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Review

A Critical Review on Lignocellulosic Biomass Yield Modeling and the Bioenergy Potential from Marginal Land

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Abstract: Lignocellulosic biomass from marginal land is needed for a social–ecologically sustainable bioeconomy transition. However, how much biomass can be expected? This study addresses this question by reviewing the limitations of current biomass yield modeling for lignocellulosic crops on marginal land and deriving recommendations to overcome these limitations. It was found that on the input side of biomass yield models, geographically limited research and the lack of universally understood definitions impose challenges on data collection. The unrecognized complexity of marginal land, the use of generic crop growth models together with data from small-scale field trials and limited resolution further reduce the comparability of modeling results. On the output side of yield models, the resistance of modeled yields to future variations is highly limited by the missing incorporation of the risk of land use changes and climatic change. Moreover, several limitations come with the translation of modeled yields into bioenergy yields: the non-specification of conversion factors, a lack of conversion capacities, feedstock yield–quality tradeoffs, as well as slow progress in breeding and the difficulty of sustainability criteria integration into models. Intensified political support and enhancement of research on a broad range of issues might increase the consistency of future yield modeling.

Keywords: bioeconomy; black locust; eucalyptus; giant reed; miscanthus; reed canary grass; Siberian elm; switchgrass; poplar; willow

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1. Introduction

Global agriculture in the 21st century is facing a multitude of challenges, especially the drastically growing demand for food, fodder and industrial biomass for an increasing population [1]. This population growth is expected to increase the need for food and animal feed from today's 2.1 to 3 billion t in 2050. Compared to 2007, a rise in the global food production by 70% until 2050 is necessary [2]. This growing demand for biomass, the intensifying impacts of climate change and incremental water scarcity require more sustainable agricultural production systems. It is estimated that the expansion of agricultural production until 2050—of which 80% is expected to take place in developing countries—demands higher yields, intensified cropping and land expansions of around 70 million ha globally. As the future availability of arable land is expected to decline in developed countries, the necessary land expansion will need to take place mostly in developing countries, especially in sub-Saharan Africa and Latin America [3]. At the same time, the transition of the global fossil-based economy towards a bio-based economy, a so-called 'bioeconomy', demands industrial biomass in large quantities for conversion into bioenergy and bio-based materials [4]. Projections suggest a total biomass demand of 6.7 to 13.4 billion t p.a. in 2050, amounting to a 198 to 396% increase compared to 2011 (3.4 billion t p.a.) [5].

A highly promising strategy to avoid the accretive competition of food and non-food crops for land is the cultivation of lignocellulosic biomass on marginal agricultural land (hereinafter referred to as "marginal land"). Agricultural land that is not suitable for the cultivation of food crops is used for growing selected industrial crops [6]. This becomes even more promising when considering that in sub-Saharan Africa and Latin America—the hotspots of future land expansions—a high share of the land potential is subject to physical–chemical limitations or lacking input factors and thus is not suitable for high-demanding food or fodder crops [3]. Two second-generation bioenergy feedstocks are of special interest for cultivation on marginal land: non-edible oilseed crops (e.g., *Millettia pinnata* L.; *Jatropha* L.) and lignocellulosic biomass crops (e.g., *Miscanthus* (*Miscanthus* Andersson)) [7]. In addition to lignocellulosic crops' adaptability to marginal land, further important benefits are their high energy yield and density per unit biomass and volume [8]. Furthermore, the low cultivation costs and reduced environmental impacts of perennial lignocellulosic crops are outstanding [9]. The high energy density is also the reason why lignocellulosic crops are recommended to not be primarily used for the production of platform chemicals for bio-based materials [9]. The cultivation of annual and perennial lignocellulosic crops on marginal land might allow an expanded production of bioenergy without endangering food security [10]. The International Energy Agency evaluates the cultivation of lignocellulosic feedstock and their transformation into biofuels as one of the best options for reducing greenhouse gas emissions. Lignocellulosic biomass can be cultivated on soils of different quality, while providing a remarkably high biomass output. This is one of the reasons for the increasing political support for the conversion of lignocellulosic feedstock to bioenergy: for instance, in the United Kingdom, double Renewable Transport Fuel Certificates are granted for lignocellulosic biofuels [11].

The growing political and economic interest in lignocellulosic feedstock cultivation on marginal land necessitates precise biomass and bioenergy yield estimations and forecasts. Reliable and science-based biomass and bioenergy estimates and projections are essential for societal, political and economic decision-making, as well as for the development, adaption and refinement of climate mitigation scenarios and strategies [12]. This review holistically assesses the current practice of lignocellulosic crop yield modeling within the scope of marginal land (Figure 1). Thereby, the focus is on the cultivation of lignocellulosic crops on marginal land for a future bioeconomy, specifically the conversion into bioenergy.

Firstly, the question will be addressed whether globally and trans-nationally consistent definitions and data available for the cultivation of lignocellulosic crops on marginal land exist.

Secondly, this review aims to reveal the predominant shortcomings limiting the informative power of biomass yield modeling on marginal land and the translation of lignocellulosic biomass yields into bioenergy potentials.

This review does not focus on socio-economic restrictions (e.g., food sovereignty), which could limit the use of the land, the biomass obtained and the energy yield. Nevertheless, reference is made to key techno-economic aspects when applicable, providing a holistic view on the underlying issues. From an economic perspective, this review only considers low- and medium-input cultivation practices on marginal land [13] and thus excludes high-input cropping systems.

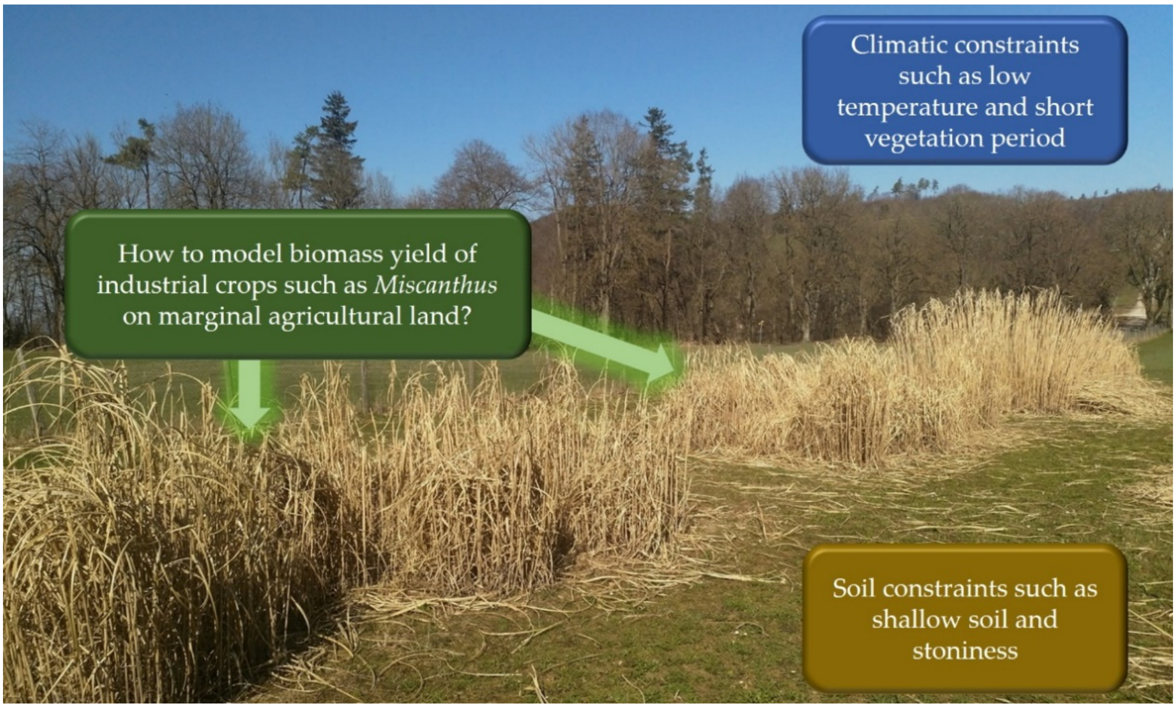

Figure 1. Schematic overview of the subject of this study using the example of the cultivation of different *Miscanthus* Andersson genotypes whose performance has been tested on a shallow stony soil in southwestern Germany since 2014. Clear differences in aboveground biomass growth can be seen here (photograph was taken in winter 2019–2020). These result not only from climatic and soil physical site influences but also from the physiological and morphological characteristics of the genotypes.

Regarding the geographical boundaries, urban marginal lands are excluded from the review. Within the scope of this research, a literature review was performed. Literature on lignocellulosic crops, industrial biomass feedstock, marginal land and crop-specific modeling studies on lignocellulosic feedstock were researched via Scopus, Google Scholar, Wiley and Web of Science. To derive shortcomings and limitations from a broad number of conducted yield modeling studies (Table 1), the authors not only researched general lignocellulosic yield modeling approaches, but also crop-specific modeling such as yield modeling of *Miscanthus* [14] (Figure 1) and *Populus* L. on marginal land [15].

In the following sections, first a contextualization of lignocellulosic crops and bioenergy will be given, including an overview on applied definitions, as well as statistical data for the global cultivation and usage. Secondly, the main characteristics of marginal land are summarized, and the ways these terms are defined in different disciplines on marginal land are analyzed. In the third part, shortcomings and limitations within the current yield modeling practice will be assessed, revealing major unknown factors today's methodology does not take into account.

2. Contextualization of Lignocellulosic Crops, Bioenergy and Marginal Land

2.1. Definitions of Lignocellulosic Crops

Lignocellulosic crops are characterized by a content of about 80% lignocellulose (the sum of celluloses, hemicelluloses, pectins and lignins), and thus could be defined as a subgroup of industrial crops, as they are not suitable for human or animal consumption and are thus cultivated exclusively for industrial use [16,17]. The European Technology and Innovation Platform for Bioenergy defines lignocellulosic crops as species containing varying contents of lignin, different chain lengths and varying degrees of polymerization [18]. The three constituents are cellulose, hemicellulose and lignin, together building the so-called microfibril [19]. Lignocellulosic crops are the most abundant renewable feedstock on this planet, and compared to crude oil, biofuels from lignocelluloses show enormous cost advantage potentials [20] Lignocellulosic crops can either be used as feedstock for renewable energy production or the lignocellulosic fibers can be used for the production of various (bio-based) materials and platform chemicals (e.g., organic acids, furfurals, sugar alcohols or 5-Hydroxymethylfurfural) [10,20,21]. Regarding the biochemical production of fuels, ethanol and butanol are the most interesting pathways [22]. For both energetic and chemical application, cellulose and hemicellulose need to be converted chemically or by (hemi-)cellulolytic enzymes to produce sugars (predominantly glucose and xylose). These sugars are then fermented by yeasts or bacteria to either ethanol/butanol or other platform chemicals [23]. A second possible bioenergy pathway—producing electricity and heat as well as liquid and gaseous fuels—is thermochemical conversion, especially via combustion, gasification, pyrolysis, liquefaction, carbonization and co-firing [24]. In the production of bioenergy from lignocellulose, lignin is the main by-product. Among other options, the production of phenols (e.g., vanillin or ferulic acid) and carbon additives or the direct usage of lignin as an additive (e.g., in the paper industry) is possible [23].

Nearly all lignocellulosic crops are perennial crops, so a re-cultivation or sowing is not necessary after cutting and harvesting for a certain number of growing cycles [17]. Lignocellulosic crops include perennial herbaceous grasses, also called grass-like crops (e.g., *Miscanthus*, *Panicum virgatum* L. (switchgrass), *Phalaris arundinacea* L. (reed canary grass), *Arundo donax* L. (giant reed), *Lolium perenne* L. (perennial rye grass)), as well as fast-growing tree species, so-called short rotation coppice or woody biomass (e.g., *Salix* L. (willow), *Eucalyptus* L'Hér (eucalyptus), *Paulownia* (Siebold & Zucc.), *Populus* L. (poplar)) [17,25]. The latter are usually cultivated in relatively short rotation cycles, and more precisely, either in coppicing systems (the stump is left for regrowth) or replanted after each harvest [10]. The European Technology and Innovation Platform for Bioenergy also includes wood from forestry in their definition of lignocellulosic crops, but does not consider it as a sustainable feedstock for bioenergy [18]. From a biochemical point of view, lignocellulosic crops can be distinguished by lignin and nutrient content; higher in lignin but lower in nutrients is woody biomass, mostly low in lignin and showing a higher nutrient content is associated with herbaceous biomass (mostly grasses) [26].

2.2. Statistics and Forecasts

Neither the Food and Agriculture Organization of the United Nations (FAO) nor other governmental or non-governmental organizations record coherent data for the cultivation and/or usage of lignocellulosic biomass on a global scale. The FAO collects data for the cultivation and harvest of different industrial and non-industrial crops, but usually does not consider their final usage (e.g., food, feed or energy) [27]. The FAO lists crops in different categories (e.g., primary crops, fiber crops), and data are collected at farm level, not considering any processing steps [28]. Having a more detailed view on fiber crops, the FAO includes different lignocellulosic crops, for instance, China grass, Indian hemp, agave or Mauritius flax [29]. As fiber-rich crops are unsuited for human or animal consumption, their industrial usage can be assumed, but there is no final evidence included in the FAO metadata [17]. Moreover, only estimations of global land use for industrial lignocellulosic feedstock cultivation are available, of which a large share is outdated and/or inconsistent [30]. Piotrowski et al. estimated a global biomass production (agriculture and forestry) of 12.1 billion tons in 2011, of which 16% were used for heat and power generation, 10% for bio-based materials and 1% for biofuels [5]. The latter is in accordance with the International Energy Agency (IEA), which estimated that in 2010, less than 1% of global agricultural land was used for cultivating feedstock for biofuels [31]. Nevertheless, these numbers might have changed since then due to rapidly increasing biofuel conversion capacities. Estimations of the land used for bioenergy feedstock cultivation resulted in a 2.7% share of global land in 2008. It is obvious that this percentage is based on outdated data and furthermore varies throughout the literature [5,30]. Data availability for feedstock production considering the type of energy carrier is similarly of poor quality (with an exception for biogas) [17,32].

When it comes to statistical data for the national or regional cultivation of industrial and/or lignocellulosic crops, the data are also insufficient. A positive exception is the European Union (EU); Eurostat not only tracks and documents the total national area dedicated to industrial crops, but also the production of industrial crops on the EU country-specific NUTS 2 scale (basic regions). According to Eurostat, the used agricultural area in the EU consists of 61% arable land, which contains a 7% share of land dedicated to industrial crops [33]. Eurostat provides data for industrial crops in 13 specific crop groups (e.g., rape and turnip rap, other oilseed crops, fiber flax). Some of these crops, parts of them or their by-products can be characterized as lignocellulosic crops, for instance, cotton, hemp, fiber flax, oil palm frond and empty fruit bunch as well as tobacco stalks and other residues [34]. In 2008, approximately 5.5 million hectares within the EU-27 were dedicated to the cultivation of bioenergy feedstock, having a 1% share in the total used agricultural area, equaling 50,000 to 60,000 ha of total landmass [17]. The largest share of the used agricultural area was dedicated to oil crops (82%; for biodiesel), followed by sugar and starch crops (11%; for bioethanol). The largest areas of industrial lignocellulosic cropping are in the United Kingdom (mainly willow and *Miscanthus*), Sweden (willow and reed canary grass), Finland (reed canary grass), Germany (*Miscanthus* and willow), Spain and Italy (*Miscanthus* and poplar) [17]. The literature shows that there are almost no further statistics of industrial lignocellulosic crops available for European countries [17]. One of the countries with sufficient data availability is the United Kingdom, publishing yearly data on crops grown as bioenergy feedstock, recording, for instance, the cultivation of *Miscanthus*, short rotation coppice and straw crops. In 2018, 1.9% of the United Kingdom's arable land was used for the cultivation of bioenergy feedstock (94,000 ha), of which 29% was dedicated to biofuel feedstock. A total of 7000 ha were dedicated to *Miscanthus* (0.1% of arable land) and 3000 ha (<0.1%) were used for the cultivation of short rotation coppice [11].

When it comes to the supply of industrial biomass for the future bioeconomy, the largest feedstock volume will be demanded by the global bioenergy sector, playing an essential role in a future low-carbon economy. For the year 2020, a usage of 84 million tons of energy crops for the production of bioenergy was estimated for Europe [35]. This equals more than a doubling in comparison to 2012 (40 million tons). Looking at the status quo regarding lignocellulosic feedstock, in 2019 only 10 million out of 5505 million liters of bioethanol produced in the EU came from lignocelluloses. In 2019, there were only two European refineries with a total capacity of 60 million liters of cellulosic ethanol production [36]. Regarding estimations of the future demand for industrial (including lignocellulosic) energy crops, a wide-ranging spectrum of biomass-based energy potential estimates is available in the literature. Starting from 2017's global energy use of 1500 EJ, the IEA estimates a possible add-on of 100 to 300 EJ from bio-based resources in 2060. A total of 60 to 100 EJ could be potentially derived from agricultural land, which does not conflict with food safety, leads to only low land use change emissions and complies with a range of sustainability criteria. The IEA considers an additional primary biomass supply of 145 EJ in 2060 as necessary to achieve the Paris climate mitigation goals. This agricultural biomass supply is evaluated as challenging, but achievable [37]. The Intergovernmental Panel on Climate Change assumes a bioenergy contribution of 120 to 160 EJ in their 2050 scenarios [38]. Studies consistently show that globally large areas of marginal and/or degraded land are available and are not suited for food or feed production, but can be used to feed the growing demand for (lignocellulosic) bioenergy feedstock [39].

2.3. Definitions of Marginal Land

The characteristic aspects of marginal land depend highly on the disciplinary terminology, which differs between the environmental biological–ecological, economic, political (legal) and social perspectives. The adjective 'marginal' commonly refers to something 'situated at a margin or border', which is therefore 'not of central importance' and 'close to the lower limit of qualification, acceptability, or function: barely exceeding the minimum requirements' [40]. A clear definition of 'marginal' is context-dependent and subjective to the overall aim of declaration [41]. Marginal land in the context of cultivating industrial crops for bioenergy or biochemical production without threatening food production is often associated with unused, under-utilized, idle, spare, abandoned, degraded, fallow or set-aside land [42]. These descriptions highlight the low quality of marginal land due to challenging climate conditions and soil characteristics, which limit its productivity and therein its suitability for food crop cultivation. This generic definition is relatively consistent across studies with different scopes and disciplines, while the working definitions of marginal land across different studies vary depending on the geographic location in focus, the background of the authors and the aim of the study [43].

2.3.1. Food vs. Fuel Definition

A very broad definition of marginal land is 'land that has bio-physical and/or socio-economic constraints for food production' [44]. Land with easily improvable soil conditions by measures such as irrigation, fertilization or drainage is usually excluded in marginal land definitions to avoid competition with food on that land [41,44]. Marginal land is therefore closely associated with low input and reduced management as economic efficiency is the main determinant of the suitability of cultivation on marginal land [45]. This concept of low input and reduced management has to be distinguished from low-input framing systems, which aim to close input and output cycles to maximize the use of resources produced on the farm site, while minimizing off-farm inputs such as purchased fertilizers and pesticides [46]. Compared to the first definition of von Cossel et al. [44], which highlights the lower productivity of food crops on marginal land, Shortall classifies marginal land as a place 'where food production cannot take place because the land is not productive enough'. Both of these definitions are normative, stating that the land is not suitable for efficient food crop cultivation but assuming that it is technically possible and economically feasible to produce industrial crops there [42]. These definitions, furthermore, indirectly assume that farmers would be willing to dedicate marginal land to industrial crops instead of cultivating these on prime land to avoid indirect land use change (iLUC), a frequently cited negative impact of energy crop cultivation [42,47].

Elbersen et al. go even further and define marginal land as land that has limited agricultural productivity due to negative human interventions that have made this land highly sensitive to degradation [41]. Some authors also include fallow land, which is arable but not cultivated during one cropping season, in their definition of marginal land as it is 'assumed to be kept out of food production in the future with regard to its lower-than-average quality' [48].

2.3.2. Environmental and Biological Definition

There are two main fields of environmental definitions on marginal land: one deals with the soil and climatic conditions (including natural or man-made conditions) of the land, while the other focuses on issues beyond the given conditions and assesses the ecological importance of marginal land. The environmental conditions that make a soil marginal are well defined and were extensively researched with respect to the growth of industrial crops in recent decades [9,41,44]. Most prominent soil and climate conditions leading to marginal land are—amongst others—drought/dryness (<200 mm per growth season), low temperatures (<5 °C), excessive soil moisture/waterlogging, soil texture, shallow rooting horizons (<35–80 cm), soil quality (chemical conditions: salinity > 4 dS m^{-1}, sodicity, acidity pH < 4), soil contamination (natural or human-made toxicity by pollutants, e.g., heavy metals or calcium) and steep slopes (>15–30°) [9,41,44,49]. Especially combinations of these limiting soil conditions, so called negative synergies, impose challenges for the cultivation of industrial crops on this type of land. There are few combinations of the individual factors that cancel each other out, resulting in positive synergies with improved conditions, and the interaction of some characteristics is still unclear [49]. The negative synergies of soil characteristics often favor soil erosion by wind and rain, for example, in Mediterranean countries where high temperatures, limited annual rainfall, steep slopes and low vegetative soil cover prevail [12]. This imposes challenging conditions on the farmers and requires adequate knowledge regarding the right time for tillage and fertilization to minimize soil erosion. Apart from the environmental conditions, biological–ecological conditions are important for assessing the marginality of land as natural vegetation and existing ecosystems can provide habitats for agricultural fauna and contribute to biodiversity [50].

2.3.3. Socio-Economic Definition

A broad economic definition characterizes marginal land by its often poor infrastructure, which leads to limited market access of the goods that could be produced on that land [41] and thereby affects mostly rural areas in regions with difficult accessibility. In more concrete economic terms, marginal land can be utilized 'at the margin of economic viability' [51], meaning that the profit obtained from these lands is close to zero. This definition is prescriptive compared to the environmental ones, as it suggests that under the given set of conditions this land should be used for industrial crop cultivation rather than for food crop cultivation to increase its economic viability [42]. The economic perspective on marginal land is not directly based on the fertility or the conditions of the soil but rather on the relation of inputs and outputs to and from the land. From this perspective, the degree of marginality can only be assessed based on the comparison of different crop production systems on this land as they have varying break-even points due to different inputs and outputs [52]. This understanding of marginality implies that food crops that could be grown on that land might not be cultivated there when a better, more economically beneficial alternative is present, leading to land use change [47].

2.3.4. Political and Legal Definition

As national tendencies and strategies for the mitigation of fossil fuel emissions in the form of energy consumption differ, the boundaries of marginal land change from country to country. For the national assessment of greenhouse gas emissions from land use, land use change and forestry, national subcategories of the six main Intergovernmental Panel on Climate Change categories are determined and evaluated [53]. Regulations regarding the distance between agricultural production and urban areas as well as fresh water sources further limit the availability of marginal land but are often not accounted for, causing an overestimation of marginal land [54]. These different definitions make a comparison between countries difficult [9], and even within Europe a common definition has not been established so far [55]. However, recent studies on marginal land in the EU are trying to establish common ground [41,44,48,49]. In 2019, the EU established criteria for identifying high indirect land use change (iLUC) feedstocks to decrease their use for bioenergy [56]. High iLUC feedstocks describe feedstocks where 'significant expansion of the production area into land with high-carbon stock is observed' [56], which are therefore a threat to the environment. The new directive only allows for an increase in the share of the high iLUC feedstocks' contribution towards the national renewable energy targets for biofuels and biomass from food and feed crops of 1%, based on 2020′s national contribution of food and feed crops to the final energy consumption in transportation by road and rail (ibid.). By 2030, feedstocks with a high risk of iLUC are not allowed to be included in the national calculation of renewable energy in the transportation sector anymore. Nevertheless, the member states are still allowed to import and use high iLUC risk feedstocks [56]. To avoid iLUC, land where no feed and food crops can be grown could be used for the cultivation of industrial crops for bioenergy [57].

2.3.5. Social Definition

The social dimension of marginal areas is very diverse and, like the ecologic-biological dimension, often neglected [43]. Marginal land can serve many purposes other than crop cultivation, such as biodiversity conservation (providing a balanced environment to live in), subsistence agriculture (which generates income and can reduce poverty), educational purposes, the provision of firewood and food in some parts of the world (allowing for a human livelihood) as well the provision of ecosystem services and maintenance of cultural heritage [42,43,58]. Due to lacking measurement methods and the intangibility of many of these social values, their assessment is usually only performed on a very reduced regional scale, if at all [58].

3. Limitations of Current Yield Modeling Approaches on Marginal Land

Several studies assessed in this paper conduct or combine previous yield modeling results to evaluate regional, national or global biomass and/or bioenergy potentials (Table 1). A recent example is the study of Pancaldi and Trindade, concluding that between 28 and 85% (for the 6.7 billion t scenario [5]) and between 14 and 42% (13.4 billion t scenario [5]) of the global biomass demand in 2050 could be met by lignocellulosic crops [59]. The base of this calculation was the yield modeling of Nijsen et al., calculating a global average yearly yield of lignocellulosic crops on marginal land of 7.9 tons per hectare as well as an overall bioenergy potential between 150 and 190 EJ per year [60]. In this review, the input data of biomass yield models for marginal land, their results (output), as well as their general methodology and the interpretation of results were critically analyzed.

Table 1. Overview of biomass yield modeling studies included in this study.

Crops.	Geographical Boundary	Date	Marginal Land Definition	Sources of Input for Biomass Yield Modeling	References
Switchgrass, Giant reed, *Miscanthus*	Mediterranean Basin (Greece and Italy)	1993/7/8 and 2004–2014	Water scarcity, salt and nutrient stress	Soil assessment: not specified Climate assessment: between 2005 and 2014 based on calculation of indices for rainfall distribution according to Monti and Venturi 2007 Yield: empirical data, compared by means of an ANOVA analysis Yield model: No projection of yields (only ex post analysis)	[61]
Low-input high-diversity mixtures of native perennials, *Miscanthus*, Switch-grass	Africa, China, Europe, India, South America and United States	Not specified	Abandoned land as well as mixed crop and vegetation land	Soil assessment: Harmonized World Soil Database (FAO/IIAS 2009) Topography assessment: Global Terrain Slope (Global Agro-Ecological Zones (GAEZ) 2008) Climate assessment: humidity and temperature (Natural Resources Conservation Service NRCS 2001 and New et al. 2000) Yield: based on empirical knowledge and expert opinions Yield model: Fuzzy logic modeling (FLM) to estimate productivity and net energy gain from marginal land	[62]
Poplar, Black locust	Germany	Not specified (part of EU SEEMLA project 2016–2018)	Soil physical and chemical parameters, which give a Soil Quality Rating score < 40	Soil assessment: Muencheberg Soil Quality Rating system based on data from European Soil Database and a geographic information system (GIS) toolset Topography assessment: National Aeronautics and Space Administration (NASA) Shuttle Radar Topography Mission (SRTM), European Environment Agency (EEA) Climate assessment: WorldClim–Global Climate Data, Institute for Veterinary Public Health Yield: empirical data of surrounding fields Yield model: Soil Quality Rating and GIS tool to calculate marginal land availability in Europe	[55]
Black locust, Pine	Greece				
Miscanthus, Poplar, Willow	Ukraine				

Table 1. *Cont.*

Crops.	Geographical Boundary	Date	Marginal Land Definition	Sources of Input for Biomass Yield Modeling	References
Switchgrass, *Miscanthus*, Poplar	Southern Appalachian Mountain region (United States)	2008–2012	Land that is currently not used for food production	Soil assessment: based on United States Department of Agriculture (USDA) Soil Survey Topography assessment: based on literature Climate assessment: *Current*: averages and standard deviations for 30 years (1981–2001) based on DayMet dataset *Future*: from global circulation model, adjusted for the IPCC's medium- and high-emissions scenarios (representative concentration pathway, RCP 4.5 and RCP 8.5) Yield: literature data (of growth period of 4 years 2008–2012), Yield model: process-based crop growth model Agricultural Land Management Alternative with Numerical Assessment Criteria (ALMANAC), comparison between current and future yields by means of an ANOVA analysis	[63]
Switchgrass	Great Plains (United States)	2010–2012	Land with a crop indemnity lower than USD 2,157,068	Soil assessment: based on literature, available soil water capacity from NRCS Topography assessment: United States Geological Survey's (USGS) National Elevation Dataset, USGS compound topographic index Climate assessment: based on literature, USGS irrigation map, USDA Natural Resources, Conservation Service (NRCS), Soil Survey Geographic Database (SSURGO) Yield: derived from satellite-derived growing season Normalized Difference Vegetation Index (NDVI) for 2010–2012, USGS crop mask (from USDA National Agricultural Statistics Service Cropland Data Layer) Economic suitability: USDA county-level crop indemnity map	[64]

Table 1. *Cont.*

Crops.	Geographical Boundary	Date	Marginal Land Definition	Sources of Input for Biomass Yield Modeling	References
Miscanthus	Hesse (Germany)	Not specified	Produces low yields, similar to set-aside farm land	Soil assessment: Integrated Administration and Control System for Payments in the Context of the EU Common Agricultural Policy (EC 2007), German Soil Rating Survey (“Bodenschätzung”), Topography assessment: Hessian Agency for the Environment and Geology (Hessisches Landesamt für Umwelt und Geologie), Digital Elevation Model Climate assessment: Hessisches Landesamt für Umwelt und Geologie, National Weather Service of Germany. Yield: estimates at field level, literature and expert knowledge Yield model: yield function of the economic GIS-based model ProLand (Prognosis of Land use)	[65]
Miscanthus	Denmark, Germany, Greece, Ireland, Italy, Netherlands, Portugal, Sweden, Turkey, United Kingdom, US	Not specified	Not specified (just labeled ‘different agro-ecological environments’)	Soil assessment: texture class, soil depth and water holding capacity from literature of experiments and FAO’s digital soil map of the word Topography assessment: slope class from literature of experiments and FAO’s digital soil map of the word Climate assessment: from global gridded databases, average monthly weather information (1961–1990) on radiation, temperature, vapor pressure, wind speed, precipitation and rainfall days Yield: Field experiments from literature (used annual biomass yields after 3rd year of growth) Yield model: LINPAC (modified LINTUL model for Perennial and Annual Crops), including sensitivity analysis	[25]
Willow	Canada, Finland, Germany, Sweden, United Kingdom, US				
Reed canary grass	Czech Republic, Finland, Lithuania, Sweden, US				
Eucalyptus	Australia, Brazil, China, Congo, India, New Zealand, South Africa, US				

Table 1. *Cont.*

Crops.	Geographical Boundary	Date	Marginal Land Definition	Sources of Input for Biomass Yield Modeling	References
Russian olive, Euphrates poplar, Siberian elm	Aral Sea Basin (Uzbekistan)	2003–2005	Increased salinity, low ground water availability and reduced irrigation water availability	Soil assessment: based on literature and empirical data Topography assessment: based on literature Climate assessment: based on literature Yield: empirical data, compared by means of an ANOVA analysis Yield model: No projection of yields (only ex post analysis)	[66]
Miscanthus	Loess Plateau (China)	2010	Reduced soil cover by severely eroded soil, landscape degradation and nutrient depletion in the soil	Soil assessment: based on literature and empirical data Topography assessment: based on literature Climate assessment: based on data from Xifeng Meteorological Station (next to the experimental site), from the Data Sharing Infrastructure of Earth System Science Yield: empirical data Yield model: based on the radiation model by Monteith 1977, modified for *Miscanthus* field trials by Beale and Long [67]; Clifton-Brown et al. [68]	[69]
Miscanthus	Italy and Greece	Not specified	Not specified	Soil assessment: literature, expert knowledge Topography assessment: literature, expert knowledge Climate assessment: literature, expert knowledge Yield: literature, expert knowledge Yield model: No projection of yields (only ex post analysis) Economic suitability: Analysis of strengths, weaknesses, opportunities and threats Social suitability: input output analysis	[70]

Table 1. *Cont.*

Crops.	Geographical Boundary	Date	Marginal Land Definition	Sources of Input for Biomass Yield Modeling	References
Switchgrass, *Miscanthus*	US	1989–2008	Abandoned land, land with mixed vegetation and marginal productivity (based on Cai et al. [62])	Soil assessment: based on data from Food and Agriculture Organization (FAO)/Civil Service Reform Committee digitalization of the FAO/United Nations Educational, Scientific and Cultural Organization (UNESCO) soil map of the world Topography assessment: based on data from NASA Shuttle Radar Topography Mission Climate assessment: based on data from European Centre for Medium-Range Weather Forecasts, National Oceanic and Atmospheric Administration Mauna Loa CO_2 record Yield: calculated based on model (based on N and C dynamics) Yield model: AgTEM including ecophysiological, biogeochemical and management-related processes into the Terrestrial Ecosystem Model framework	[71]
Miscanthus, Switchgrass, Giant Reed, Reed canary Grass, Cardoon, Willow, Poplar, Eucalyptus	Europe	Not specified	Low quality land, where only non-competitive yields for rotational food and feed crops can be achieved	Soil assessment: based on data from literature (European Soil classification) Topography assessment: based on data from literature (European Soil classification) Climate assessment: based on data from literature Yield: calculated based on the Aqua Crop model for low, medium and high management practices Yield model: Aqua Crop model from FAO Economic suitability: ABC cost model (for minimum cost prices of feedstock production)	[45]

Table 1. *Cont.*

Crops.	Geographical Boundary	Date	Marginal Land Definition	Sources of Input for Biomass Yield Modeling	References
Miscanthus, Switchgrass, Jatropha	China	Miscanthus 2009–2010, for switchgrass and jatropha not specified	Land that is not a forest, an environmental reserve, a residential area and that is not currently used as cropland or pastoral land	Soil assessment: HWSD (2000–2016), Data Center for Resources and Environmental Sciences, Chinese Academy of Sciences (RESDC, 2015), Institute of Soil Science, Chinese Academy of Sciences (ISSCAS) Topography assessment: NASA Shuttle Radar Topography Mission (SRTM) Climate assessment: Climatic Research Unit Time Series (CRU TS; 2000–2016), China Meteorological Administration (CMA), General circulation model (GCM) Yield: *Miscanthus'* yields (as input for MiscanFor) for 2009–2010 from expert knowledge Calculated based on the respective yield model Yield model: MiscanFor (for *Miscanthus*, Hastings et al. [72]), GIS-based Environmental Policy Integrated Climate Model (GEPIC, for switchgrass; Liu et al. [73]), GAEZ Model (for *Miscanthus*, switchgrass and jatropha; International Institute for Applied Systems Analysis (IIASA)/FAO, 2012)	[74]

3.1. Overview on Yield Modeling Practice and Approaches for Marginal Land

Most studies assessed in this review focus on a select few regions/countries, mainly China, Germany, Greece, Italy, Sweden and the United States, where the cultivation potential of the most common perennial crops including *Miscanthus*, switchgrass, poplar and willow is assessed. The studies frequently use crop yield data from 2000 to 2015 as input parameters, while for the climatic data usually more historical information from 1960 to 1990 is used as this time horizon is commonly provided within the different databases. Several databases are used in yield models to provide all information needed in order to adequately calculate the biomass growth. This includes, for instance, topological data, including soil classification according to different limiting factors, as well as data on crop demands and their development along the growth cycle [65]. This information for each parameter is then transferred onto the respective map of the region(s) under study. Thereby, several maps with different information are generated. Through laying the different maps on top of each other and analyzing overlapping areas, the suitable marginal area for lignocellulosic crop cultivation is determined [45]. Some of the studies additionally assessed estimated future yields, for instance, under different climatic conditions [63]. Another common approach is the comparison of the average biomass yield for a specific region (calculated by a generic model) with empirical regional data to highlight important input parameters that have to be adjusted in the generic models to enable a suitable assessment [25]. For this purpose, these studies make use of generic or crop-specific biomass yield models that go beyond the creation and stacking of maps. In cases where the suitability of cultivating different crops on the same marginal area is compared, authors often have to refer to different generic biomass yield models as only few crop-specific models are currently available (cf. Zhang et al. using MiscanFor, GAEZ and GEPIC [74]).

If different crops in different regions are to be compared, often primary data that have been collected over short or medium time spans are inserted into equations for biomass growth calculation. The limited long-term data availability makes modeling future situations with the current biomass yield models challenging as the increased variance between the different locations and crops cannot be represented sufficiently [61]. The same holds true for models that take multiple ecological, economic and social constraints into consideration, especially if the assessment takes place at field or farm level [65,75].

Depending on the focus of the study, additional disciplinary perspectives might be included: Ramirez-Almeyda et al. [45] extended their study to account for the economic costs associated with cultivating switchgrass and *Miscanthus* in the Mediterranean. Gu and Wylie [64] also assessed the possibility to grow switchgrass on marginal land in the Great Plains (United States) from an economic perspective [64]. Based on the value of the indemnity that has to be paid when cultivating common crops on that land, a threshold was derived that serves as an indicator for the suitability of marginal land for switchgrass cultivation. Harvolk et al. [65], assessed the technical potential to cultivate *Miscanthus* on an area in a small municipality in Hesse (Germany) under consideration of different ecological situations.

Most of the studies reviewed use different sources from the literature, varying databases and sometimes expert opinions when sufficient data are lacking. Due to their different foci, assumptions and boundaries, the results obtained differ widely and provide an adequate snapshot of the current heterogeneity within the field of biomass yield modeling.

3.2. Overview on Limitations and Shortcomings

A summary of the identified challenges and limitations on the input and output side of biomass yield modeling is given in Figure 2. All these factors decrease the comparability of the results from different studies, limiting their interpretation and contextualization [76]. A typical yield modeling sequence starts with the definition of scope and the basic terms and continues with the selection of the model and the input parameters. The resilience of the modeling results can be controlled by means of a comparison with future variations. In addition, several yield modeling studies translate the biomass yields into bioenergy potentials. The final predictions of the yield modeling have to be constantly revised by making use of new models or by updating existing ones. In both cases, the modeling cycle is repeated.

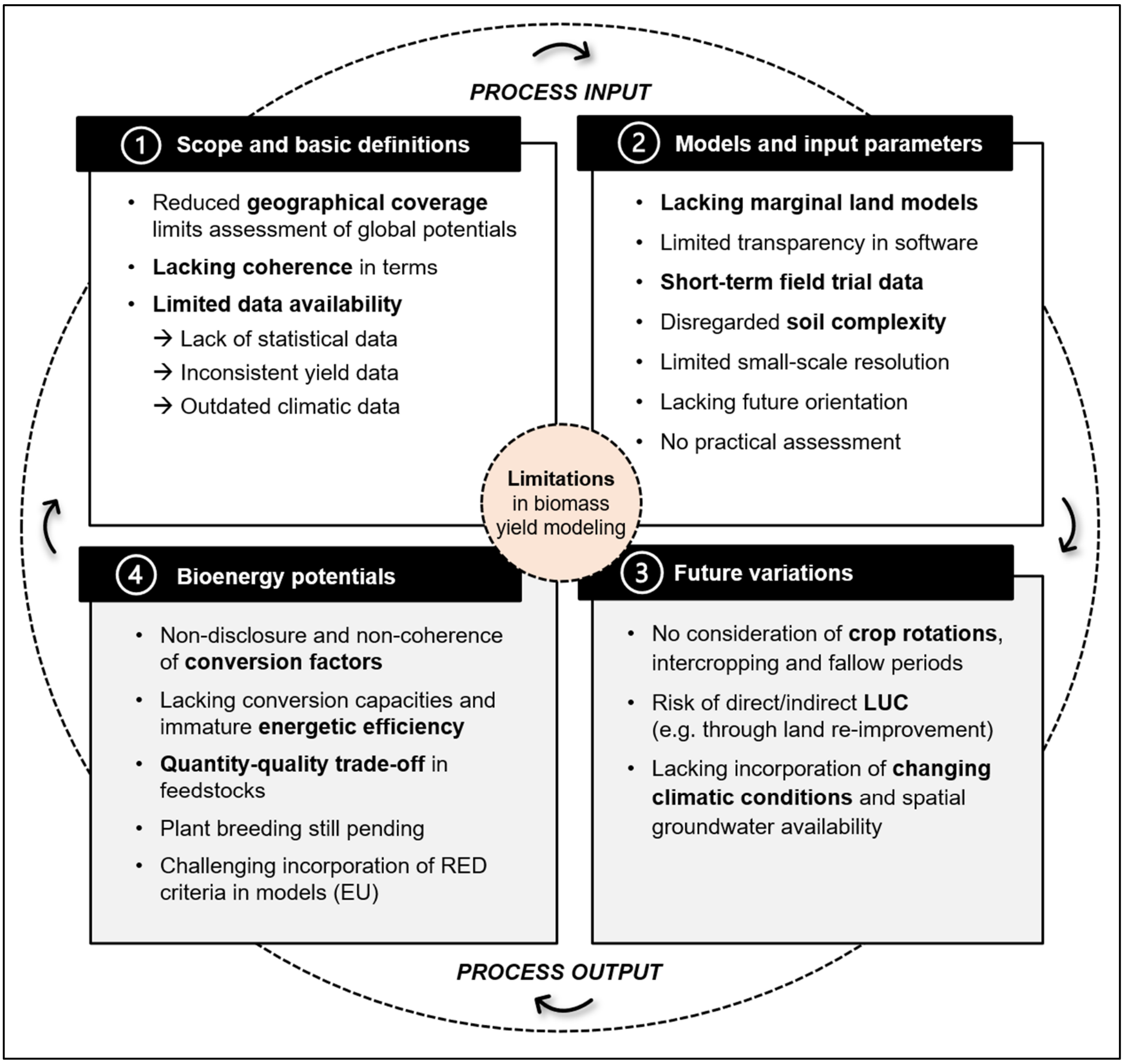

Figure 2. Overview on the most relevant limitations on input and output side of the modeling cycle (RED = Renewable Energy Directive, LUC = land use change).

3.3. Challenges on the Input Side of Biomass Yield Modeling

On the input side, limitations of the current yield modeling practice (including the models applied) can be grouped into two categories: (i) the scope and basic definitions underlying the biomass yield assessment, and (ii) the models and input parameters applied in the modeling (Figure 2). The second category is subdivided into shortcomings related to general aspects of the model while a second category focuses specifically on the challenges of the input parameters used by the models.

3.3.1. Scope and Basic Definitions

The scope of the current research undertaken in biomass yield modeling is geographically narrow and focuses mostly on member states of the Organization for Economic Co-operation and Development, especially North America, Europe and China [58,77].

Models and approaches developed there are presently state-of-the-art and applied in studies conducted all over the world. Due to the varying environmental conditions within and between different countries, models calibrated with data from the Northern Hemisphere are only limitedly suitable for other regions such as Africa or Latin America [25]. Many countries are therefore still unconsidered in biomass yield modeling research. The lack of geographical coverage limits the holistic assessment of the global potential of biomass yield from lignocellulosic crops and might lead to forgone potentials.

To ensure comparable, realistic and detailed results from biomass yield leading to suitable decisions on the spatial and temporal distribution of biomass cultivation, the underlying basic definitions of the input parameters have to be coherent [42]. Currently, there are no standardized globally accepted definitions of the most important inputs to the modeling process including marginal land and industrial and lignocellulosic crops. These definitions are highly contextual and study-dependent, and even though most of them share a common core, variances in the wording and the conscious inclusion or exclusion of certain aspects lead to very different perceptions and interpretations [43]. For example, while a common guideline to assess marginal land in Europe exists [49], the amount of land classified as marginal varies widely between studies. This implies that the validity and reliability of studies calculating the global marginal land availability are reduced because they do not account for differences in local definitions. Instead, they often apply the same definition to all locations, which can result in an overestimation or underestimation of the actual potential. To avoid this problem, some studies assess marginal land from the perspective of the current use of the land and the potential to change this land use to favor lignocellulosic crop cultivation. This approach does not consider the reasons for a certain current land use and will lead to inadequate results, which can only be corrected if biophysical data are additionally considered [55]. In the case of crops, the lack of coherent definitions leads to vague distinctions of the different types as few classification criteria exist [78]. In some statistical assessments, for example, corn is classified as an industrial crop for animal feed but it can also be destined for human consumption (with or without refinement), which would then convert it into a food crop. The same holds true for other multipurpose crops such as soybean, sorghum and cotton. Without a precise, internationally agreed definition (or a fixed set of definitions) of industrial, lignocellulosic and food crops, the underlying competition for land between these crops cannot be evaluated.

The lack of definitions further imposes challenges on the data collection of marginal land availability and biomass yield achievability. On a global scale, accurate statistical data are often missing [79], and even between the different European countries the quality and quantity of datasets vary widely (for instance on soil conditions) [55]. This leads to situations where the input parameters date back to different years, increasing the uncertainty and inaccuracy of the final result, especially for climate data where values from the 1960 to 1990s are often used. Comparisons of studies thereby become more challenging, and especially for promising lignocellulosic crops such as *Miscanthus*, very few long-term yields are available at national or international level. This might be due to the recent interest in *Miscanthus* as a bioenergy crop and the complex interactions between a number of factors such as planting method, species and site conditions [45]. Not only for cultivation on marginal land, but also for growth on arable land, no data are (publicly) available for *Miscanthus* from Eurostat, FAO or USDA. Assessing if yields on marginal land are significantly lower than on arable land is nearly impossible then and might lead to less accurate definitions of marginal land, their estimated future availability and the amount of biomass yields that can be achieved from that land. Overall, the contextualization of biomass yield modeling results becomes more difficult if the availability of representative, high-quality data, which is based on the same definitions at regional, national and global scale, is limited [61].

3.3.2. Models and Input Parameters

Modeling approaches also need to shift their focus towards a more detailed and holistic evaluation of biomass growth, as currently used biomass yield models are mostly generic. Generic models such as the frequently used GAEZ or GEPIC model are based on average growth data for a variety of crops [74]. Zhang et al. in their study on *Miscanthus* growth on marginal land in China calculated an average annual dry matter yield of 0.318 Mg ha^{-1} with the GAEZ model, while the MiscanFor model predicted annual dry matter yields of 14.6 Mg ha^{-1}. MiscanFor is a software for biomass yield modeling (developed in Europe) that is specifically calibrated for the *Miscanthus* genotype *Miscanthus* × *giganteus* [74]. The differences in the yield might not only be caused by the different types of models, but it is reasonable to assume that the more detailed MiscanFor estimations lead to more precise results [61]. Nevertheless, no specially tailored models for biomass growth on marginal land exist currently [55]. The results obtained from the applied models are thus based on information from arable land. Some marginal land parameters—such as specific soil and climatic conditions—can be inserted into models, yet they cannot be represented in their whole complexity.

Besides having arable land as a basis for biomass yield modeling, most crop growth models are compiled software packages that do not provide open access to the source code used [80]. The model users can therefore not trace and reproduce the calculations performed by the model. This reduced transparency increases model uncertainty as the influence of the model's internal structure on the simulation output cannot be fully assessed and the chosen input parameters might only be limitedly related to the calculated output [81]. Semenov and Porter [82] additionally highlight the limited range of data on which the calculations were based and the increased amount of assumptions and hypotheses underlying the biomass yield models. These input uncertainties together with the model uncertainty increase the output uncertainty and the reliability of the results [83]. Holzworth et al. [84] mention the lack of focus on universal software platforms as a reason for the reduced efficiency in agricultural modeling. This also leads to an increased gap between the software industry and agricultural production researchers [84]. This lacking connection between the two most important actors within the biomass yield model sphere promotes inadequate representations of the growth process. For example, the MiscanFor model calculates biomass yields of *Miscanthus* based on yields of mature rhizomes, which are usually only achieved after three to five years [79]. In the first years after the establishment, *Miscanthus* yields are much lower, which should be adequately represented in the models to avoid an overestimation of the results [61]. However, the relatively stable yields after the establishing period allow predictions of biomass yields from perennial crops if adequate data for all input parameters are available [25]. The sequence in which the different input parameters and their thresholds accounting for the marginality of the land are inserted into the model is also important. Different data compiling methods and pre-selections alter the amount and characteristics of marginal land estimated [74]. The points mentioned above provide reasons for the very limited comparability of the results obtained from biomass yield models and the huge variations in marginal land, yield and energy potential estimations.

The concrete input parameters used in biomass yield models on marginal land are often grounded on short-term field trial data [85]. These data are not representative, as only certain management practices and few soil characteristics are included, which insufficiently account for the complexity of marginal land [45]. In addition, the whole growth cycle cannot be assessed by means of three-year trials and the use of average yield data further reduces the accuracy of the model outputs [79]. This puts the importance of local environmental and climatic conditions into focus [74]. One of the most important parameters is the soil, as it provides the basis for biomass growth. The interactions within the soil and between the soil and the other environmental parameters are highly complex and site-specific. The combination of individual marginal soil characteristics can create positive, negative or unclear synergies [49]. Unclear synergies were reported for the combinations of excess soil moisture and stoniness, organic soil texture and steep slope, stoniness and heavy clay texture, sandy texture and heavy clay as well as heavy clay and steep slope [49]. As the interactions between soil, crop and climate are very complex, it is difficult to assess the performance of a crop on marginal land, especially when negative synergies are present. These mutual influences increase the complexity of soil systems even further, making a detailed assessment of the soil necessary for an adequate representation in the model. Many models neglect this complexity by determining a land's marginality based on only one threshold or a few averaged values. For instance, on marginal land where low crop management and no/very limited irrigation are prevailing, the various soil conditions influencing the water holding capacity (e.g., slope, soil texture and soil cover) need to be assessed in conjunction with each other to assess if sufficiently high yields can be achieved [76]. *Miscanthus*, as one of the most promising future bioenergy crops, is often given as an example for cultivation on marginal land due to its reduced environmental and management demands. Nevertheless, *Miscanthus* has a low resistance to drought and abiotic stress [86]. This reduces its suitability to be grown on marginal land, for example, on steep slopes in the warm Mediterranean regions, because abiotic stresses are often present in combinations, for example, drought coming along with heat, or in successions as in the case of waterlogging followed by drought [87]. As not all crops are equally suitable for the same soil and environmental conditions, the assessment of only one type of crop on marginal land might not be sufficient to identify the best land–environment–crop fit [74]. As important as a detailed environmental assessment is, it is often practically difficult to model certain physical constraints such as damages from strong winds. Apart from modeling the damage, a probability for the damaging event as well as a recovery period with lower growth would additionally have to be modeled, which further increases complexity. Depending on the specific location, for example, coastal areas, it is useful and necessary to take these aspects into consideration [88]. Overall, the degree of detail of each study depends on its objective as well as time and financial constraints.

In addition to input data, the modeling process needs to be conducted at high resolution [74]. The resolution of the results depends on the lowest resolution of the input data and studies highlight the assessment at a 1 km^2 scale as most adequate [55,65]. For example, Richter et al. [89] calculated an average dry matter yield of 9.6 t ha^{-1} for *Miscanthus* cultivated in the United Kingdom, while Aylott et al. [90] modeled a combined short rotation coppice yield (willow and poplar) of 9.7 DM t ha^{-1} for the same area. Bauen et al. [88], however, using a 1 km^2 grid resolution, predicted an average yield of 11.9 DM Mg ha^{-1} for the United Kingdom when selecting the highest yielding crop (*Miscanthus*, poplar or willow) for each grid. Schorling et al. [91] in their study on *Miscanthus* yields on marginal land in Germany also obtained more accurate results compared to a Europe-wide study assessing the same. Their detailed geographical, climatic and geological data input allowed for the avoidance of an overlap in the types of areas (e.g., rural villages and marginal land) and accounted in detail for areas where the soil composition changed [91].

The time dependency of the yields calculated by the models is an additional source of uncertainty [55]. Changes in the climatic data have a severe influence on the yields, but few studies predict future yields based on future data, instead using past data, though valid predictions exist, e.g., from Intergovernmental Panel on Climate Change for climatic data [74]. Most studies therefore claim to make an ex ante assessment but make use of ex post data, which provide only limited suitability and reduce the study's validity. This insufficient long-term orientation of the input data is caused by a combination of all the aforementioned factors.

With regard to the extensiveness and inclusion of different perspectives, biomass yield models have to be improved. Many studies model the technical potential of biomass cultivation on marginal land but lack a practical orientation. Yields are thereby calculated based on input environmental data (especially area) that do not take the social, cultural and ecological value of the land into consideration [77]. The estimated yields from these models are therefore theoretically and technically available, but not practically feasible as they might come along with great socio-economic changes and distortions. Therefore, calculating the technical potential provides a rough overview of the spatial distribution of biomass cultivation potentials and highlights areas that might be worth further investigation [74]. To avoid an overestimation of biomass yields and to adequately assess the long-term feasibility of perennial crop cultivation on marginal land, taking socio-economic and political criteria into consideration is necessary [61].

Marginal lands provide ecosystem services that are positively or negatively influenced by the crop cultivated and the applied management system [92]. These changes drastically affect the local population, their lifestyle and livelihoods and should therefore be assessed as part of a realistic biomass yield model. In addition, the land that is considered marginal is frequently privately owned, so including this land in the calculation is only suitable if the owner is willing to cultivate the selected crop on their land [45]. Apart from land availability, crop cultivation also requires labor. Beyond the recurring crop management activities such as fertilization and harvesting, labor is especially needed for the initial field preparation and the planting of the *Miscanthus* rhizomes as this is usually performed by hand [93]. Recently, many people moved from rural areas, where marginal land is located, to cities, leading to a decrease in the rural labor force, which in the long run can impose challenges on the crop cultivation on marginal land [3].

Biomass growth is an investment, and planting costs, in particular for crops such as *Miscanthus* that cannot be sown, are high and likely to increase if perennial crops are cultivated on marginal soils [45]. These planting costs are sunk costs, which cannot be recovered by the farmer and might deter marginal landowners from investing in *Miscanthus* cultivation, especially because the yield obtained is rather lower in the first years, which increases risk. Considering the economic perspective of biomass growth on marginal land is also important because the stable long-term yields (starting from the fourth or fifth year of cultivation) reduce the farmers' flexibility to grow other crops when the market conditions for the perennial crops negatively change [45].

The aspects considered above are closely related to the political and institutional environment. Policy support for the industrial use of biomass is needed to increase the cultural and social acceptability of biomass as an energy feedstock [74]. To convince the local society that crop cultivation on marginal land is useful, more long-term data over the whole growth cycle of the crop must be generated and made available. This is difficult when the funding for most studies is limited to two to three years [55]. Furthermore, current research is mostly conducted on field trial areas with a limited amount of different environments available, which further decreases the validity and thereby society's trust in the obtained results [74]. Another challenge is the limited transnational cooperation, which reduces the exchange of experience and the potential to develop a standardized framework that is applied consistently [55]. In addition to data generation, the implementation and promotion of the studies' recommendations throughout the different sectors is an important task where political guidance can still be improved [57].

3.4. Challenges on the Output Side of Yield Modeling

The following chapter will shed light on the limitations and shortcomings related to the output side of yield modeling (Figure 2). Therefore, the suitability of selected yield modeling to incorporate future variations and issues related to the translation of yield modeling results into bioenergy potentials and the incorporation of Renewable Energy Directive-related sustainability criteria into models will be critically assessed.

3.4.1. Challenges Due to Future Variations

Yield modeling studies are often conducted for only a certain crop or species on a defined area of land, ignoring future variations (Figure 2). The modeling results cannot be considered as a sufficient statistical base for biomass yield predictions, as also marginal land, crop rotation and partially also intercropping can play an important role [12,13]. The failure to incorporate the necessity of crop rotations and the potentials of intercropping is a common problem of yield modeling studies. *Miscanthus*, for instance, cannot be grown alone over decades with consistently high yields [74]. That a long-term mono-cropping of lignocellulosic crops should be avoided is part of the Renewable Energy Directive and thus a criterion for the sustainable production of biofuel feedstocks. To support agro-biodiversity within the EU, a mix of at least three perennial crops (covering both herbaceous crops and short rotation coppice) per region is required according to the guideline EU 2018/2001 [94]. With this in mind, the extensive modeling of single crops or single crop categories for whole regions or even whole agricultural zones within the EU is unfavorable [25,65,70]. Furthermore, it needs to be considered that farmers might also leave marginal land fallow within their lignocellulosic crop rotation systems [57]. Marginal land might not be agriculturally used for one cropping season to recover, or because of several socio-economic decisions (e.g., lacking market opportunities). The critical issue is that this practice would influence the overall yield, which would then differ from the modeled yield (if no crop rotations, intercropping or fallow periods are assigned). Especially in the case of biomass and bioenergy potential predictions for several decades, the lack of modeling crop rotations might subvert the mid- and long-term validity. This becomes even more alarming when considering that crop rotations were neither mentioned nor incorporated in any of the studies assessed within the scope of this research, even though there are some promising tools available such as CropSyst (http://modeling.bsyse.wsu.edu/CS_Suite/index.html (accessed on 22 November 2021)).

Depending on the definition of marginal land—especially if fallow land is declared as marginal land—and depending on the intensity of crowding out effects, iLUC and direct land use changes (dLUC) can occur. Firstly, these might undermine the ecological benefits of lignocellulosic crops cultivated on marginal land. Secondly, they might subvert the results of biomass yield modeling. Crowding out effects might occur when marginal land was originally defined as economically marginal, but a higher demand for food crops revokes economic marginality. Furthermore, there is the possibility to use marginal land as food crop land after a certain period of energy crop cultivation, during which the soil quality has improved sufficiently. Zhang et al. suggest a period of 15 years as a sufficient timespan for soil amelioration [74]. It is reported in the literature that the cultivation of perennials can reduce soil erosion, capture nutrients, stabilize the soil through rooting, maintain a more firm structure, provide a habitat for wildlife and boost biodiversity, and moreover store carbon in the soil (soil-carbon sequestration) [92]. These beneficial effects might lead to a sufficient remediation of marginal land and allow future food production. This would reduce the mid- and long-term biomass potential on the affected marginal land. These possible shifts are not at all incorporated in the assessed biomass yield modeling studies, even though the risk of drastic changes in the future land availability is high. Two conceivable scenarios might come with the remediation of marginal land: in the first case, improved soils continue to be used for lignocellulosic feedstock cultivation. Assuming an increasing demand for food and feed, food production might be displaced to other areas, resulting in iLUC. In the second case, the cultivation of lignocellulosic crops might be relocated to new land, causing dLUC. This presupposes that the originally environmentally marginal land has sufficiently improved and is again used for food cultivation. If in both scenarios the sum of LUC equals the sum of re-improved land, the land available for biomass cultivation might remain unchanged. Nevertheless, significant greenhouse gas emissions might occur due to land use changes [95]. If the land dedicated to lignocellulosic crops shifts to new (marginal or non-marginal) land with divergent environmental conditions, the originally calculated biomass yields might be incorrect.

The most severe limitation might be the lack of sensitivity of biomass yield models to future environmental variations, especially regarding highly complex climatic changes. For common food crops, significantly decreasing yields are already reported as an effect of extreme weather, temperature and precipitation events [96,97]. Nevertheless, varying climatic conditions affect crops in different ways, as they can be either positive, negative or outbalance each other. Especially for lignocellulosic crops, it is not known yet how quickly they can adjust to shifts in climatic conditions [74]. The main problem with modeling systems is the uncertainty inherent in the construction of the future meteorological scenario used as input for the models [82]. This becomes even more problematic when taking into account that precise climatic and ecological data at regional and/or local level would be necessary to properly map environmental changes [88]. For instance, short rotation coppice demands sufficient groundwater levels. Future shifts in groundwater must be investigated and integrated via parameters into models to adequately assess yield potentials of trees on marginal land [74,98]. Once again, the spatial distribution of crop cultivation plays an important role to assess shifts in groundwater [88]. However, not only the environmental conditions but also the crops cultivated might change in the next few decades. Graves et al. observed a tendency of shifting from herbaceous-grassy-like biomass to woody-tree-like biomass due to global climatic change. One of the possible reasons for this systematic change in the agricultural pattern of farmers is the increasing productivity of C3 plants with rising temperatures, compared to C4 plants, where the productivity-increasing effect is limited [63]. This tendency still needs to be statistically proven, but nonetheless adds to the general uncertainty inherent in the methodology of mid- and long-term yield predictions.

In conclusion, yield modeling for lignocellulosic crops on marginal land can lead to drastic over- or underestimations of the exploitable biomass potential. Furthermore, the depiction of actual and historical climatic developments in yield models is already challenging, and the incorporation of future changes is an additional challenge.

3.4.2. Limitations of Bioenergy Potential Assessments

Studies show that the global energy demand in 2030 could be fully covered by the conversion of biomass grown on non-arable land [99,100]. This and other bioenergy projections rely on quantitative data of biomass potentials, often gathered through yield modeling. In fact, one of the main applications of the results of yield modeling studies on marginal lands is the calculation and assessment of bioenergy potentials.

The Compilation of Reliable Quantitative Data

The focus on bioenergy potentials of lignocellulosic crops grown on marginal land can be explained by the increasing need for reliable, quantitative data on the potential of biomass and bioenergy within the scope of climate change mitigation. In the Special Report on 1.5 Degrees [101] and the Special Report on Climate Change and Land [95], an even broader view on bioenergy was taken. Amongst other issues, socio-economic and environmental limitations of biomass cultivation were assessed in detail by the Intergovernmental Panel on Climate Change, especially in the Special Report on Climate Change and Land. This is an important indication of the increasing relevance of qualitative risk assessments and quantitative bioenergy potential analyses, providing a basis for climate mitigation strategies. Often, a bioenergy yield estimation is performed as part of a yield modeling study (Figure 2). For instance, Scagline-Mellor et al. model yields for *Miscanthus* and switchgrass on marginal land for the eastern part of the US [102]. The biomass yields per hectare are used to further model bioethanol yields per hectare. Regarding marginal land within the area of Boston, outgoing from a crop yield of 42,130 tons of poplar (per growing season), a bioenergy yield of 830 TJ (higher heating value, HVV) is calculated in a study of Saha and Eckelmann [103]. Mehmood et al. list 15 crops (e.g., *Miscanthus*, switchgrass, reed canary grass and agave) and summarize studies conducted and yields modeled, as well as their geographical boundaries [76]. Furthermore, the listed biomass yields are connected to bioenergy potentials, citing relevant biomass and bioenergy yield modeling studies. However, it was not always clear how the conversion from biomass yields to bioenergy potentials was performed [76]. Panoutsou and Chiaramonti evaluated the positive impacts of cultivation and conversion of *Miscanthus* into bioenergy (by means of a combined heat and power plant and fast pyrolysis) on the social and economic situation (employment and income) of people in the southern part of Italy and Greece [70]. Despite the growing data and research base, there are several limitations in the modeling of bioenergy potentials.

Smith and Porter concur that there has been a significant improvement in the quantification of mitigation potentials of bioenergy in the Intergovernmental Panel on Climate Change reports [104], but uncertainties are still tremendous. Different variations in data—for instance, assumptions on land availability, yield improvements over time, efficiency increases in conversion technology and optimization of infrastructure—come with an enormous level of uncertainty. A good example for this uncertainty is the study of Hoogwijk et al., assessing the geographical and technical potential of bioenergy crops on abandoned and low-productive land for the time span between 2050 and 2100. Their analysis is based on the IPCC's Special Report on Emission Scenarios, computing bioenergy potentials between 130 to 410 EJ/year for 2050 and 240 to 850 EJ/year for 2100 [105]. The authors conclude that—based on the geographical and technical potential—the potential of bioenergy from low-productive and abandoned land could hypothetically be several times as high as the energy supply through crude oil at the beginning of the 2000s. Moreover, the study takes different socio-economic and environmental developments into account. For instance, the global agricultural area between 1970 and 2100 (in Gha) is simulated, incorporating various scenarios for population, GDP, land management factors, diet and trade. The different scenarios result in a hypothetical global agricultural area in 2100 between 1.5 Gha and 6.5 Gha. This discrepancy again dramatically influences the exploitable biomass and bioenergy yield, and thereby the climate mitigation potential from bioenergy. These uncertainties ask for an overview of the most relevant limitations of yield modeling and its connection to the simulation of bioenergy potentials.

The Conversion from Biomass to Bioenergy Potential

If a transformation of modeled yields into energy potentials is performed within or attached to biomass yield modeling on marginal land, a conversion factor needs to be applied to convert the biomass yield (in t per ha) into bioenergy potentials (in GJ, MJ or EJ per ha). The biomass yield therefore needs to be multiplied by the energy yield exploitable within the dedicated bioenergy pathway [106]. The wide range of possible bioenergy pathways includes the co-combustion of biomass with coal in electricity generation plants, the conversion of biomass into cellulosic ethanol and electricity (as a by-product), the conversion of biomass into gasoline, diesel synfuels and electricity via integrated gasification and Fischer–Tropsch hydrocarbon synthesis (IGCC-FT). Different conversion pathways of low-input high-diversity (LIHD) mixtures of native grassland perennials come with highly differing energy yields, ranging from 18.1 GJ/ha/y for electricity to 17.8 GJ/ha/y for cellulosic ethanol and electricity to 28.4 GJ/ha/y for gasoline via IGCC-FT [106]. Unfortunately, in several studies analyzed, either the conversion factor (biomass–bioenergy) is not given nor explained, or the pursued energy carrier is missing. In the global assessment of bioenergy potentials on marginal land by Nijsen et al., neither the conversion factor is given, nor the energy carrier is declared [60]. In the study of Harvolk et al., the conversion of biomass to thermal energy is mentioned, but neither the assumed conversion technology nor the conversion factor was applied [65]. Quin et al. converted the biomass yield of *Miscanthus* and switchgrass into liters of ethanol following a two-sided approach [71]: following current and potential biomass-to-biofuel conversion efficiencies as well as the parameters of Lynd et al. [107]. Unfortunately, Lynd et al. simply derived an average bioenergy yield of biomass energy crops of 105.4 gallons ethanol/dry ton (approx. 399.0 L), without further specification or classification into crops or crop categories [107]. Quin et al. applied this average ratio on *Miscanthus* and switchgrass [71], while for instance Scagline-Mellor et al. calculated significantly different, and among themselves also slightly diverging, ethanol yields (i.e., 453 L/dry ton of *Miscanthus* and 450 L/dry ton switchgrass) [102]. Furthermore, the potential values adduced by Quin et al. can only be obtained if appropriate technologies are available [107], of which several are not state-of-the-art today, and their future realization is still unclear. The uncertainty along with the methodologies applied by Lynd et al. and Quin et al. are significant. Zhan et al. transformed within their study a biomass potential into a technical energy potential, defined by the authors as the available energy content potential provided by the biomass production per grid cell. The technical potential was calculated by multiplying the yield by the crop-specific higher heating value (HVV) [74]. The declaration of the methodological approach by Zhang et al. is sufficient. Nevertheless, the calculation of the technical potential excludes energy losses through conversion [108]. As Zhang et al. furthermore analyze the hypothetical, proportional contribution of the calculated energy yield to China's energy demand, the involvement of a technical potential in the calculation without a conversion step highly skews the results. All given issues regarding the non-declaration or inconsistency of the conversion factor complicate the comparison and interpretation of bioenergy potentials.

The Conversion Capacities for Lignocellulosic Crops

Another important limitation undermining the meaningfulness of modeled bioenergy yields is the lack of capacities for the conversion of lignocellulosic crops. Ethanol from lignocellulosic crops (CH_3CH_2OH) is chemically identical to first-generation ethanol, but is produced through cellulose hydrolysis, which is a more complex process, requiring highly sophisticated production plants. Taking the EU as an example, in 2019 only 10 out of 5505 million liters of bioethanol production came from cellulosic feedstock. There were only two European refineries with a total capacity of 60 million liters of cellulosic ethanol production per year [36]. The first commercialization ventures for the production of lignocellulosic-based ethanol can be observed in Europe, especially two commercial cellulosic ethanol plants: one in Romania (run by Clariant International Ltd.) and another one in Slovakia (operated by Enviral). Furthermore, a pre-commercial demonstration plant in Germany is run by Clariant International Ltd. [109,110]. On a global scale, the largest cellulosic ethanol plants are located in the United States (DuPont, Iowa, 83,000 t/y; POET-DSM Advanced Biofuels, Iowa, 75,000 t/y; Abengoa Bioenergy Biomass of Kansa, 75,000 t/y), in Brazil (GranBio, Alagoas, 65,000 t/y) and in China (Longlive Bio-technology Co. Ltd., Shandong, 60,000 t/y) [111]. Unfortunately, only the plants in Brazil and China are still in operation. The DuPont facility was sold in 2019 and is currently converted to a natural gas plant [112], the facility of POET-DSM Advanced Biofuels is currently idle [113] and the operator of the plant in Kansas is bankrupt [114]. Furthermore, a large amount of demonstration and flagship plants testing different conversion pathways of lignocellulosic crops to ethanol or butanol can be found in various countries, for instance in Italy, Denmark, Spain and Finland [22]. As estimated in the 2020s market report of the Global Industry Analysts Inc., the global market for cellulosic ethanol summed up to USD 631.7 million in 2020 and is expected to grow to USD 6.6 billion at a rate of 39.8% between 2020 and 2027. The growth of the cellulosic ethanol market (2020–2027) is forecasted highest for China (46.5% share in the Compound Annual Growth Rate (CAGR)), followed by Canada (37.4%), Japan (33.2%) and Germany (35.6%) [115]. Nevertheless, the idle and bankrupt large-scale plants in the United States show the vulnerability of this capital- and research-intensive business field. Furthermore, the cellulosic bioethanol sector often consists of fragmented markets and is characterized by geographically differing market regulations [77]. The spectacular CAGR of the global cellulosic ethanol sector should not intend to divert attention from the fact that there are no mature markets for cellulosic ethanol yet. The systematic lack of transportation infrastructure and logistics and the currently limited access of smallholder farmers to the bioenergy feedstock market [63] are other socio-economic issues to be considered when mapping global bioenergy potentials. Without governmental support and/or subsidies, sufficient conversion capacities and an appropriate spatial distribution (with short distances to the cultivation sites), the exploitable biomass and bioenergy potentials calculated in various studies will remain only theoretical potentials. In conclusion, their informative and predictive value is highly limited.

The Energetic Efficiency of Lignocellulosic Ethanol

Furthermore, there is still a significantly immature energetic efficiency of lignocellulosic ethanol. For the conversion, either acid or enzyme hydrolysis can be applied, and both have been intensively researched since the 1970s in the United States and Europe. Besides investments into conversion capacities, the enzymatic pathways are currently optimized through strain development and novel strain discovery, as well as innovative feedstock pretreatment (e.g., ionic liquid pretreatment) [111]. Suitable technologies for the biochemical conversion of lignocellulosic feedstock to biofuels are still under development and not economically competitive to fossil fuels yet [116]. The technological and commercial maturity of the conversion technology is currently evaluated as poor [88]. The energetic efficiency of biofuels can be assessed through the energy return on invest ratio (EROI), calculating the ratio between the energy delivered by a fuel and the energy invested in the production and delivery of this energy [117]. The input energy either includes only non-renewable energy or non-renewable and renewable energy (e.g., electricity and steam produced from lignin) [118]. Hall et al. conclude from 74 assessed EROIs for bioethanol, of which 33 values were below a 5:1 ratio, that—besides optimal values obtained in the tropics—most ethanol EROI values are at or below 3:1. This ratio is defined by Hall et al. as the minimal value for societal usefulness. Thus, most bioethanol pathways assessed are not socially desirable regarding their energetic efficiency [117]. The Natural Resources Defense Council and Climate Solutions in cooperation with Hammerschlag et al. assessed three studies for cellulosic ethanol between 1994 and 2005 [119,120]. While only considering non-renewable energy input, the resulting EROIs of 4.40 (corn stover), 4.55 (poplar) and 6.61 (various) show that bioethanol from cellulosic crops came with significantly higher EROIs than bioethanol from corn (ranges from 0.84 to 1.65). Nevertheless, other assessments conclude drastically lower EROIs for cellulosic ethanol: for instance, 0.2 for ethanol from switchgrass [121] and 0.64 for ethanol from wood [122]. Latter numbers are based on a techno-pessimistic approach, which assumes fossil fuel inputs are used to produce distillation steam instead of energy from lignin combustion. This approach is highly criticized in the literature [117,123]. From the calculations of Barel et al., it can be concluded that even if renewable process energy is considered, the EROI of cellulosic ethanol from switchgrass is lower than that of gasoline [118]. Based on these calculations, it can hypothetically be concluded that lignin-poor lignocellulosic crops might come with lower EROIs than lignin-rich feedstocks, but there is no evidence in the literature. Murphy et al. list several insecurities and limitations of the EROI methodology, pointing out that the quantitative results highly depend on a range of parameters (e.g., boundary and co-products) [124]. Nevertheless, the numbers mentioned show that efficiency in the production of cellulosic ethanol is still immature and highly depends on the crops cultivated, the agricultural management practices and the geographical location [125]. The importance of the crop choice is in line with Baral et al., assessing drastic differences in the EROI of yellow poplar and switchgrass [118]. From the highly diverging and partially outdated literature available, no general and definite statement on energetic advantages of cellulosic ethanol to other biofuels and energy carriers can be made.

The Tradeoff between Yield and Feedstock Quality

Another shortcoming links the production of lignocellulosic biomass with the conversion to bioenergy, especially biofuels. There is a tradeoff between high yields and a high feedstock quality. It is elaborated that high agricultural yields might result in a feedstock with a high water, ash or salt content [4]. Ash and certain inorganic elements in particular lead to difficulties in processing. Energy-intensive drying might be necessary for wet feedstock, and corrosion, slugging or plugging of the conversion reactor might occur in the presence of minerals [126]. Not only the biomass quality in general but also its quantitative and qualitative constancy over time play an important role for conversion in biorefineries. A constant and qualitatively-reliable feedstock supply is essential for conversion plants [45]. Furthermore, the final application of the lignocellulosic biomass determines the cell wall ideotype. The extraction of target molecules is still cost-intensive, as the loosening and fractionation of cell wall components require intensive pre-treatments [127,128]. Thus, one of the major quality parameters of lignocellulosic feedstock is the easy destructibility of cell walls [127,129]. Moreover, the relative content of desired molecules within the cell walls in consistency with the dedicated end-use of the feedstock is vitally important [130]. For combustion, a high lignin, high cellulose and high hemicellulose content is preferable, as those factors increase the calorific value [126]. Feedstock with a low lignin, high cellulose and high hemicellulose, low cross-linking of cellulose–hemicellulose, low crystallinity index, low cellulose–lignin branching and reduced polymerization is known for good suitability for ethanol production [129,131,132]. Thus, high yields alone are not a sufficient parameter for assessing biomass potentials. If the end-use-dependent feedstock quality, quantity and constancy over seasons do not meet the requirements of the conversion pathways, the bioenergy potentials of lignocellulosic biomass cannot be realized.

The Knowledge on the Crops' Genetic Potentials

Most perennial grasses, which are used as bioenergy feedstock, are undomesticated crops, collected from wild environments and tested in field trials. Hence, some are still in the first stage of breeding programs [133], or even novel orphan crops without any previous genetic improvement. This applies especially with regard to biomass-related characteristics [134–137]. Consequently, the biomass yields and qualities of many perennial grasses are highly variable and in many cases drastically lower than the crops' genetic potentials [138]. For the achievement of the climate mitigation objectives of the Paris agreement, a yearly 145 EJ biomass increment until 2060 will be necessary. The International Energy Agency calls the cultivation of high yield energy crops a key element for the time span 2017 to 2025 to reach the energy potentials [37]. For an intensive cultivation of, e.g., *Miscanthus*, further optimization of the plant is necessary [139,140]. Differing environmental conditions require an accurate selection of suitable species. For instance, the Renewable Energy Directive includes criteria for assessing the availability of land for bioenergy-dedicated biomass. Following this sustainability approach, an avoidance of negative impacts on water resources needs to be included in the crop choice [94]. Thus, for instance, in Mediterranean areas, a variety of highly drought-tolerant (lignocellulosic) crops is required [45], which must be developed through breeding programs. A whole range of new crops tailored to marginal environments needs to be bred and tested [59]. Without a general intensification in breeding and an eco-physical adoption of lignocellulosic crops to specific environmental conditions, high energy potentials calculated and projected by the International Energy Agency, Intergovernmental Panel on Climate Change and others might not be realistic.

The Demand for Higher Sustainability

Within the recast of the Renewable Energy Directive, the European Commission updated goals and regulations for the production of renewable energy [141]. The production of feedstocks and biofuels has to comply with several sustainability criteria to be eligible for financial support by public authorities and to be credited to the national renewable energy targets [142]. The Renewable Energy Directive contains several criteria that can be applied to the assessment of land availability for dedicated biomass crops, and in particular, to the selection of marginal sites for the cultivation of lignocellulosic bioenergy feedstock. The end-user roadmap of Dees et al. [94] summarizes rules that come with the criteria defined in the Renewable Energy Directive. Amongst others, land selection for bioenergy feedstock within the EU has to meet the following requirements: only using lands that have been registered as agricultural lands since 1990, the exclusion of permeable grasslands, the sole usage of surplus, marginal and polluted lands to avoid LUC, no usage of fallow land if the fallow land share (of total arable land) declines to <10%, the avoidance of monocultures and the consideration of a maximum slope limit to perennial plantations. The CAPRI model is the only model available that incorporates the diverse regional circumstances regarding land use changes between 2020 and 2030 within the EU 28 [57]. Nevertheless, even the CAPRI baseline needs to be further adapted to include all Renewable Energy Directive criteria, as, for instance, the rule on fallow land is not considered [94]. It can be assumed that not all yield modeling studies scoping the EU incorporate the Renewable Energy Directive criteria within the assessment of marginal land availability and the cultivation of lignocellulosic crops. This especially applies to yield modeling conducted before the resolution of the directive EU 2018/2001 in 2018. Unfortunately, the compliance of recent studies with the Renewable Energy Directive criteria is not assessed within the scope of this research. If a non-compliance of yield models with the EU directive 2018/2001 should be the case, biomass and bioenergy potentials calculated in those scenarios might be unusable. This aspect might also affect yield modeling outside of the EU. Coming with the updated Renewable Energy Directive, biofuel feedstocks with a high iLUC risk—also originating from non-EU countries—are gradually phased out [143]. It is furthermore assumed that there are yield modelings performed for non-EU areas without incorporating an iLUC risk assessment in coherence with the Renewable Energy Directive regulations.

4. Recommendations and Milestones for Reliable Future Predictions

The first recommendations for biomass yield models/modeling improvement were derived based on the assessment of shortcomings and limitations, which lead to input and model uncertainty on the one side and output uncertainty regarding the biomass and bioenergy potential on the other side. The order of the recommendations equals the order of the limitations assessed in part one of this study. A graphical overview of all derived recommendations and milestones is shown in Figure 3.

4.1. General Recommendation Regarding the Scope and Definitions

To provide sufficient and reliable data to develop models and calculate biomass yields, a globally standardized set of definitions on marginal land, industrial and lignocellulosic crops is necessary. These definitions should provide sufficient guidance and a regulated framework that is applicable to countries globally and limits possibilities for national/regional adjustments and interpretation. Based on these definitions, data collection must take place at regional, national and international levels to achieve reliable and adequate results for all regions and to ultimately be able to meet the global biomass demand for non-food purposes. A strong focus on developing countries is thereby required as these countries are often abundant in marginal land [58].

4.2. Recommendations for Models and Input Parameters

The obtained data on lignocellulosic biomass growth and their collection process need to be documented in a detailed way and made available, for example, on statistical databases of the FAO, to provide reference for future studies and assessments. In biomass yield modeling, the future focus should be on the development of crop-specific models such as MiscanFor, which are calibrated based on the genotype-specific demand of the crop [45]. The development of models specifically for marginal land, in which the different environmental (mainly soil) parameters can be represented in detail, is also necessary. To establish these types of models, an integrated, interdisciplinary approach is necessary that brings modeling and plant experts together to adequately represent the different growth stages and underlying calculations in the models [65]. In addition, it is important to increase software and model transparency, making the assumptions and calculations in the background accessible for the model users [81].

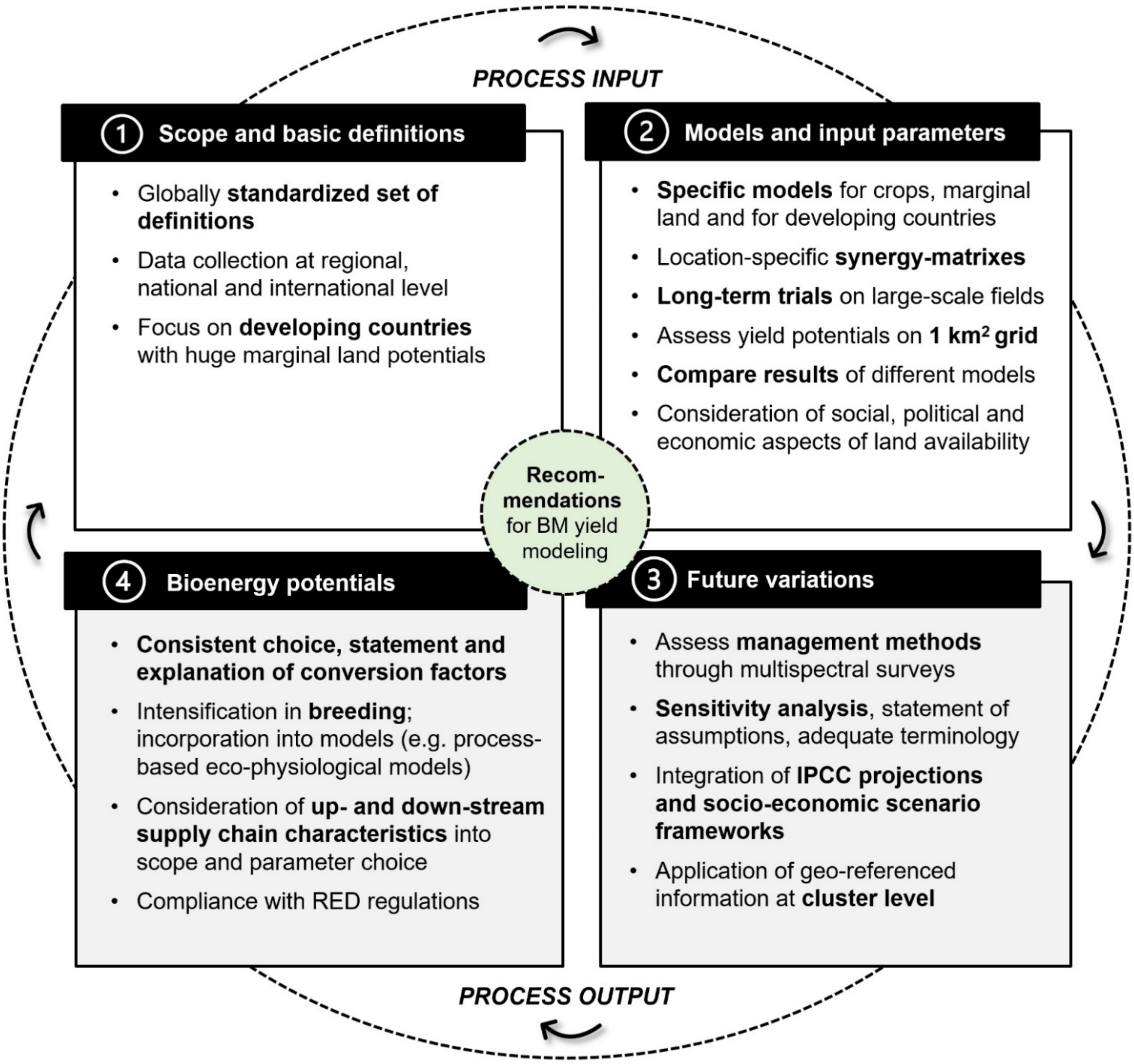

Figure 3. Overview on the most relevant recommendations and milestones for future biomass (BM) yield modeling.

To account for the complexity and diversity of marginal land, a detailed soil and environmental assessment is recommended, especially for European studies [49]. Furthermore, it has to be determined if the same synergies are applicable for other regions, and whether more regional synergy matrixes have to be developed and applied. Until then, the use of a selection of adequate, locally representative soil and environmental parameters is suggested [61]. These should be combined with yield results from long-term trials on commercial-sized fields under similar climatic and management conditions to represent the crop yield development along the growth cycle [74] and further expand the database on crop yield expectations. A comparison of yields from different crops [88] and different crop varieties on the assessed marginal land provides more in-depth insights into the realistic yield range as the varieties' yields can divert significantly from the crop average [45]. If the best crop among several theoretically feasible options should be selected, similar assumptions and the avoidance of average yield data are key aspects [61,79]. Yield calculations best take place on a small scale, using grids with a 1 km^2 size to identify the best land–environment–crop fit that provides the highest yield per 1 km^2 and thereby increases the overall modeled yields. If no crop-specific model is available, a comparison of the results from different models, e.g., GAEZ and GEPIC, helps narrow down the spatial and timely range of the yield potential [74]. Furthermore, a comparison of the modeling results with data obtained from several field trials, for example, from different locations across the country for which the biomass yield potential is modeled, could help benchmark the model results and provide a suitable option for comparison [88]. Clearly stating the assumptions made and presenting the limitations of the chosen analytical method further contribute to more robust and reproducible results [41]. Based on this, a transparent quantification of the uncertainty of the individual input parameters as well as of the overall results increases the comparability of the results and the reliability of the study [61]. A sensitivity analysis identifying the most influential parameters on the yield outcome is useful to estimate the impact of wrong assumptions on the model results [25].

To provide a holistic assessment of the practical biomass yield potential on marginal land, it is crucial to include the social, political and economic characteristics related to the use of that land. A local assessment of the non-environmental conditions of the marginal land is important as the social, economic and political conditions vary widely between regions, and local decision-making is necessary to turn theoretical into practical yield potential [65]. Here, political guidance and support for feedstock cultivation on marginal land is most important as cultural and social acceptability of the usage of biomass as energy feedstock can only be achieved by transparently informing people on the advantages and disadvantages and by listening to their fears [74]. Simultaneously, local, regional, national and supranational governments (such as the EU) have to actively promote the cultivation of bioenergy crops on marginal land, for instance, by making use of coherent energy, environmental and agricultural policies [77]. Long-term, future-oriented strategies and adjustments in the Common Agricultural Policy (CAP) to ensure compliance with environmental and social requirements to avoid, for example, indirect and direct land use change are the main political instruments that could be used [55]. However, not only in the primary sector but also in the feedstock-to-bioenergy conversion sector incentives such as subsidies are necessary to extend the value chains to an industrial scale, connecting rural areas where the marginal land is located with the conversion plant operators and finally with the consumers [45]. Beyond the social and political assessment, taking the economic perspective into consideration is important, especially as future research and development is likely to reduce the establishment costs and increase the yields of perennial crops, which enhances the economic attractiveness of biomass production on marginal land considerably [88]. This potential can only be used if the accompanying infrastructure is adequately established and value chains to exploit the regional biomass potential are developed and fortified [45].

The variety of input parameters and underlying assumptions increases the complexity of biomass yield modeling on marginal land. This complexity must be reduced to a manageable and understandable amount while leaving the basic interactions and their impact dimensions unchanged. Therefore, a careful, concise and transparent documentation and reasoning for the selected input parameters is decisive to provide high-quality, realistic and comparable results that can be interpreted in a meaningful way.

Agricultural management strategies for low-input systems need to be in line with sustainable cultivation practices to yield environmentally sustainable produced biomass with a high quality, for example, by incorporating agricultural practices such as crop rotations into agricultural systems on marginal land [44]. Thus, it might be beneficial for the soil and the nutrient balance to grow crops in a certain sequence or even intercrop them. These practices and their impacts on overall biomass yields must be represented in yield modeling. Therefore, regionally specific data from the respective farmers might be necessary [91]. Multispectral surveys need to be conducted to precisely assess time series of crop cultivation and rotation [91]. Intensive input on a regional and local level is required to correctly depict farmers' actual and future agricultural operation and management strategies.

4.3. Recommendations for Consideration of Future Variations

Uncertainties and fluctuations in biomass and bioenergy yield modeling cannot be fully eliminated. Models always contain uncertainty and are a simplification of reality. This is the reason why assumptions made must be clearly stated, limitations of the methodology and input data must be highlighted and the inherent uncertainty in modeling results must be analyzed in future studies [41]. A sensitivity analysis of the yield modeling results and a transparent description of assumptions are crucial. Moreover, sensitivity regarding the use of terms is necessary. The results of yield modeling should only be published as 'forecasts' or 'predictions' if the projection is the most likely one. This needs to be analyzed through a deterministic model and a comparison of a sufficiently large number of scenarios [144].

Furthermore, there is a need for biophysical models, which can cover various ecological parameters and their dynamic changes over time. A good example is the assessment of global bioenergy potentials of *Miscanthus*, conducted by Shepherd et al. [79]. The MiscanFor model was therefore not only extended to incorporate the RCP 2.6 climate scenario of the Intergovernmental Panel on Climate Change, but also the SSP2 socio-economic scenario of the Intergovernmental Panel on Climate Change, gaining anticipating weight to at least some extent. There is an urgent need to integrate environmental scenarios into yield models via a direct embedding or through baseline extensions, especially for climate and groundwater predictions. To comply with the current state of research and to apply internally consistent data, the Intergovernmental Panel on Climate Change projections and scenario frameworks should be starting point for the incorporation of 'future' into models. This accounts for socio-economic scenarios, land use and land cover change scenarios, environmental scenarios (e.g., carbon dioxide, water resources, acidifying compounds), climatic scenarios, sea-level rise scenarios as well as their interactions [144]. Global data need to be combined with national, regional, or in the best case, even local datasets on a 1 km^2 scale. An assessment of, for instance, NUTS 2 resolution levels in the EU does not provide sufficiently detailed information on the regional and local environmental conditions. If, for instance, the CARPI model is used, the option of integrating geo-referenced information at cluster level (1 km^2 grid cell) must be chosen to increase specificity [145]. For yield modeling on marginal land in the EU, a whole range of models can and should be used and interconnected for regulation-consistent scenarios: non-carbon dioxide emissions and pollutants (GAINS model), land use change and forestry (GLOBIUM/G4M model), agriculture (GAPRI), energy, including transport and processes (especially PRIMES biomass supply model, PRIMES energy system model) and overall framework assumptions (Prometheus model, GEM-E3 model) [146].

4.4. Milestones for Improving Bioenergy Potential Assessments

It is highly indispensable that applied conversion factors, projected bioenergy pathways and the specific conversion technologies need to be stated and explained in future bioenergy-potential projecting yield modelings. The conversion factors and technologies incorporated in the modeling of bioenergy scenarios must be time- and location-specific. Thus, conversion factors need to represent the technological state of the art (for status quo assessments) or realistic future technological advancements (for mid- and long-term projections), respectively. The choice of bioenergy carriers (e.g., fuels, heat/power) needs to be consistent with national and socio-economic patterns, markets and regulations. Furthermore, conversion factors must account for conversion and delivery losses to depict realistic end-use values.

A rapid and targeted expansion of conversion capacities, suitable infrastructure and supply chains need to come along with the progressing projection and incorporation of biomass and bioenergy potentials into governmental and non-governmental climate mitigation strategies. The conversion plants need to be adequately spatially distributed, considering land use patterns and regional biomass potentials, and have to come with sufficient infrastructural connections to local markets and up- as well as downstream supply chains. At the same time, innovative and efficiency-boosting pretreatments and bio- as well as thermochemical conversion technologies need to be developed, tested in demonstration plants and upscaled to commercial level. A promising approach is, for instance, the sunliquid® technology developed by Clariant International Ltd. Thereby, process-specific enzymes and simultaneous C5 and C6 fermentation of (ligno-)cellulosics (so far only wheat and other cereal straw) are applied to boost the commercial performance of cellulosic ethanol production [109]. An expansion of governmental subsidies for research and development, as well as financial support for the upscaling of innovative concepts, has to be fostered globally. Furthermore, holistic Life Cycle Sustainability Assessments [147], energetic efficiency analysis and techno-economic assessments of (ligno-)cellulosic ethanol life cycle chains [148] need to evaluate the economic, ecological and social impacts and performance of biofuels from lignocellulosic feedstock. The bare suitability of marginal land for bioenergy feedstock production does not imply that cultivation and production are automatically sustainable, but on the contrary, the whole value chain needs to be assessed [55]. In conclusion, only a scientific, qualitative and quantitative sustainability assessment can lead to objective and holistic judgements of the performance of lignocellulosic biofuels or different conversion pathways, respectively.

The opportunities and potentials coming with intensive breeding of perennial grasses are evaluated as enormous [149]. The extensive knowledge on plant biology and genetics, as well as the large toolbox for analytical and genomic approaches, can result in innovative, high-yielding and low-demanding perennial crops, tailored to diverse agroecological systems. Higher yields, a higher resource use efficiency (especially nutrients and water) and a better exploitability of soil come with higher efforts in the breeding of C4 grasses [129,149]. It is obvious that intensive research, breeding and field trials need to be fostered within the next few years. The breeding should not only focus on single crops, but a whole range of species, as agroecological environments differ and the demands of biorefineries are broad. It needs to be highlighted that due to the evolutionary relation of C4 grasses, advances in the breeding of one crop can boost the development of other crops [129]. Focusing on *Miscanthus* again, this recommendation is fully applicable. Twenty species of *Miscanthus* are known, and the genus holds significant potential for adaptations to the environmental conditions or the assigned conversion pathway. The market potential of lignocellulosic ethanol from *Miscanthus* and other grasses can be scaled up through current and future breeding efforts, especially the development of new hybrids, which come with higher biomass yields and streamlined degradability [139,140]. A promising but highly complex approach [137] is the engineering of a C4 photosynthesis in C3 crops to further increase biomass yields of highly productive C3 species (e.g., giant reed or tall wheatgrass) [150]. Consequently, innovative, molecular breeding for lignocellulosic crops must be taken into account to exploit genetic resources, for instance, via next generation sequencing, high-throughput genotyping, molecular breeding, marker-assisted selection and genomic selection [138]. A more challenging but highly promising approach is the development and improvement of methods to analyze cell wall compositions and nanoscale structures [151]. The exploration of molecules in cell walls, their chemically specific imaging tags and their development over the life cycle of plants (from cell wall formation, over maturation, transformation, dehydration and processing into feedstocks) can support the predictive modeling of feedstock qualities and quantities. New findings are necessary to develop and improve advanced feedstocks and optimize their processing pathways. Ultimately, these research and breeding methods must be both accurate and relatively inexpensive, allowing the handling of large amounts of samples in breeding programs [151]. The United States Department of Energy published a plant-physiological, genetic and biotechnological roadmap for lignocellulosic crops in 2006, including technical milestones to increase the market potential of cellulosic ethanol within 15 years—for instance, the optimization of cell wall composition to increase the content of fermentable sugar and the discovery of genetic regulatory factors that determine the synthesis and deposition of lignin [151]. In future research, the achievement of those milestones as well as limitations and future objectives need to be assessed for a wide range of lignocellulosic crops in well-coordinated field experimentations worldwide, as also noted by Reinhardt et al. [152]. If current and future breeding efforts are successful, the achieved and updated yield levels promptly need to be incorporated into yield modeling, so realistic biomass potentials for future decades can be computed. Process-based eco-physiological models could be combined with genomics to make progress in plant phenotyping [153]. Connections between controlled-conditions phenotyping and crop performance in the field can be made to reduce model uncertainty. Furthermore, yield modeling for newly domesticated varieties, genotypes and their performance on marginal land urgently need to be assessed, providing meaningful predictions of potentials.

The breeding approaches assessed will highly support the optimization of the lignocellulose composition of the feedstock, which is necessary to allow an efficient conversion into biofuels. Researchers performing yield modeling should also see a mission in assessing the potentials of different bioenergy value chains. The final use and conversion technology of the lignocellulosic feedstock highly influences the crop choice. Thus, the incorporation of socio-economic factors and the technological state-of-the-art for biomass conversion need to be taken into account in yield modeling. Crops in yield models shall not exclusively be chosen regarding the best yield performance, but also under consideration of the upstream supply chain's requirements.

The overall goal of yield modeling on marginal land can be defined as the assessment of biomass yield potentials under consideration of environmental, crop-specific and (partially) socio-economic and other constraints. Thus, yield modeling needs to take environmental regulations into account, depicting societal judgements on current and future agricultural practices [12]. A good example is the reflected Renewable Energy Directive (EU 2018/2001), which not only affects yield modeling practices inside, but also outside of the EU. Future yield modeling needs to be performed in consistency with all relevant sustainability criteria and rules that are applicable to the scope and boundary of the modeling [57]. Even the baseline in the CAPARI model was in compliance with EU policies on bioenergy targets (based on the PRIMES energy model), and a further upgrading was necessary to incorporate all relevant Renewable Energy Directive criteria.

5. Conclusions

Marginal land is defined primarily by limiting soil and climatic conditions that a variety of lignocellulosic industrial crops can tolerate. Applied in several studies, yield modeling aims to precisely predict future yields. The modeled yields are further transformed into bioenergy potentials, representing tangible energy contributions of lignocellulosic crops. However, a massive lack of globally or trans-nationally coherent definitions of lignocellulosic crops inevitably leads to inconsistency in statistical data on current and future yields. Several other key limitations also reduce the informative power of yield modeling studies.

This study shows that there are no sufficient data available to precisely model lignocellulosic biomass on marginal land. Even though there are several modeling approaches, an increased number of parameters and various data sources available for the modeling of lignocellulosic feedstocks, their suitability for the modeling of biomass cultivation on marginal land is still limited. Several limitations and shortcomings were assessed to point out a multitude of data and methodology limitations on both the input and output side of yield modeling. These issues derived from a review of several yield modeling studies prove that, currently, yields of lignocellulosic biomass on marginal land are not modeled precisely. The relevance of lignocellulosic crops for the growing global bioeconomy was substantiated with political incentives, forecasts of organizations (e.g., the International Energy Agency) and statistical data, buttressing the promising potentials of lignocellulosic crops as a bioenergy feedstock.

The need for modeling the biomass potentials on marginal land was confirmed by analyzing the significant need of biomass and bioenergy within the next few decades, and the partially insufficient data basis for the calculation of those biomass potentials. The cultivation of perennial lignocellulosic crops on marginal land comes with promising advantageous benefits. The increase in biodiversity, ecosystem services such as pollination [154,155] and pest suppression through perennials [156] is not only reflected on the areas they take place but also on neighboring agricultural land, for instance, used for food crop cultivation. A potential yield increase by up to 25% on annual croplands is reported [157]. This, together with the production of lignocellulosic feedstock for bioenergy, can significantly improve food security, boost rural development, create employment opportunities and deliver sustainable energy sources, improving living standards of rural communities [158].

Ultimately, this review has demonstrated the complexity of biomass yield modeling on the one side and the potentials of the methodology on the other side. Several crucial shortcomings limiting the use of biomass yield model approaches for lignocellulosic crops on marginal land were derived. The rapidly increasing demand for food and non-food crops asks for transparent, multi-dimensional and highly adaptable models, producing clear and meaningful scenarios of exploitable biomass and bioenergy potentials. Quantitative data on the supply and demand of biomass and bioenergy are an essential base for international negotiations of climate mitigation agreements, strategic sustainability goals and their practical implementation into (trans-)national policies. Nevertheless, the biomass potentials resulting from yield modeling on marginal land shall not be interpreted as easily exploitable bioenergy potentials, but rather as first drafts of future bioenergy supply chains.

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References

1. Department of Economic and Social Affairs, Population Division, United Nations. World Population Prospects 2019 Highlights. 2019. Available online: https://population.un.org/wpp/Publications/Files/WPP2019_Highlights.pdf (accessed on 19 October 2021).
2. Tomlinson, I. Doubling Food Production to Feed the 9 Billion: A Critical Perspective on a Key Discourse of Food Security in the UK. *J. Rural Stud.* **2011**, *29*, 81–90. [CrossRef]
3. High Level Expert Forum, FAO Global Agriculture towards 2050. 2009. Available online: http://www.fao.org/fileadmin/templates/wsfs/docs/Issues_papers/HLEF2050_Global_Agriculture.pdf (accessed on 19 October 2021).
4. Lewandowski, I.; Lippe, M.; Castro Montoya, J.; Dickhöfer, U. Agricultural Production. In *Bioeconomy: Shaping the Transition to a Sustainable, Biobased Economy*; Lewandowski, I., Ed.; Springer: Berlin/Heidelberg, Germany; New York, NY, USA, 2018; pp. 99–123. ISBN 978-3-319-68151-1.
5. Piotrowski, S.; Carus, M.; Essel, R. Global Bioeconomy in the Conflict between Biomass Supply and Demand. *Ind. Biotechnol.* **2015**, *11*, 308–315. [CrossRef]
6. Abideen, Z.; Ansari, R.; Khan, M.A. Halophytes: Potential Source of Ligno-Cellulosic Biomass for Ethanol Production. *Biomass Bioenergy* **2011**, *35*, 1818–1822. [CrossRef]
7. Hadar, Y. Sources for Lignocellulosic Raw Materials for the Production of Ethanol. In *Lignocellulose Conversion: Enzymatic and Microbial Tools for Bioethanol Production*; Faraco, V., Ed.; Springer: Berlin/Heidelberg, Germany, 2013; pp. 21–38. ISBN 978-3-642-37861-4.

8. Chiaramonti, D.; Giovannini, A.; Janssen, R.; Mergner, R. *Lignocellulosic Ethanol Process and Demonstration*; WIP Renewable Energies: München, Germany, 2013. Available online: https://www.wip-munich.de/biolyfe-handbook/1_7_1_BIOLYFE_Handbook_Part-I.pdf (accessed on 19 October 2021).
9. Milbrandt, A.; Overend, R.P. *Assessment of Biomass Resources from Marginal Lands in APEC Economies*; National Renewable Energy Lab. (NREL): Golden, CO, USA, 2009. Available online: https://www.nrel.gov/docs/fy10osti/46209.pdf (accessed on 19 October 2021).
10. IEA. Bioenergy Mobilising Sustainable Bioenergy Supply Chains: Opportunities for Agriculture. *Summary and Conclusions from the IEA Bioenergy ExCo77 Workshop*. 2016. Available online: https://www.ieabioenergy.com/blog/publications/ws20-mobilising-sustainable-bioenergy-supply-chains-opportunities-for-agriculture/ (accessed on 19 October 2021).
11. Department for Environment, Food and Rural Affairs. *Crops Grown For Bioenergy in the UK: 2018*; Department for Environment Food & Rural Affairs: London, UK, 2019. Available online: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/856695/nonfood-statsnotice2018-08jan20.pdf (accessed on 22 November 2021).
12. von Cossel, M.; Wagner, M.; Lask, J.; Magenau, E.; Bauerle, A.; Von Cossel, V.; Warrach-Sagi, K.; Elbersen, B.; Staritsky, I.; Van Eupen, M.; et al. Prospects of Bioenergy Cropping Systems for a More Social-Ecologically Sound Bioeconomy. *Agronomy* **2019**, *9*, 605. [CrossRef]
13. Von Cossel, M.; Lewandowski, I.; Elbersen, B.; Staritsky, I.; Van Eupen, M.; Iqbal, Y.; Mantel, S.; Scordia, D.; Testa, G.; Cosentino, S.L.; et al. Marginal Agricultural Land Low-Input Systems for Biomass Production. *Energies* **2019**, *12*, 3123. [CrossRef]
14. Xue, S.; Lewandowski, I.; Wang, X.; Yi, Z. Assessment of the Production Potentials of Miscanthus on Marginal Land in China. *Renew. Sustain. Energy Rev.* **2016**, *54*, 932–943. [CrossRef]
15. Schweier, J.; Becker, G. Economics of Poplar Short Rotation Coppice Plantations on Marginal Land in Germany. *Biomass Bioenergy* **2013**, *59*, 494–502. [CrossRef]
16. Cheah, W.Y.; Sankaran, R.; Show, P.L.; Ibrahim, T.N.B.; Chew, K.W.; Culaba, A.; Chang, J.-S. Pretreatment Methods for Lignocellulosic Biofuels Production: Current Advances, Challenges and Future Prospects. *Biofuel Res. J.* **2020**, *7*, 1115–1127. [CrossRef]
17. Janssen, R.; Khawaja, C. Sustainable Supply of Non-Food Biomass for a Resource Efficient Bioeconomy. A Review Paper on the State-of-the-Art. 2014. Available online: http://www.s2biom.eu/images/Publications/S2biom_review_state-of_the_art_Final.pdf (accessed on 19 October 2021).
18. ETIP. Bioenergy Lignocellulosic Crops for Production of Advanced Biofuels. Available online: https://www.etipbioenergy.eu/value-chains/feedstocks/agriculture/lignocellulosic-crops (accessed on 19 October 2021).
19. Hao, L.C.; Sapuan, S.M.; Hassan, M.R.; Sheltami, R.M. 2—Natural fiber reinforced vinyl polymer composites. In *Natural Fibre Reinforced Vinyl Ester and Vinyl Polymer Composites*; Sapuan, S.M., Ismail, H., Zainudin, E.S., Eds.; Woodhead Publishing Series in Composites Science and Engineering; Woodhead Publishing: Sawston, UK, 2018; pp. 27–70. ISBN 978-0-08-102160-6.
20. Ge, X.; Chang, C.; Zhang, L.; Cui, S.; Luo, X.; Hu, S.; Qin, Y.; Li, Y. Chapter Five—Conversion of Lignocellulosic Biomass Into Platform Chemicals for Biobased Polyurethane Application. In *Advances in Bioenergy*; Li, Y., Ge, X., Eds.; Elsevier: Amsterdam, The Netherlands, 2018; Volume 3, pp. 161–213.
21. Shankaran, D.R. Chapter 14—Cellulose Nanocrystals for Health Care Applications. In *Applications of Nanomaterials*; Mohan Bhagyaraj, S., Oluwafemi, O.S., Kalarikkal, N., Thomas, S., Eds.; Micro and Nano Technologies; Woodhead Publishing: Sawston, UK, 2018; pp. 415–459. ISBN 978-0-08-101971-9.
22. European Biofuels Technology Platform, Bioenergy Value Chain 5: Sugar to Alcohols. 2016. Available online: https://etipbioenergy.eu/images/EIBI-5-sugar-to-alcohols.pdf (accessed on 19 October 2021).
23. Ding, H.; Xu, F. Chapter 20—Production of Phytochemicals, Dyes and Pigments as Coproducts in Bioenergy Processes. In *Bioenergy* Research: Advances and Applications; Gupta, V.K., Tuohy, M.G., Kubicek, C.P., Saddler, J., Xu, F., Eds.; Elsevier: Amsterdam, The Netherlands, 2014; pp. 353–365. ISBN 978-0-444-59561-4.
24. Patel, M.; Zhang, X.; Kumar, A. Techno-Economic and Life Cycle Assessment on Lignocellulosic Biomass Thermochemical Conversion Technologies: A Review. *Renew. Sustain. Energy Rev.* **2016**, *53*, 1486–1499. [CrossRef]
25. Jing, Q.; Conijn, S.J.G.; Jongschaap, R.E.E.; Bindraban, P.S. Modeling the Productivity of Energy Crops in Different Agro-Ecological Environments. *Biomass Bioenergy* **2012**, *46*, 618–633. [CrossRef]
26. Elbersen, H.W.; Lammens, T.M.; Alankangas, E.A.; Annevelink, E.; Harmsen, P.F.H.; Elbersen, B.S. Lignocellulosic Biomass Quality: Matching Characteristics With Biomass Conversion Requirements. In *Modeling and Optimization of Biomass Supply Chains: Top down and Bottom up Assessment for Agricultural, Forest and Waste Feedstock*; Academic Press: Cambridge, MA, USA, 2017; pp. 55–78. [CrossRef]
27. FAO FAOSTAT. Available online: http://www.fao.org/faostat/en/#home (accessed on 19 October 2021).
28. FAO. *Food Balance Sheets. A Handbook*; Food and Agriculture Organization of the United Nations: Rome, Italy, 2011. Available online: http://www.fao.org/3/x9892e/x9892e00.htm (accessed on 19 October 2021).
29. FAO Definition and Classification of Commodities. Fibres of Vegetal and Animal Origin. Available online: http://www.fao.org/waicent/faoinfo/economic/faodef/fdef09e.htm (accessed on 19 October 2021).
30. Raschka, A.; Carus, M. *Stoffliche Nutzung von Biomasse Basisdaten für Deutschland, Europa und die Welt*; Nova-Institut GmbH: Hürth, Germany, 2012. Available online: https://www.iwbio.de/fileadmin/Publikationen/IWBio-Publikationen/Stoffliche_Nutzung_von_Biomasse_nova.pdf (accessed on 19 October 2021).

31. Berndes, G. Bioenergy, Land Use Change and Climate Change Mitigation. 2010. Available online: https://www.ieabioenergy.com/wp-content/uploads/2013/10/Bioenergy-Land-Use-Change-and-Climate-Change-Mitigation-Background-Technical-Report.pdf (accessed on 19 October 2021).
32. Edrisi, S.A.; Abhilash, P.C. Exploring Marginal and Degraded Lands for Biomass and Bioenergy Production: An Indian Scenario. *Renew. Sustain. Energy Rev.* **2016**, *54*, 1537–1551. [CrossRef]
33. Eurostat, Archive: Main Annual Crop Statistics. Available online: https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Main_annual_crop_statistics&oldid=258003 (accessed on 19 October 2021).
34. Eurostat Eurostat—Data Explorer—Industrial Crops by NUTS 2 Regions. Available online: https://appsso.eurostat.ec.europa.eu/nui/submitViewTableAction.do (accessed on 19 October 2021).
35. Scarlat, N.; Dallemand, J.-F.; Monforti-Ferrario, F.; Nita, V. The Role of Biomass and Bioenergy in a Future Bioeconomy: Policies and Facts. *Environ. Dev.* **2015**, *15*, 3–34. [CrossRef]
36. Phillips, S.; Flach, B.; Lieberz, S.; Bolla, S. Biofuels Annual EU-28. 2019. Available online: https://apps.fas.usda.gov/newgainapi/api/report/downloadreportbyfilename?filename=Biofuels%20Annual_The%20Hague_EU-28_7-15-2019.pdf (accessed on 19 October 2021).
37. International Energy Agency (IEA). Technology Roadmap: Delivering Sustainable Bioenergy 2017. Available online: https://www.ieabioenergy.com/publications/technology-roadmap-delivering-sustainable-bioenergy/ (accessed on 19 October 2021).
38. Intergovernmental Panel on Climate Change (IPCC). Special Report on Renewable Energy and Climate Mitigation. 2011. Available online: https://www.ipcc.ch/2011/06/28/special-report-on-renewable-energy-sources-and-climate-change-mitigation-srren/ (accessed on 19 October 2021).
39. Fritsche, U.; Eppler, U.; Fehrenbach, H.; Giergrich, J. Linkages between the Sustainable Development Goals (SDGs) and the GBEP Sustainability Indicators for Bioenergy (GSI)—Technical Paper for the GBEP Task Force on Sustainability. 2018. Available online: http://www.globalbioenergy.org/fileadmin/user_upload/gbep/docs/Indicators/IINAS_IFEU__2018__Linkages_SDGs_and_GSIs_-_final.pdf (accessed on 19 October 2021).
40. Merriam-Webster Dictionary, Definition of MARGINAL. Available online: https://www.merriam-webster.com/dictionary/marginal (accessed on 19 October 2021).
41. Elbersen, B.; Van Eupen, E.; Mantel, S.; Verzandvoort, S.; Boogaard, H.; Mucher, S.; Cicarreli, T.; Elbersen, W.; Bai, Z.; Iqbal, Y.; et al. *Methodological Approaches to Identify and Map Marginal Land Suitable for Industrial Crops in Europe*; WUR: Wageningen, The Netherlands, 2018.
42. Shortall, O.K. "Marginal Land" for Energy Crops: Exploring Definitions and Embedded Assumptions. *Energy Policy* **2013**, *62*, 19–27. [CrossRef]
43. Lewis, S.; Kelly, M. Mapping the Potential for Biofuel Production on Marginal Lands: Differences in Definitions, Data and Models across Scales. *IJGI* **2014**, *3*, 430–459. [CrossRef]
44. von Cossel, M.; Iqbal, Y.; Scordia, D.; Cosentino, S.L.; Elbersen, B.; Staritsky, I.; Van Eupen, M.; Mantel, S.; Prysiazhniuk, O.; Maliarenko, O.; et al. D4.1 Low-Input Agricultural Practices for Industrial Crops on Marginal Land. *Zenodo* **2019**. [CrossRef]
45. Ramirez-Almeyda, J.; Elbersen, B.; Monti, A.; Staritsky, I.; Panoutsou, C.; Alexopoulou, E.; Schrijver, R.; Elbersen, W. Assessing the Potentials for Nonfood Crops. In *Modeling and Optimization of Biomass Supply Chains: Top down and Bottom up Assessment for Agricultural, Forest and Waste Feedstock*; Panoutsou, C., Ed.; Elsevier: Cambridge, CA, USA, 2017; pp. 219–251. ISBN 978-0-12-812303-4.
46. Parr, J.F.; Stewart, B.A.; Hornick, S.B.; Singh, R.P. Improving the Sustainability of Dryland Farming Systems: A Global Perspective. In *Advances in Soil Science*; Singh, R.P., Parr, J.F., Stewart, B.A., Eds.; Advances in Soil Science; Springer: New York, NY, USA, 1990; Volume 13, pp. 1–8. ISBN 978-1-4613-8984-2.
47. Searchinger, T.; Heimlich, R.; Houghton, R.A.; Dong, F.; Elobeid, A.; Fabiosa, J.; Tokgoz, S.; Hayes, D.; Yu, T.-H. Use of U.S. Croplands for Biofuels Increases Greenhouse Gases through Emissions from Land-Use Change. *Science* **2008**, *319*, 1238–1240. [CrossRef]
48. Krasuska, E.; Cadórniga, C.; Tenorio, J.L.; Testa, G.; Scordia, D. Potential Land Availability for Energy Crops Production in Europe. *Biofuels Bioprod. Bioref.* **2010**, *4*, 658–673. [CrossRef]
49. Confalonieri, R.; Jones, B.; Van Diepen, K.; Van Orshoven, J. *Scientific Contribution on Combining Biophysical Criteria Underpinning the Delineation of Agricultural Areas Affected by Specific Constraints: Methodology and Factsheets for Plausible Criteria Combinations*; Terres, J.M., Hagyo, A., Wania, A., Eds.; European Comission-Joint Research Centre, Institute for Environment and Sustainability: Luxembourg, 2014; ISBN 978-92-79-44340-4. Available online: http://publications.jrc.ec.europa.eu/repository/bitstream/JRC92686/lbna26940enn.pdf (accessed on 19 October 2021).
50. Gopalakrishnan, G.; Negri, M.C.; Wang, M.; Wu, M.; Snyder, S.W.; LaFreniere, L. Biofuels, Land, and Water: A Systems Approach to Sustainability. *Environ. Sci. Technol.* **2009**, *43*, 6094–6100. [CrossRef]
51. Strijker, D. Marginal Lands in Europe—Causes of Decline. *Basic Appl. Ecol.* **2005**, *6*, 99–106. [CrossRef]
52. Peterson, G.M.; Galbraith, J.K. The Concept of Marginal Land. *J. Farm. Econ.* **1932**, *14*, 295. [CrossRef]
53. Plassmann, K. Direct and Indirect Land Use Change. In *Biokerosene*; Kaltschmitt, M., Neuling, U., Eds.; Springer: Berlin/Heidelberg, Germany, 2018; pp. 375–402. ISBN 978-3-662-53063-4.
54. Young, A. Is There Really Spare Land? A Critique of Estimates of Available Cultivable Land in Developing Countries. *Environ. Dev. Sustain.* **1999**, *1*, 3–18. [CrossRef]

55. Gerwin, W.; Repmann, F.; Galatsidas, S.; Vlachaki, D.; Gounaris, N.; Baumgarten, W.; Volkmann, C.; Keramitzis, D.; Kiourtsis, F.; Freese, D. Assessment and Quantification of Marginal Lands for Biomass Production in Europe Using Soil-Quality Indicators. *SOIL* **2018**, *4*, 267–290. [CrossRef]
56. European Commission. Report From The Commission to the European Parliament, The Council, The European Economic and Social Committee and the Committee of the Regions on the Status of Production Expansion of Relevant Food and Feed Crops Worldwide. 2019. Available online: https://ec.europa.eu/energy/sites/ener/files/documents/report.pdf (accessed on 22 November 2021).
57. Ramirez-Almeyda, J. Lignocellulosic Crops in Europe: Integrating Crop Yield Potentials with Land Potentials. Ph.D. Thesis, University of Bologna, Bologna, Italy, 2017. Available online: http://amsdottorato.unibo.it/7854/ (accessed on 19 October 2021).
58. Eisentraut, A. SuStainable Production of Second-Generation Biofuels-Potential and Perspectives in Major Economies and Developing Countries. 2010. Available online: https://www.oecd-ilibrary.org/energy/sustainable-production-of-second-generation-biofuels_5kmh3njpt6r0-en (accessed on 19 October 2021).
59. Pancaldi, F.; Trindade, L.M. Marginal Lands to Grow Novel Bio-Based Crops: A Plant Breeding Perspective. *Front. Plant. Sci.* **2020**, *11*, 227. [CrossRef]
60. Nijsen, M.; Smeets, E.; Stehfest, E.; Vuuren, D.P. An Evaluation of the Global Potential of Bioenergy Production on Degraded Lands. *Glob. Chang. Biol. Bioenergy* **2012**, *4*, 130–147. [CrossRef]
61. Alexopoulou, E.; Zanetti, F.; Scordia, D.; Zegada-Lizarazu, W.; Christou, M.; Testa, G.; Cosentino, S.L.; Monti, A. Long-Term Yields of Switchgrass, Giant Reed, and Miscanthus in the Mediterranean Basin. *Bioenerg. Res.* **2015**, *8*, 1492–1499. [CrossRef]
62. Cai, X.; Zhang, X.; Wang, D. Land Availability for Biofuel Production. *Environ. Sci. Technol.* **2011**, *45*, 334–339. [CrossRef] [PubMed]
63. Graves, R.A.; Pearson, S.M.; Turner, M.G. Landscape Patterns of Bioenergy in a Changing Climate: Implications for Crop Allocation and Land-Use Competition. *Ecol. Appl.* **2016**, *26*, 515–529. [CrossRef]
64. Gu, Y.; Wylie, B.K. Mapping Marginal Croplands Suitable for Cellulosic Feedstock Crops in the Great Plains, United States. *GCB Bioenergy* **2017**, *9*, 836–844. [CrossRef]
65. Harvolk, S.; Kornatz, P.; Otte, A.; Simmering, D. Using Existing Landscape Data to Assess the Ecological Potential of Miscanthus Cultivation in a Marginal Landscape. *GCB Bioenergy* **2014**, *6*, 227–241. [CrossRef]
66. Khamzina, A.; Lamers, J.P.A.; Vlek, P.L.G. Tree Establishment under Deficit Irrigation on Degraded Agricultural Land in the Lower Amu Darya River Region, Aral Sea Basin. *For. Ecol. Manag.* **2008**, *255*, 168–178. [CrossRef]
67. Beale, C.V.; Long, S.P. Can Perennial C4 Grasses Attain High Efficiencies of Radiant Energy Conversion in Cool Climates? *Plant. Cell Environ.* **1995**, *18*, 641–650. [CrossRef]
68. Clifton-Brown, J.C.; Lewandowski, I.; Andersson, B.; Basch, G.; Christian, D.G.; Kjeldsen, J.B.; Jørgensen, U.; Mortensen, J.V.; Riche, A.B.; Schwarz, K.-U. Performance of 15 Miscanthus Genotypes at Five Sites in Europe. *Agron. J.* **2001**, *93*, 1013–1019. [CrossRef]
69. Liu, W.; Yan, J.; Li, J.; Sang, T. Yield Potential of Miscanthus Energy Crops in the Loess Plateau of China. *Glob. Chang. Biol. Bioenergy* **2012**, *4*, 545–554. [CrossRef]
70. Panoutsou, C.; Chiaramonti, D. Socio-Economic Opportunities from Miscanthus Cultivation in Marginal Land for Bioenergy. *Energies* **2020**, *13*, 2741. [CrossRef]
71. Qin, Z.; Zhuang, Q.; Cai, X. Bioenergy Crop Productivity and Potential Climate Change Mitigation from Marginal Lands in the United States: An Ecosystem Modeling Perspective. *GCB Bioenergy* **2015**, *7*, 1211–1221. [CrossRef]
72. Hastings, A.; Clifton-Browon, J.; Wattenbach, M.; Mitchell, C.P.; Smith, P. The Development of MISCANFOR, a New Miscanthus Crop Growth Model: Towards More Robust Yield Predictions under Different Climatic and Soil Conditions. *GCB Bioenergy* **2009**, *1*, 154–170. [CrossRef]
73. Liu, J.; Williams, J.R.; Zehnder, A.J.B.; Yang, H. GEPIC—Modelling Wheat Yield and Crop Water Productivity with High Resolution on a Global Scale. *Agric. Syst.* **2007**, *94*, 478–493. [CrossRef]
74. Zhang, B.; Hastings, A.; Clifton-Brown, J.C.; Jiang, D.; Faaij, A.P.C. Modeled Spatial Assessment of Biomass Productivity and Technical Potential of *Miscanthus* × *Giganteus*, *Panicum Virgatum* L., and *Jatropha* on Marginal Land in China. *GCB Bioenergy* **2020**, *12*, 328–345. [CrossRef]
75. Cobuloglu, H.I.; Büyüktahtakın, İ.E. A Mixed-Integer Optimization Model for the Economic and Environmental Analysis of Biomass Production. *Biomass Bioenergy* **2014**, *67*, 8–23. [CrossRef]
76. Mehmood, M.A.; Ibrahim, M.; Rashid, U.; Nawaz, M.; Ali, S.; Hussain, A.; Gull, M. Biomass Production for Bioenergy Using Marginal Lands. *Sustain. Prod. Consum.* **2017**, *9*, 3–21. [CrossRef]
77. Pulighe, G.; Bonati, G.; Colangeli, M.; Morese, M.M.; Traverso, L.; Lupia, F.; Khawaja, C.; Janssen, R.; Fava, F. Ongoing and Emerging Issues for Sustainable Bioenergy Production on Marginal Lands in the Mediterranean Regions. *Renew. Sustain. Energy Rev.* **2019**, *103*, 58–70. [CrossRef]
78. Wiggins, S.; Henley, G.; Keats, S. Competitive or Complementary? Industrial Crops and Food Security in Sub-Saharan Africa. *ODI Rep.* **2015**. Available online: https://odi.org/en/publications/competitive-or-complementary-industrial-crops-and-food-security-in-sub-saharan-africa/ (accessed on 19 October 2021).

79. Shepherd, A.; Littleton, E.; Clifton-Brown, J.; Martin, M.; Hastings, A. Projections of Global and UK Bioenergy Potential from Miscanthus × Giganteus—Feedstock Yield, Carbon Cycling and Electricity Generation in the 21st Century. *GCB Bioenergy* **2020**, *12*, 287–305. [CrossRef]
80. Peng, R.D. Reproducible Research in Computational Science. *Science* **2011**, *334*, 1226–1227. [CrossRef] [PubMed]
81. Foster, T.; Brozović, N.; Butler, A.P.; Neale, C.M.U.; Raes, D.; Steduto, P.; Fereres, E.; Hsiao, T.C. AquaCrop-OS: An Open Source Version of FAO's Crop Water Productivity Model. *Agric. Water Manag.* **2017**, *181*, 18–22. [CrossRef]
82. Semenov, M.A.; Porter, J.R. Climatic Variability and the Modelling of Crop Yields. *Agric. For. Meteorol.* **1995**, *73*, 265–283. [CrossRef]
83. Jiang, R.; Wang, T.; Shao, J.; Guo, S.; Zhu, W.; Yu, Y.; Chen, S.; Hatano, R. Modeling the Biomass of Energy Crops: Descriptions, Strengths and Prospective. *J. Integr. Agric.* **2017**, *16*, 1197–1210. [CrossRef]
84. Holzworth, D.P.; Snow, V.; Janssen, S.; Athanasiadis, I.N.; Donatelli, M.; Hoogenboom, G.; White, J.W.; Thorburn, P. Agricultural Production Systems Modelling and Software: Current Status and Future Prospects. *Environ. Model. Softw.* **2015**, *72*, 276–286. [CrossRef]
85. Lewandowski, I.; Clifton-Brown, J.; Kiesel, A.; Hastings, A.; Iqbal, Y. Miscanthus. In *Perennial Grasses for Bioenergy and Bioproducts*; Alexopoulou, E., Ed.; Elsevier: Amsterdam, The Netherlands, 2018; pp. 35–59. ISBN 978-0-12-812900-5.
86. Clifton-Brown, J.; Lewandowski, I. Water Use Efficiency and Biomass Partitioning of Three Different Miscanthus Genotypes with Limited and Unlimited Water Supply. *Ann. Bot.* **2000**, *86*, 191–200. [CrossRef]
87. Mickelbart, M.V.; Hasegawa, P.M.; Bailey-Serres, J. Genetic Mechanisms of Abiotic Stress Tolerance That Translate to Crop Yield Stability. *Nat. Rev. Genet.* **2015**, *16*, 237–251. [CrossRef]
88. Bauen, A.W.; Dunnett, A.J.; Richter, G.M.; Dailey, A.G.; Aylott, M.; Casella, E.; Taylor, G. Modelling Supply and Demand of Bioenergy from Short Rotation Coppice and Miscanthus in the UK. *Bioresour. Technol.* **2010**, *101*, 8132–8143. [CrossRef]
89. Richter, G.M.; Riche, A.B.; Dailey, A.G.; Gezan, S.A.; Powlson, D.S. Is UK Biofuel Supply from Miscanthus Water-Limited? *Soil Use Manag.* **2008**, *24*, 235–245. [CrossRef]
90. Aylott, M.J.; Casella, E.; Tubby, I.; Street, N.R.; Smith, P.; Taylor, G. Yield and Spatial Supply of Bioenergy Poplar and Willow Short-Rotation Coppice in the UK. *New Phytol.* **2008**, *178*, 358–370. [CrossRef] [PubMed]
91. Schorling, M.; Enders, C.; Voigt, C.A. Assessing the Cultivation Potential of the Energy Crop *Miscanthus* × *Giganteus* for Germany. *GCB Bioenergy* **2015**, *7*, 763–773. [CrossRef]
92. Blanco-Canqui, H. Growing Dedicated Energy Crops on Marginal Lands and Ecosystem Services. *Soil Sci. Soc. Am. J.* **2016**, *80*, 845–858. [CrossRef]
93. McIsaac, G.F.; David, M.B.; Mitchell, C.A. Miscanthus and Switchgrass Production in Central Illinois: Impacts on Hydrology and Inorganic Nitrogen Leaching. *J. Environ. Qual.* **2010**, *39*, 1790–1799. [CrossRef] [PubMed]
94. Dees, M.; Elbersen, B.; Fitzgerald, J.; Vis, M.; Anttila, P.; Forsell, N.; Ramirez-Almeyda, J.; García Galindo, D.; Glavonjic, B.; Staritsky, I.; et al. *A Spatial Data Base on Sustainable Biomass Cost-Supply of Lignocellulosic Biomass in Europe—Methods & Data Sources*; S2BIOM Project Report 1.6; University of Freiburg: Breisgau, Germany, 2017; 176p. [CrossRef]
95. Intergovernmental Panel on Climate Change (IPCC). Special Report on Climate Change and Land. 2019. Available online: https://www.ipcc.ch/site/assets/uploads/2019/11/SRCCL-Full-Report-Compiled-191128.pdf (accessed on 19 October 2021).
96. Haberl, H.; Erb, K.-H.; Krausmann, F.; Bondeau, A.; Lauk, C.; Müller, C.; Plutzar, C.; Steinberger, J.K. Global Bioenergy Potentials from Agricultural Land in 2050: Sensitivity to Climate Change, Diets and Yields. *Biomass Bioenergy* **2011**, *35*, 4753–4769. [CrossRef]
97. Powell, J.P.; Reinhard, S. Measuring the Effects of Extreme Weather Events on Yields. *Weather Clim. Extrem.* **2016**, *12*, 69–79. [CrossRef]
98. Wicke, B. *Bioenergy Production on Degraded and Marginal Land: Assessing Its Potentials, Economic Performance, and Environmental Impacts for Different Settings and Geographical Scales*; Utrecht University: Utrecht, The Netherlands, 2011. Available online: /paper/Bioenergy-production-on-degraded-and-marginal-land-Wicke/b6b235cafcdb8139039fa28ff3c0be17369df4b5 (accessed on 19 October 2021).
99. Metzger, J.O.; Hüttermann, A. Sustainable Global Energy Supply Based on Lignocellulosic Biomass from Afforestation of Degraded Areas. *Naturwissenschaften* **2009**, *96*, 279–288. [CrossRef]
100. Skevas, T.; Swinton, S.M.; Hayden, N.J. What Type of Landowner Would Supply Marginal Land for Energy Crops? *Biomass Bioenergy* **2014**, *67*, 252–259. [CrossRef]
101. Intergovernmental Panel on Climate Change. In *Global Warming of 1.5 °C*; World Meteorological Organization: Geneva, Switzerland, 2019. Available online: https://www.ipcc.ch/sr15/ (accessed on 19 October 2021).
102. Scagline-Mellor, S.; Griggs, T.; Skousen, J.; Wolfrum, E.; Holásková, I. Switchgrass and Giant Miscanthus Biomass and Theoretical Ethanol Production from Reclaimed Mine Lands. *Bioenerg. Res.* **2018**, *11*, 562–573. [CrossRef]
103. Saha, M.; Eckelman, M.J. Geospatial Assessment of Potential Bioenergy Crop Production on Urban Marginal Land. *Appl. Energy* **2015**, *159*, 540–547. [CrossRef]
104. Smith, P.; Porter, J.R. Bioenergy in the IPCC Assessments. *GCB Bioenergy* **2018**, *10*, 428–431. [CrossRef]
105. Hoogwijk, M.; Faaij, A.; Eickhout, B.; Devries, B.; Turkenburg, W. Potential of Biomass Energy out to 2100, for Four IPCC SRES Land-Use Scenarios. *Biomass Bioenergy* **2005**, *29*, 225–257. [CrossRef]
106. Tilman, D.; Hill, J.; Lehman, C. Carbon-Negative Biofuels from Low-Input High-Diversity Grassland Biomass. *Science* **2006**, *314*, 1598–1600. [CrossRef]

107. Lynd, L.R.; Laser, M.S.; Bransby, D.; Dale, B.E.; Davison, B.; Hamilton, R.; Himmel, M.; Keller, M.; McMillan, J.D.; Sheehan, J.; et al. How Biotech Can Transform Biofuels. *Nat. Biotechnol.* **2008**, *26*, 169–172. [CrossRef]
108. BASIS – Biomass Availability and Sustainability Information System. Report on Conversion Efficiency of Biomass. 2015. Available online: http://www.basisbioenergy.eu/fileadmin/BASIS/D3.5_Report_on_conversion_efficiency_of_biomass.pdf (accessed on 19 October 2021).
109. Clariant International Ltd. Clariant and Enviral Announce First License Agreement on Sunliquid® Cellulosic Ethanol Technology. Available online: https://www.clariant.com/en/Corporate/News/2017/09/Clariant-and-Enviral-announce-first-license-agreement-on-sunliquid-cellulosic-ethanol-technology (accessed on 19 October 2021).
110. Clariant International Ltd. Clariant to Build Flagship Sunliquid® Cellulosic Ethanol Plant in Romania. Available online: https://www.clariant.com/en/Corporate/News/2017/10/Clariant-to-build-flagship-sunliquid-cellulosic-ethanol-plant-in-Romania (accessed on 19 October 2021).
111. ETIP. Bioenergy Cellulosic Ethanol. Available online: https://www.etipbioenergy.eu/value-chains/products-end-use/products/cellulosic-ethanol#ce1 (accessed on 19 October 2021).
112. Witsch, K. Biosprit: So Kann der Durchbruch in Europa Gelingen. Available online: https://www.handelsblatt.com/unternehmen/energie/erneuerbare-energien-umstrittener-biosprit-wie-der-durchbruch-auch-in-europa-gelingen-kann/25427964.html (accessed on 19 October 2021).
113. Mayer, A. Amid Biofuels Uncertainties, Iowa Cellulosic Ethanol Plant Halts Production. Available online: https://www.iowapublicradio.org/agriculture/2019-11-19/amid-biofuels-uncertainties-iowa-cellulosic-ethanol-plant-halts-production (accessed on 19 October 2021).
114. Grzincic, B.; Abengoa Affiliates Can't Recoup $70 Million in Loans to Bankrupt Biomass Plant—10th Circuit. Reuters 2020. Available online: https://www.reuters.com/article/abengoa-affiliates-cant-recoup-70-millio-idUSL1N2CO0BZ (accessed on 22 November 2021).
115. Global Industry Analysts, Inc. Cellulosic Ethanol—Global Market Trajectory & Analytics. Available online: https://www.researchandmarkets.com/reports/5029784/cellulosic-ethanol-global-market-trajectory-and (accessed on 19 October 2021).
116. Chundawat, S.P.S.; Beckham, G.T.; Himmel, M.E.; Dale, B.E. Deconstruction of Lignocellulosic Biomass to Fuels and Chemicals. *Annu. Rev. Chem. Biomol. Eng.* **2011**, *2*, 121–145. [CrossRef]
117. Hall, C.A.S.; Lambert, J.G.; Balogh, S.B. EROI of Different Fuels and the Implications for Society. *Energy Policy* **2014**, *64*, 141–152. [CrossRef]
118. Baral, A.; Bakshi, B.R.; Smith, R.L. Assessing Resource Intensity and Renewability of Cellulosic Ethanol Technologies Using Eco-LCA. *Environ. Sci. Technol.* **2012**, *46*, 2436–2444. [CrossRef] [PubMed]
119. NRDC. Ethanol: Energy Well Spent—A Survey of Studies Published Since 1990. 2006. Available online: https://www.nrdc.org/sites/default/files/ethanol.pdf (accessed on 19 October 2021).
120. Hammerschlag, R. Ethanol's Energy Return on Investment: A Survey of the Literature 1990−Present. *Environ. Sci. Technol.* **2006**, *40*, 1744–1750. [CrossRef] [PubMed]
121. Patzek, T. A Probabilistic Analysis of the Switchgrass Ethanol Cycle. *Sustainability* **2010**, *2*, 3158–3194. [CrossRef]
122. Pimentel, D.; Patzek, T.W. Ethanol Production Using Corn, Switchgrass, and Wood; Biodiesel Production Using Soybean and Sunflower. *Nat. Resour. Res.* **2005**, *14*, 65–76. [CrossRef]
123. Cleveland, C.J.; Hall, C.A.S.; Herendeen, R.A. Energy Returns on Ethanol Production. *Science* **2006**, *312*, 1746–1748. [CrossRef] [PubMed]
124. Murphy, D.J.; Hall, C.A.S.; Dale, M.; Cleveland, C. Order from Chaos: A Preliminary Protocol for Determining the EROI of Fuels. *Sustainability* **2011**, *3*, 1888–1907. [CrossRef]
125. Robertson, P.G.; Landis, D.A.; Khanna, M. The Sustainability of Cellulosic Biofuels 2012. Available online: https://lter.kbs.msu.edu/wp-content/uploads/2012/06/sustainability-of-cellulosic-biofuels.pdf (accessed on 19 October 2021).
126. van der Weijde, T.; Kiesel, A.; Iqbal, Y.; Muylle, H.; Dolstra, O.; Visser, R.G.F.; Lewandowski, I.; Trindade, L.M. Evaluation of *Miscanthus Sinensis* Biomass Quality as Feedstock for Conversion into Different Bioenergy Products. *GCB Bioenergy* **2017**, *9*, 176–190. [CrossRef]
127. Isikgor, F.H.; Becer, C.R. Lignocellulosic Biomass: A Sustainable Platform for the Production of Bio-Based Chemicals and Polymers. *Polym. Chem.* **2015**, *6*, 4497–4559. [CrossRef]
128. Kralova, K.; Masarovičová, E. Plants for the Future. *Ecol. Chem. Engineering. S Chem. I Inżynieria Ekologiczna. S* **2006**, *13*, 1179–1207.
129. van der Weijde, T.; Alvim Kamei, C.L.; Torres, A.F.; Vermerris, W.; Dolstra, O.; Visser, R.G.F.; Trindade, L.M. The Potential of C4 Grasses for Cellulosic Biofuel Production. *Front. Plant Sci.* **2013**, *4*, 107. [CrossRef] [PubMed]
130. Trindade, L.M.; Dolstra, O.; van Loo, E.N.; Visser, R.G.F. *Plant Breeding and Its Role in a Biobased Economy*; Routledge: London, UK, 2010; ISBN 978-1-84407-770-0.
131. da Costa, R.M.F.; Pattathil, S.; Avci, U.; Winters, A.; Hahn, M.G.; Bosch, M. Desirable Plant Cell Wall Traits for Higher-Quality Miscanthus Lignocellulosic Biomass. *Biotechnol. Biofuels* **2019**, *12*, 85. [CrossRef] [PubMed]
132. Torres, A.F.; Visser, R.G.F.; Trindade, L.M. Bioethanol from Maize Cell Walls: Genes, Molecular Tools, and Breeding Prospects. *GCB Bioenergy* **2015**, *7*, 591–607. [CrossRef]
133. Zegada-Lizarazu, W.; Parrish, D.; Berti, M.; Monti, A. Dedicated Crops for Advanced Biofuels: Consistent and Diverging Agronomic Points of View between the USA and the EU-27. *Biofuels Bioprod. Bioref.* **2013**, *7*, 715–731. [CrossRef]

134. Dauber, J.; Brown, C.; Fernando, A.L.; Finnan, J.; Krasuska, E.; Ponitka, J.; Styles, D.; Thrän, D.; Van Groenigen, K.J.; Weih, M.; et al. Bioenergy from "Surplus" Land: Environmental and Socio-Economic Implications. *BioRisk* **2012**, *7*, 5–50. [CrossRef]
135. Jones, M.B.; Finnan, J.; Hodkinson, T.R. Morphological and Physiological Traits for Higher Biomass Production in Perennial Rhizomatous Grasses Grown on Marginal Land. *GCB Bioenergy* **2015**, *7*, 375–385. [CrossRef]
136. Zegada-Lizarazu, W.; Elbersen, H.W.; Cosentino, S.L.; Zatta, A.; Alexopoulou, E.; Monti, A. Agronomic Aspects of Future Energy Crops in Europe. *Biofuels Bioprod. Bioref.* **2010**, *4*, 674–691. [CrossRef]
137. Zhu, X.-G.; Chang, T.-G.; Song, Q.-F.; Finnan, J.; Barth, S.; Mårtensson, L.-M.; Jones, M.B. A Systems Approach Guiding Future Biomass Crop Development on Marginal Land. In Proceedings of the Perennial Biomass Crops for a Resource-Constrained World; Barth, S., Murphy-Bokern, D., Kalinina, O., Taylor, G., Jones, M., Eds.; Springer International Publishing: Cham, Switzerland, 2016; pp. 209–224.
138. Allwright, M.R.; Taylor, G. Molecular Breeding for Improved Second Generation Bioenergy Crops. *Trends Plant Sci.* **2016**, *21*, 43–54. [CrossRef]
139. van der Weijde, T.; Torres, A.F.; Dolstra, O.; Dechesne, A.; Visser, R.G.F.; Trindade, L.M. Impact of Different Lignin Fractions on Saccharification Efficiency in Diverse Species of the Bioenergy Crop Miscanthus. *Bioenerg. Res.* **2016**, *9*, 146–156. [CrossRef]
140. Purdy, S.J.; Maddison, A.L.; Cunniff, J.; Donnison, I.; Clifton-Brown, J. Non-Structural Carbohydrate Profiles and Ratios between Soluble Sugars and Starch Serve as Indicators of Productivity for a Bioenergy Grass. *AoB Plants* **2015**, *7*, plv032. [CrossRef] [PubMed]
141. European Comission, 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 (Text with EEA Relevance). *OJL* **2018**, *328*, 82–209. Available online: https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=uriserv:OJ.L_.2018.328.01.0082.01.ENG (accessed on 19 October 2021).
142. European Commission. Sustainable and Optimal Use of Biomass for Energy in the EU beyond 2020—Annexes of the Final Report. 2017. Available online: https://ec.europa.eu/energy/studies/sustainable-and-optimal-use-biomass-energy-eu-beyond-2020_en (accessed on 19 October 2021).
143. European Commission (EC). Sustainability Criteria for Biofuels Specified. Available online: https://ec.europa.eu/commission/presscorner/detail/en/MEMO_19_1656 (accessed on 19 October 2021).
144. Carter, T.R.; La Rovere, E.L. Developing and Applying Scenarios. 2018. Available online: https://www.ipcc.ch/site/assets/uploads/2018/03/wg2TARchap3.pdf (accessed on 19 October 2021).
145. European Commission. Methodology Underlying the CAPRI Model. Available online: https://ec.europa.eu/clima/sites/default/files/strategies/analysis/models/docs/capri_model_methodology_en.pdf (accessed on 19 October 2021).
146. European Commission. Modelling Tools for EU Analysis. Available online: https://ec.europa.eu/clima/policies/strategies/analysis/models_en (accessed on 19 October 2021).
147. Lask, J.; Wagner, M.; Trindade, L.M.; Lewandowski, I. Life Cycle Assessment of Ethanol Production from Miscanthus: A Comparison of Production Pathways at Two European Sites. *GCB Bioenergy* **2018**, *11*, 269–288. [CrossRef]
148. Li, Q.; Hu, G. Techno-Economic Analysis of Biofuel Production Considering Logistic Configurations. *Bioresour. Technol.* **2016**, *206*, 195–203. [CrossRef]
149. Crews, T.; Cattani, D. Strategies, Advances, and Challenges in Breeding Perennial Grain Crops. *Sustainability* **2018**, *10*, 2192. [CrossRef]
150. Schuler, M.L.; Mantegazza, O.; Weber, A.P.M. Engineering C_4 Photosynthesis into C_3 Chassis in the Synthetic Biology Age. *Plant J.* **2016**, *87*, 51–65. [CrossRef]
151. Houghton, J.; Weatherwax, S.; Ferrell, J. *Breaking the Biological Barriers to Cellulosic Ethanol: A Joint Research Agenda*; EERE Publication and Product Library: Washington, DC, USA, 2006. Available online: https://www.osti.gov/biblio/1218382 (accessed on 22 November 2021).
152. Reinhardt, J.; Hilgert, P.; Von Cossel, M. A Review of Industrial Crop Yield Performances on Unfavorable Soil Types. *Agronomy* **2021**, *11*, 2382. [CrossRef]
153. White, J.W. Combining Ecophysiological Models and Genomics to Decipher the GEM-to-P Problem. *NJAS Wagening. J. Life Sci.* **2009**, *57*, 53–58. [CrossRef]
154. Bennett, A.B.; Isaacs, R. Landscape Composition Influences Pollinators and Pollination Services in Perennial Biofuel Plantings. *Agric. Ecosyst. Environ.* **2014**, *193*, 1–8. [CrossRef]
155. Carlsson, G.; Mårtensson, L.-M.; Prade, T.; Svensson, S.-E.; Jensen, E.S. Perennial Species Mixtures for Multifunctional Production of Biomass on Marginal Land. *GCB Bioenergy* **2017**, *9*, 191–201. [CrossRef]
156. Werling, B.P.; Meehan, T.D.; Robertson, B.A.; Gratton, C.; Landis, D.A. Biocontrol Potential Varies with Changes in Biofuel–Crop Plant Communities and Landscape Perenniality. *GCB Bioenergy* **2011**, *3*, 347–359. [CrossRef]
157. Liere, H.; Kim, T.N.; Werling, B.P.; Meehan, T.D.; Landis, D.A.; Gratton, C. Trophic Cascades in Agricultural Landscapes: Indirect Effects of Landscape Composition on Crop Yield. *Ecol. Appl.* **2015**, *25*, 652–661. [CrossRef]
158. Valentine, J.; Clifton-Brown, J.; Hastings, A.; Robson, P.; Allison, G.; Smith, P. Food vs. Fuel: The Use of Land for Lignocellulosic 'next Generation' Energy Crops That Minimize Competition with Primary Food Production. *GCB Bioenergy* **2012**, *4*, 1–19. [CrossRef]