. Changes in average livestock productivity result from changes in feed composition and subsequently changes in the relative distribution of animals across the production systems as the profitability of each production system varies with varying feed prices. CAPRI allocates feed input for each livestock activity based on feed requirements of the animals, including

energy and crude protein requirements, fibre requirements and a margin for dry matter content. The feed composition mix is determined by feed requirements and minimal costs and is selected from five feed concentrate categories and five fodder categories. CAPRI distinguishes between intensively and extensively managed grasslands with different yields. Changes in average livestock productivity in CAPRI result from changes in feed composition due to changes in feed costs.

Crop yield growth rates and livestock productivity changes are not explicitly given in the studies and comparing between the projected rates among the different studies is therefore impossible. Changes in crop yield and livestock productivity are driven by several factors reflecting changes of economic, ecological, technological and policy-related origin [65]. These factors affect productivity changes and differ temporally and spatially. Endogenous productivity changes in agro-economic models are often only driven by few factors, mainly related to economics. This disconnect both the actual origins of yield developments and the different roles that influencing factors have among regions [66].

3.1.1.2.3. Environmental impacts of agricultural production. The environmental impacts of the agricultural sector and changes in activity and intensity levels of its production are calculated by agricultural partial equilibrium models, IMAGE and biophysical models, such as MITERRA-Europe. All models calculate GHG emissions. EUFASOM, CAPRI, IMAGE and MITERRA-Europe also assess nutrient leaching leading to eutrophication. Biodiversity effects are only assessed by CAPRI and IMAGE.

The partial equilibrium models use an emission factor approach to quantify GHG emissions. GHG emissions in CAPRI are calculated per agricultural production activity and include all emissions from involved activities up to the farm-gate and emissions from land use change. Nitrogen balances are calculated with a mass balance approach developed for MITERRA-Europe [52]. The gross balance is defined as the difference between the different nitrogen inputs (i.e. from mineral fertiliser, manure, crop residues, biological fixation and atmospheric deposition) and nitrogen export by harvested crop material. EUFASOM includes emission impact factors calculated by EPIC to quantify GHG emissions, soil organic carbon (SOC), soil erosion and nutrient leaching specific for each Homogenous Response Units (HRU), land use and management alternative. The total environmental impact of agricultural production is calculated by summing the agricultural activity levels multiplied by the impact factors. GLOBIOM quantifies GHG emissions from synthetic and organic fertiliser application based on fertilisation rates as calculated by EPIC for the different management systems alternatives. Emissions from livestock production include CH₄ emissions from enteric fermentation and manure management, and N₂O emissions from manure management and manure left on pastureland. These emissions are based on outputs from the RUMINANT model for the different countries and livestock production systems. Land use change emissions are only partially included. Changes in SOC are only calculated for Europe and are based on data from the Joint Research Centre [45].

Changes in agricultural production could also affect biodiversity. EUFASOM and GLOBIOM do not assess biodiversity effects of changes in agricultural production other than the loss of grasslands as important habitats for biodiversity. CAPRI calculates crop diversity of annual crops on regional level in three ways, the simplest indicator is the number of crops per reference unit, while two more elaborated indicators are the Simpson's diversity index and the Shannon's diversity index [42]. In the IMAGE modelling framework, changes in biodiversity are assessed by GLOBIO, modelling species richness and habitat intactness [48].

The total environmental impact from the agricultural sectors is altered by measures that increase agricultural productivity. The extent and direction of the change in environmental impacts depend on the

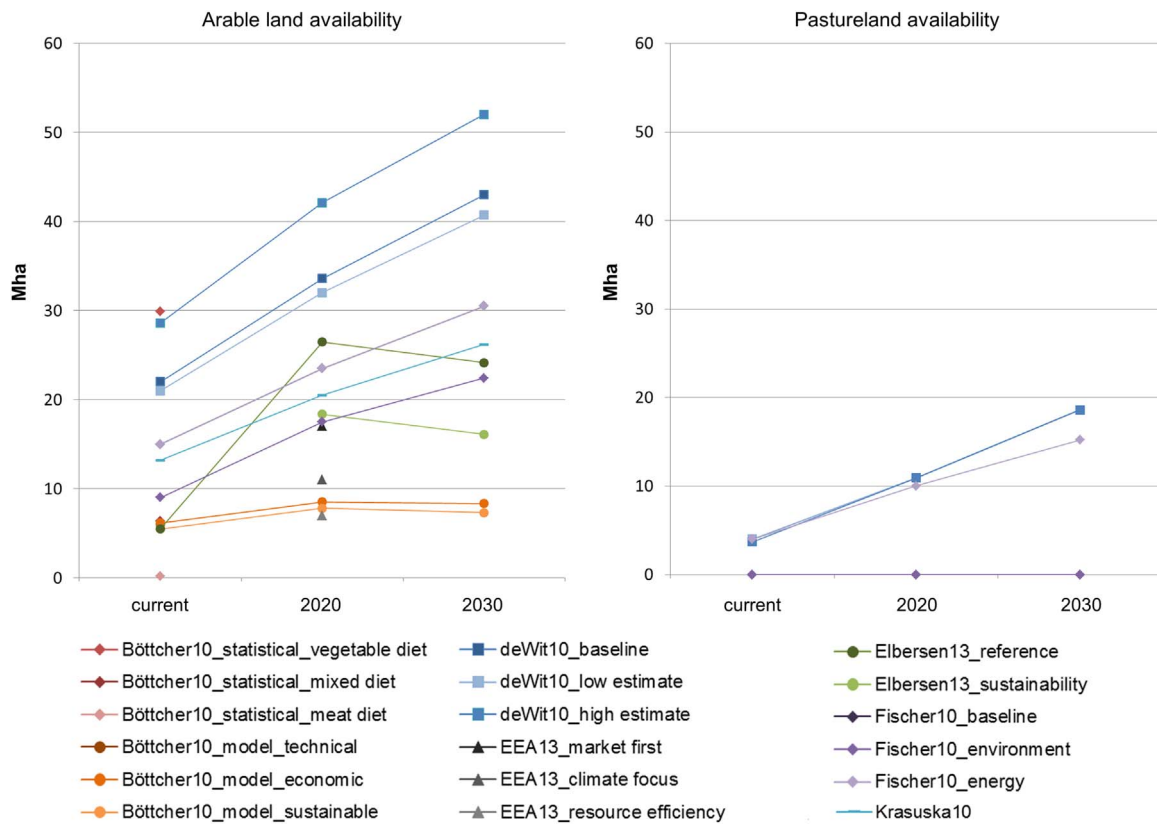


Fig. 1. : Land area available for energy crop cultivation in Europe estimated by the studies included in the review.

type of intensification measures. Sustainable intensification measures increase land productivity without necessarily increasing the level of inputs [9]. EUFASOM and GLOBIOM both use yield estimations from EPIC derived from optimised crop rotations. In addition, production technologies are defined for different levels of tillage, fertiliser input and irrigation. These factors are, however, not reflecting the whole range of possible sustainable intensification measures, excluding for example intercropping, cover crops and precision farming. In addition, intensification measures for pastures are poorly covered in all models. GLOBIOM is the most comprehensive model concerning livestock production systems defining ten livestock production systems, allowing for shifts from grazed to mixed management alternatives, and including grassland productivity changes based on EPIC. More sustainable intensification measures and the associated effect on land use and environment could be included in the models by adding sustainable management alternatives and related production functions or including pathways of increased productivity. Intensification pathways are for example defined by Valin et al. [46]. They used GLOBIOM to assess the effects of different agricultural intensification pathways on GHG emissions in developing countries. The emission savings from the sustainable intensification pathways (i.e. higher productivity achieved through optimised rotation, crop–livestock system integration, and precision farming) are one-third higher than for the high-input pathway (i.e. higher productivity through higher synthetic fertiliser inputs) [46].

3.1.2. Exclusion of high biodiverse and high carbon stock areas

The EU Renewable Energy Directive [21] prohibits the use of raw materials from high biodiverse areas (i.e. primary forests, legally protected areas and highly biodiverse grasslands) and high carbon stock areas (i.e. wetlands and forests). Although all studies exclude certain of these areas from the land available for energy cropping, the definitions and datasets used to exclude areas vary among studies (Table 3).

Forests were excluded in all studies, except in the statistical and spatially explicit methods applied by Böttcher10. The datasets used to quantify the European forest area differ among the studies: FRA2000 [67] is used by deWit10 and Fischer10, GEO-BENE [68] is used by Böttcher13, and the Global Forest Map [69] is used by Schueler13. GEO-BENE and the Global Forest Map are both based on the Global Land Cover 2000 dataset produced by the Joint Research Centre [70]. Legally protected areas are excluded by Schueler13 based on the World Database on Protected Areas [71]. The exclusion of wetlands is based on Schlepner [72] in EUFASOM used by Böttcher10 and on the GLWD database [73] by Schueler13. In addition, Schueler13 exclude high carbon stock areas by restricting feedstock production to areas where compensation time for GHG emissions is less than five years. These areas are identified through the application of a GHG layer to the LPJmL model. DeWit10 and Fischer10 are the only studies considering pastures not used for food production or nature protection, to be available for the production of woody and grassy energy crops. The reviewed studies do not identify agricultural land areas with high biodiversity other than described above, such as biodiverse sensitive areas or areas under agro-environmental support, extensive or organic farming (see also Section 3.3.2).

Böttcher13, Elbersen13 and EEA13 use a different approach to determine high biodiverse and high carbon stock areas. High nature value (HNV) farmland area is used in these studies as a proxy for both areas to be excluded. HNV-farmland are areas where agriculture is a major land use and where this agriculture maintains or contributes to high biodiversity [74]. A HNV-farmland spatial distribution map developed by Paracchini et al. [75] is used to quantify the land area to be excluded. This is done by estimating the probability of HNV-farmland in a grid cell [76]. In addition, Böttcher13 identified high biodiverse areas outside of Europe based on the Carbon and Biodiversity Report [77].

All studies thus ignore nature conservation areas for energy cropping, focusing on agricultural land only. Nature conservation areas

Table 4
Consideration of ecological sustainability constraints in the estimation of the bioenergy potential (\checkmark =included; \times =not included).

| | Soil, water and air | | Biodiversity | | | GHG emissions |
|-----------------------------------|---|--|--|---------------------------------|--------------------------------|---|
| | Adaptation of management practices to local biophysical conditions | Limitations on irrigation | Adaptation of management practices in specific areas and to local biophysical conditions | Buffer zones in sensitive areas | Diversity within cropping area | GHG emission mitigation target ^a |
| Böttcher10 | \times | \times | \times | \times | \times | \times |
| Böttcher13 _reference | \times | \times | \times | \times | \times | \checkmark - 50% for biofuels only |
| Böttcher13 _sustainability | \times | \times | \times | \times | \times | \checkmark - 70% and 80% for all bioenergy in 2020, and 2030, respectively (including ILUC) |
| deWit10 | \checkmark - Only perennial crops on released grassland. | \times | \checkmark - Organic farming yields 20% lower than standard | \times | \times | \times |
| EEA13 _market first | \times | \times | \times | \times | \times | \times |
| EEA13 _climate focus | \checkmark - Only perennial crops and no-till on fallow land, released land in vineyards and olive orchards and recently abandoned agricultural land. | \times | \times | \times | \times | \checkmark - 50% for biofuels only (including ILUC) |
| EEA13 _resource efficiency | \checkmark - Only perennial crops and no-till on fallow land, released land in vineyards and olive orchards and recently abandoned agricultural land. Apt selection of energy crop mixes and rotations to local conditions. | \checkmark - No irrigation for dedicated energy crop cultivation | \times | \times | \times | \checkmark - 50% for all bioenergy (including ILUC) |
| Elbersen13 _reference | \times | \times | \times | \times | \times | \checkmark - 50% for biofuels only |
| Elbersen13 _sustainability | \times | \times | \times | \times | \times | \checkmark - 80% for all bioenergy (including ILUC) |
| Schueler13 | \times | \checkmark - No irrigation for energy crop cultivation | \times | \times | \times | \checkmark - restricted to areas where compensation time for C-emissions is < 5 years |

^a Mitigation of GHG emissions as compared to fossil comparators.

could, however, add a vast amount of biomass to the biomass potential [78]. Many European conservation areas are managed to prevent ecological succession and maintain high species richness [e.g. 79]. Although the main goal of this management should be conservation, the cultivation of woody and grassy energy crops in such areas might reconcile renewable energy and biodiversity conservation targets [78]. Management of energy crop cultivation in such areas, or other areas with high biodiversity, should be adapted to local conditions (see also Section 3.3.2).

3.2. Land availability for energy cropping

Fig. 1 shows the estimated arable and pastureland area available for energy crop cultivation. This area ranges from 0 to 30 Mha currently, 7 to 42 Mha in 2020 and 7 to 52 Mha in 2030. This is the equivalent of 7–39% of current (2012) arable land in the EU-27 and 7–48% in 2030. In addition, deWit10 and Fischer10 estimate the amount of pastureland available for the cultivation of woody and grassy energy crops at approximately 10 Mha in 2020 and 15 to 19 Mha in 2030, corresponding to a share of around 15% of current (2012) pastureland in the EU-27 in 2020 and 23–28% in 2030.

An increase in land availability until 2020 is observed in all studies. DeWit10, Fischer10 and Krasuska10 project a further increase in land availability between 2020 and 2030, while Elbersen13 project a decline in land availability in this period due to an expected increase in land demand for food and feed production. The land availability projections of Böttcher10 (modelling approach) remain constant between 2020 and 2030.

Applying stricter sustainability criteria lead to a lower estimated land area available for energy cropping. This is mainly caused by a higher share of land reserved for nature reservation. For example, Elbersen13 show that the land available for energy crop cultivation is

smaller in their ‘sustainability scenario’ compared to their ‘reference scenario’ in countries with a large share of HNV-farmland. Similar, the land availability in Fischer10’s scenario with stricter environmental sustainability criteria (i.e. ‘Land use-Environment scenario’) is lower since set-aside areas are reserved for future nature. In addition, stricter sustainability criteria on GHG emissions lead to fewer regions where the GHG mitigation requirements are reached (EEA13, Elbersen13).

Scarlat13 estimate that approximately 18 Mha of agricultural land is needed to comply to EU’s 2020 bioenergy target as proposed in the national renewable energy action plans. Accounting for the use of co-products from biofuel production for animal feed, thereby substituting conventional fodder, such as grain crops, reduces the required land area to 10 Mha. This is still higher than the lowest estimates of land available in EU-27 in 2020.

Different types of land are considered suitable for energy crop production. Two main categories can be distinguished, namely unused agricultural land and low productive land that is not suitable for conventional crop production [18]. Allen10 estimates an additional 1.35 Mha of cropland and pastureland available for energy crop cultivation in the future, of which the main part (0.8 Mha) is recently abandoned agricultural land. Fallow land could also be considered unused land, although agricultural land that is left fallow for a certain period may be part of crop rotation and is therefore not necessarily available for energy crop cultivation. In addition, the use of fallow land and recently abandoned pastures for energy crop cultivation should be considered carefully as these are important agricultural habitats for biodiversity. The cultivation of annual energy crops on surplus pastureland emits many GHGs due to soil disturbances by tillage. This possibly offsets the emission reduction of bioenergy use [29]. DeWit10 and Fischer10 consider surplus pastureland therefore only to be available for the cultivation of perennial crops as no regular tillage is required.

3.3. Environmental sustainability constraints to bioenergy potential

Constraints related to impacts on soil, water and air (Section 3.3.1), biodiversity (Section 3.3.2) and GHG emissions (Section 3.3.3) must be considered to estimate the sustainable bioenergy potential. Table 4 presents an overview of the inclusion of environmental sustainability criteria in the studies included in this review.

3.3.1. Soil, water and air

The consideration of management practices adapted to local biophysical conditions is necessary to avoid negative impacts on soil, water and air, such as soil erosion, water shortages and pollution through volatilisation and deposition of nitrogen and other substances from the production and use of fertilisers [19].

3.3.1.1. Selection of energy crops. Energy crop selection should be adapted to local bio-physical conditions to reduce the need for fertilisers, pesticides, tillage and irrigation [19]. An appropriate selection includes the choice between annual and perennial crops, the crop species and crop rotations. For example, perennial crops are favoured on sites susceptible to soil erosion since no tillage is required and root and SOC formation is higher for perennial crops compared to annual crops. This results in less erosion and increased soil quality [8,80]. In addition, nitrate leaching is lower on land cropped with perennial crops than annual crops [81]. The introduction of energy crops in existing cropping systems could lead to both negative and positive effects on yield, both the yield of the energy crop and the subsequent crop when in rotation, and environmental impacts (e.g. soil carbon, GHG emissions, nutrient losses and water consumption) [82], and should therefore be carefully assessed.

The selection of energy crops in studies using partial equilibrium models (Böttcher10, Böttcher13, EEA13 and Elbersen13) is determined by production price levels. These are partially determined by yields, which in turn are influenced by regional soil and climate characteristics and management (see Section 3.1.1). EEA13 assess different levels of management requirements to energy cropping in one of the three scenarios (Storyline 3 'Resource efficiency'). The selection of energy crops and their management has to follow certain environmental guidance in the resource efficiency scenario. This includes the adaptation to regional biophysical constraints and ecological values, and the selection of an appropriate crop mix and rotation [8]. How this is implemented is, however, not explicitly stated in EEA13's documentation. Elbersen13 determine the crop mix per region as the cheapest mix in terms of lowest production costs in their 'reference scenario', while in their 'sustainability scenario' the crop mix with the highest GHG emission mitigation potential is selected with cost level as the secondary selection criterion. Water limitations influencing biomass yields are included in the different models or separately calculated in the attainable yield (Elbersen13). However, irrigation of energy crops is prohibited in only one scenario in the EEA13 study (Storyline 3 'Resource efficiency').

Both Böttcher10 (spatially explicit method) and deWit10 assess the total supply potential if the whole area of surplus land is cultivated with one crop only. Böttcher10's statistical method considers four crops (reed canary grass, miscanthus, rapeseed and sunflower) with European average yields. DeWit10 include five crop types (i.e. starch, sugar, oil, grassy and woody crops) with average regional (NUTS-2) yields. Crop selection is based on the highest regional yield within each crop group.

Selection of the appropriate energy crops and management based on local biophysical conditions to limit fertiliser input and tillage is thus considered in varying extent. EEA13's resource efficiency scenario and Schueler13 consider an additional criterion to select energy crops, namely that only rainfed cultivation is allowed. None of the studies

consider the integration of energy crops in existing or new crop rotations, or intercropping possibilities in the selection of energy crops.

3.3.1.2. Maximum slope limits for areas under cultivation. Energy crop cultivation on areas with steep slopes increases the risk of soil erosion and should therefore be excluded from the sustainable bioenergy potential. Slope classes are defined in the HRU and HSMU concepts used in EPIC and agro-economic models [42,83], and slope is one of the variables determining land suitability for agricultural production and therefore production costs. Since steep slopes increase production costs, less of this land is allocated to agriculture. No additional constraints on slope limits specific for energy crops are applied in the studies.

3.3.1.3. Maximum extraction rates for primary agricultural residues. The primary agricultural residues availability is constrained by the amount of residues to be left on the field to maintain soil quality. Agricultural harvest residue incorporation into the soil has several ecological soil-quality functions, namely maintaining and improving soil organic matter, providing organic nutrients, protecting from soil erosion and improving water retention [41]. The removal of all residues from the field could jeopardize these ecological functions. Therefore, a maximum sustainable extraction rate for harvest residues should be considered. The sustainable removal rate is location specific and affected by management practices, harvesting equipment and local site and climate conditions [35,37]. Certain management practices, such as no-tillage and crop rotations, might limit soil erosion and SOC loss [84], thereby also affecting the amount of residues to be removed from the field while maintaining soil functions. Besides, higher crop yields might enable, to a certain extent, more residues to be removed when a constant residue cover is assumed. However, general sustainable residue removal rates are assumed in all studies, except Monforti15 (Table 5), since location specific removal rates are not available from field experiments yet [41]. Monforti15 estimate site-specific sustainable removal rates with a simulation platform, including a biophysical process model (CENTURY) considering SOC dynamics influenced by soil texture, soil moisture and soil temperature [85]. A better understanding of the effect of site-specific conditions and management practices on the sustainable removal rate improves the residue availability assessments, as is shown by Monforti15 [35] and Haase et al. [86].

Scarlat10 estimate sustainable removal rates of 40% for cereal crops and 50% for maize, rice, rapeseed and sunflower based on literature review. These removal rates are also used by Elbersen13, Monforti13, Pudelko13 and Searle13. Spöttle13 adjust these rates to country-specific conditions in ten selected countries based on literature and consultation with several national experts. Spöttle13 assume lower removal rates for cereal crops for Germany (34%) and Hungary (33%),

Table 5
Sustainable removal rates applied in studies included in the review.

| | Cereals | Maize, rice, rapeseed, sunflower |
|------------------------------|---------------------------|----------------------------------|
| Daiglou16 | | 50–60% |
| deWit10 and Fischer10 | 50% | |
| Elbersen13 | 40% | 50% |
| Monforti13 | 40% | 50% |
| Monforti15 | | 0–100% (site-specific) |
| Pudelko13 | max. 70% | 50% (maize); 60% (rice) |
| Scarlat10 | 40% | 50% |
| Searle13 | | 66% |
| Spöttle13 | 33–50% (country-specific) | 30% (maize) |

while a removal rate of 50% is assumed for France [41]. Sustainable removal rates as estimated by Monforti15 range from 0–100% collection depending on local conditions. Their assessment shows that, in general, the optimal removal rate in for example Denmark, northern part of France and the United Kingdom is higher than the assumed default rates (i.e. 40–50%), while optimal removal rates in Estonia, Romania and Hungary should be lower than the default rate to sustain SOC levels. Daioglou16 assume a constant residue cover of 2.5 t ha^{-1} , independent of crop type, location and time, corresponding to a removal rate of around 50–60%. Removal rates up to 70% for cereal crops and 60% for rice straw are assumed by Pudelko13. Pudelko13 further assume that all rapeseed straw is left on the field to be incorporated into the soil due to low suitability of rapeseed straw for combustion. Böttcher10 use an availability factor of 30% for all crops, as defined in the BEE Best Practices and Methods Handbook [19], considering both a sustainable removal rate and competitive uses for straw.

3.3.2. Biodiversity

Biodiversity conservation puts several additional constraints on the cultivation of energy crops. First, management practices need to be adapted in biodiverse sensitive areas or areas under agro-environmental support, extensive or organic farming, and to local biophysical conditions [19]. This leads to specific requirements in the selection of energy crops (as described in Section 3.3.1) and to yield adjustments for energy crops cultivated on areas under agro-environmental support, extensive or organic farming. No study considers such yield adjustment. Also, organic and conventional agricultural systems are not specifically distinguished in CAPRI, EPIC, EUFASOM and GLOBIOM. Second, buffer zones need to be created between biodiverse sensitive areas and land used for energy crop cultivation. The implementation of buffer zones between cultivated land and areas of high biodiversity value is only considered by Allen14 through the exclusion of these zones from the land available for energy crop cultivation. Third, a minimum number of crop species and structural diversity within cropping areas should be considered according to Vis et al. [19]. Crop diversity is available to include as a landscape indicator in CAPRI but only for annual crops.

Immerzeel et al. [87] review the biodiversity impacts of energy crop cultivation and conclude that the reported impacts of perennial energy crops on biodiversity are less negative compared to annual arable crops and sometimes even positive, in particular for grassy energy crops and short rotation coppice crops. The benefits of perennial crops include the creation of more suitable habitats for specific species, enhancement of connectivity and the restoration of marginal lands [8]. The extent of the impacts also depends on the initial land use. Different indicators are used to assess the change in biodiversity due to energy crop cultivation. For example, farmland bird assemblage [EEA13; 8] and HNV as a qualitative indicator and mean species abundance as a quantitative indicator [88]. Changes in biodiversity as a result of energy crop cultivation could thus also be positive. For example, the cultivation of multiple species, in agroforestry or intercropping systems combining energy-energy or energy-food crops, increases local biodiversity [89,90]. As mentioned before in Section 3.3.1, the studies do not include intercropping systems in the resource assessment. In addition, the indirect effects from land use change on biodiversity are not taken into account in the studies.

3.3.3. GHG emissions

The amount of GHGs emitted during the cultivation and harvesting phase is specific to crop, soil type, climatic conditions and management practices. The impact of bioenergy on land use change and the resulting GHG emissions from carbon stock changes can either be direct or indirect [7,91]. In general, these effects are lowest for woody and grassy crops, followed by sugar, starch and oil crops [92]. However, large ranges are found in land use change related GHG emission for these

crops [91].

GLOBIOM quantifies GHG emissions from the cultivation and harvesting phases based on fertiliser requirements as defined by EPIC. EEA13 and Elbersen13 quantify GHG emissions through the linkage of the biophysical model MITERRA-Europe with CAPRI. De Wit et al. [16] also use MITERRA-Europe to quantify cumulative GHG mitigation balances for different energy crops (i.e. oil, starch, sugar, woody and grassy crops) and explicitly also include GHG emissions from the intensification of agricultural land to release land for energy crops. They find significantly higher GHG emission mitigation from the cultivation of perennial crops on released land compared to the cultivation of annual crops. Perennial crops generate more soil organic matter compared to annual crops due to the deeper rooting systems and lower tillage requirements. In addition, fertiliser requirements are lower for perennials thereby reducing N_2O emissions. This combined with higher yields than annual crops, lead to higher GHG mitigation potential per unit land [16]. De Wit et al. [16] show that the mitigation potential of agricultural intensification through sustainable measures (reduced tillage, soil carbon enhancement and more efficient fertilisation) is further increased by perennial energy cropping on the released land.

GHG emission mitigation targets can only be examined in studies applying a demand-driven approach, since the whole supply chain should be considered. Böttcher13, Elbersen13 and EEA13 apply a minimum GHG emission savings. These studies follow the same method: direct land use emissions from energy cropping are calculated with MITERRA-Europe, while the GEMIS database is used for the calculation of downstream emissions of the feedstock conversion routes. EEA13, Böttcher13 and Elbersen13 present median land use change related GHG emission factors based on literature review. CAPRI results are used to project agricultural land use and land use implications of energy crop cultivation for the different scenarios in these studies. Land use change emission factors are applied if these CAPRI results show land use displacement.

3.4. European bioenergy potentials

Fig. 2 summarises the bioenergy potentials from energy crops as estimated by all reviewed studies. Böttcher10 and deWit10 estimate the technical potential of energy crops without any other sustainability constraints than food security and the exclusion of nature conservation areas. This technical potential varies between 0.7 and 5.7 EJ yr^{-1} now, to 2.7 and 12.1 EJ yr^{-1} in 2020 and 3.3 and 15.8 EJ yr^{-1} in 2030, depending on the energy crop cultivated and which land is considered for production. Elbersen13 estimate an ecologically sustainable potential varying between 2.2 and 3.2 EJ yr^{-1} in 2020 and 1.5 and 2.7 EJ yr^{-1} in 2030. The high technical potentials found by deWit10 are explained by the cultivation of all land with one specific crop group, and assumed high yield increases in Eastern European countries. DeWit10's results show the importance of crop selection on the potential. The highest potential is from grassy crops, followed by woody crops. Grassy and woody crops reach high yields with relative extensive agriculture management practices. This lowers costs and GHG emissions [29]. The cultivation of only one crop type (e.g. only miscanthus, switch-grass and reed canary grass or only poplar, willow and eucalyptus), is not desirable for biodiversity reasons.

Woody and grassy crops are expected to play a key role in the future bioenergy potential, in particular in scenarios which apply stricter sustainability criteria. The estimated potential derived from arable crops is reduced to zero in the scenarios considering stricter sustainability criteria in Böttcher13, EEA13 and Elbersen13, due to the avoidance of bioenergy production with high ILUC impacts in these scenarios (Fig. 2).

Primary agricultural residues are also expected to play a key role in the future bioenergy potential. The annual amount of straw and stover that is available in the EU-27 and that includes environmental

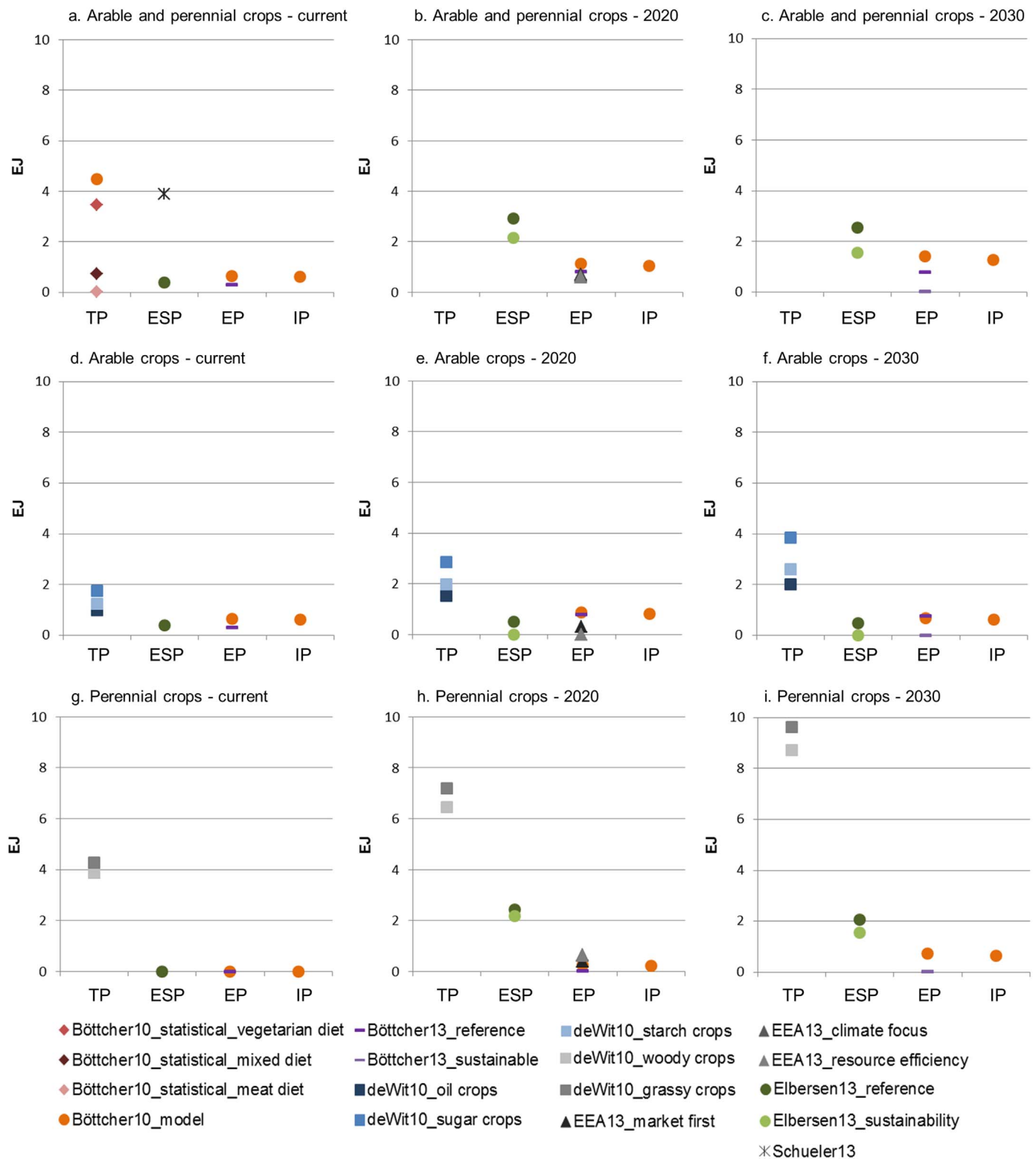


Fig. 2. : Bioenergy potential from energy crops as estimated by different studies. TP: Technical potential; ESP: Ecologically sustainable potential; EP: Economic potential; IP: Implementation potential. Potentials from deWit10 are estimations of the whole land area cropped with one specific crop type. EEA13 calculated the economic potentials with the following feedstock prices: EEA13_market focus < 3 €/GJ; EEA13_climate focus and EEA13_resource efficiency < 6 €/GJ. Böttcher10_modelling approach and Böttcher13 did not state the feedstock prices.

constraints, is estimated to range from 45 to 215 Mt dry matter currently, 115 to 185 Mt dry matter in 2020 and 110 to 165 Mt dry matter in 2030. The annual ecologically sustainable energy potential from these residues ranges from 0.7 to 3.6 EJ currently, 1.9 to 3.1 EJ in 2020 and 1.9 to 2.8 EJ in 2030 (based on a lower heating value of

17.0 MJ kg⁻¹ dry matter) (Fig. 3). DeWit10 and Fischer10 do not account for competitive uses in their residue potential while the other studies do (see the Online Supplementary Information). When also the non-EU Member States are included, the annual ecologically sustainable potential is estimated to be 3.5 EJ currently [24,28], 3.7 EJ in

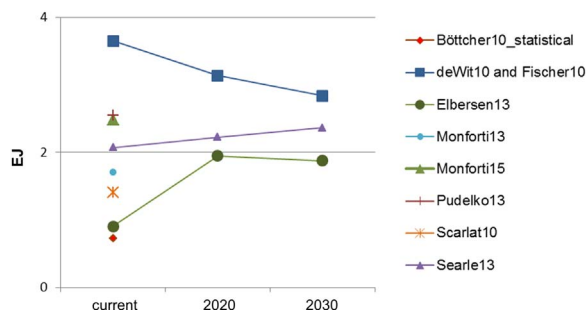


Fig. 3. : Ecologically sustainable potentials from straw in the EU-27 as estimated by different studies. The energy potentials from the different studies are calculated with lower heating value of 17 MJ kg^{-1} for this comparison. DeWit10 and Fischer10 do not exclude competitive uses from their potential.

2020 and 3.9 EJ in 2030 [28] (based on a lower heating value of 17.0 MJ kg^{-1} dry matter). However, large temporal variation in residue availability is caused by weather influences. Scarlet et al. [37], for example, estimated this yearly variation to be in the range of +23% to –28% compared to average residue availability.

Most studies included in this review (Bentsen14, Daioglou16, deWit10, Fischer10, Monforti13, Monforti15, Scarlet10) only estimate potentials from straw and maize stover, while Elbersen13 and Pudelko13 also include cuttings and pruning residues. The current total contribution of straw to primary agricultural residues is estimated to be 93% [36]. Overall, wheat straw contributes most to these primary agricultural residues (c. 35%), followed by barley and maize (both c. 15%) [36,37].

An increase in crop yield likely leads to a decrease in the residue to product ratio of crops as the share of the harvestable component of the crop has been increased through crop breeding over the last decades [24]. DeWit10 and Fischer10 consequently project a decrease of approximately 9–14% per decade in agricultural residue availability (Fig. 3). However, Bentsen14, Daioglou16 and Monforti15 estimate more residue availability with increased yields because the use of crop residues for soil protection is proportional to the amount of land used. Bentsen14 estimates a 12% increase in agricultural residues which are theoretically available through agricultural intensification in Western, Northern and Southern Europe (from 204 to 229 Mt dry matter yr^{-1}). This increase in crop residues through agricultural intensification is relatively low in these regions, since high input agriculture is already commonplace here.

To summarise, whereas some studies project an increase in the bioenergy potential from energy crops, other studies project a slight decrease. All studies show a shift in shares from annual crops to perennial crops. The larger shares of perennial crops occur with stricter sustainability constraints. Projections of primary residue availability remain equal between now and 2030. Future estimates on the share of energy crops and primary agricultural residues in the total agricultural feedstock vary between studies. But the share of energy crops is expected to decrease by including stricter sustainability constraints on biodiversity conservation and GHG emissions.

Although the bioenergy potentials from the studies are compared to each other, separate model potentials are based on different assumptions. A detailed comparison of biomass potential studies is only possible if studies precisely state their key assumptions, such as projections on food demand, productivity increases, and energy crop selection and yields [18]. Some of these key assumptions are, however, not explicitly discussed in the reviewed studies thereby lowering the comparability of these studies. The review, however, clearly shows that identifying sustainable pathways for European bioenergy production requires an integrative modelling approach. Land demand for food, feed and energy crop production should be combined and the consequent environmental impacts, including GHG emissions, nature and biodiversity conservation, and soil, water and air protection,

should be determined. The environmental effects of agricultural intensification, in particular livestock intensification and sustainable intensification measures, need to be parameterised and included in studies and models to enable a comprehensive assessment of the sustainability of bioenergy.

4. Conclusions

This study identified shortcomings in bioenergy potential estimates by reviewing how studies include agricultural intensification measures and environmental sustainability constraints, and subsequently how the associated environmental and land use effects are modelled.

One of the key factors in bioenergy potential studies is the rate and nature of intensification of existing agriculture land to release more land for energy crops while simultaneously securing food supply. Our review shows that the biomass potential studies partly include the effects of agricultural intensification on the extent of surplus land to cultivate energy crops and on straw availability. Crop and livestock productivity developments are included in all the studies projecting future energy potential. Different methodologies are applied, which vary in completeness, level of parametric detail and representativeness of future developments. However, the environmental impacts of intensification are nearly always ignored, while these impacts should be accounted for if intensification is required to make land available for energy cropping.

In particular, livestock productivity developments are less detailed in their parameterisation included in most studies and models. Livestock production requires a large extent of both arable land and pastures. A detailed representation of agricultural developments is therefore essential to estimate land availability for energy crops. In particular, pasture productivity is ignored in most studies while pastures occupy the largest share of agricultural land, while they only provide a small share of food and its intensification potential is large. The effects of changes in pasture productivity on biodiversity, GHG emissions and nutrient leaching should also be carefully considered. Data on pasture productivity and the effects of intensification of pastures is, however, limited. Livestock productivity developments should also be considered in estimating future straw potentials, because the demand for straw for animal feed and bedding varies between livestock systems. Agro-economic models and biophysical models are able to assess the environmental effects of changes in crop and livestock productivity, although often limited to GHG emissions, and nutrient leaching and runoff. All environmental effects (also on biodiversity, soil, water and air) should be recognised in future studies to assess the sustainability of bioenergy. This could be done through the better coupling of comprehensive agro-economic models (that estimate the demand for agricultural land) and biophysical models (that estimate the environmental effects of crop and livestock production and land use).

Our review further shows that all studies incorporate sustainability criteria on biodiversity conservation and GHG emissions by excluding certain areas (primarily forests and wetlands). Most studies, however, neglect sustainability constraints other than GHG emissions on the crop type selected and rather select crops on basis of highest yield, highest GHG abatement or lowest production costs. Sustainability constraints on crop selection considered are mostly limited to rainfed agriculture and perennial crops only on pastureland, while constraints to diversity (e.g. minimum number of crop species and structural diversity within cropping areas) are not considered. In addition, management practices leading to possible positive environmental effects of energy crops, for example intercropping food-energy or energy-energy crops or integrating energy crops in existing crop rotations, are missing in the reviewed studies.

Future productivity developments of crops and livestock in models are currently limited to conventional intensification whereby the proportion between inputs and outputs is fixed. Sustainable manage-

ment practices, such as intercropping, precision farming and optimising feed efficiencies, increase yields with similar or lower inputs. In general, the environmental effects of such advanced practices are lower than conventional intensification measures. A better inclusion of such sustainable practices into the model-based analyses will thus improve the assessment of intensification and its environmental consequences.

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Appendix A. Supplementary information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.rser.2016.11.036.

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