sustainability

Review

Applying a Sustainable Development Lens to Global Biomass Potentials

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Abstract: The Sustainable Development Goals (SDGs), adopted by all UN Member States in 2015, guide societies to achieve a better and more sustainable future. Depleting fossil fuels and climate change will strongly increase the demand for biomass, as governments shift towards bioeconomies. Though research has estimated future biomass availability for bioenergetic uses, the implications for sustainable development have hardly been discussed; e.g., how far the estimates account for food security, sustainability and the satisfaction of basic human needs, and what this implies for intragenerational equity. This research addresses the gap through a systematic literature review and our own modeling. It shows that the biomass models insufficiently account for food security; e.g., by modeling future food consumption below current levels. The available biomass, if fairly distributed, can globally replace fossil fuels required for future material needs but hardly any additional energy needs. To satisfy basic human needs, the material use of biomass should, therefore, be prioritized over bioenergy. The different possibilities for biomass allocation and distribution need to be analyzed for their potential negative implications, especially for the poorer regions of the world. Research, society, business and politicians have to address those to ensure the 'leave no one behind´ commitment of the SDGs.

Keywords: biomass scenarios; global biomass; bioenergy; sustainability; food security; basic needs; intragenerational justice; equity; fairness; development

1. Introduction

Bioeconomies focus on the production and utilization of biological resources to generate bio-based products, including bioenergy [1]. There is a global trend to substitute biomass for fossil fuels for material or chemical use and energy, which is in part due to climate change, but is mainly driven by depleting fossil fuel stocks. Estimates for fossil fuel peaks and depletion vary [2,3], but researchers have increasingly pointed out that by 2050, hardly any oil will be available and coal reserves will be the main remaining fossil fuel [3,4]. Therefore, high-value bio-based products are receiving increasing attention, especially in the industrialized countries, and bioenergy is perceived as crucial, given its potential to combat climate change [5]. Today, almost 50 countries are pursuing bioeconomy development in their policy strategies, 15 of which have developed dedicated bioeconomy policy strategies [1]. The emerging bioeconomies are expected to lead to a strong increase in biomass demand in the next decades.

At the same time, the concept of sustainability has become very important for societal development, as recently reflected by the universal adoption of the Sustainable Development Goals (SDGs) [6]. The SDGs guide societies in their attempt to adjust their economies towards ecological and social objectives with the overall aim to "leave no one behind" [7,8]. The notions of sustainability or sustainable development comprise a societal vision of how to act within social and natural systems over the long term [9]. Many concepts and definitions of sustainability exist [6,7,10–12]. According to Baumgärtner and Quaas [10,11] (page 2057), "Sustainability aims at justice in the domain of human–nature relationships and in view of the long-term and inherently uncertain future, including (i) justice between humans of different generations ("intergenerational" justice), (ii) justice between different humans of the same generation, in particular the present generation ("intragenerational" justice), and (iii) justice between humans and nature." Both justice and equity relate to a fair balance of mutual claims and obligations within a local or global community [9]. The World Commission on Environment and Development has defined sustainable development in its report "Our Common Future," also known as the Brundtland Report, as "development that meets the needs of the present without compromising the ability of future generations to meet their own needs" [12] (page 54). From this report, Holden et al. [6] derive four sustainability dimensions: (i) The need for long-term ecological sustainability, (ii) the satisfaction of human needs, (iii) intragenerational equity; i.e., equity between humans within a country and between countries of the same generation, and (iv) intergenerational equity, which means that future generations must also be able to meet their needs.

The growing biomass demand poses new challenges to the sustainability of biomass production, the efficient use of biomass and the economies of scale in biomass mobilization [13]. Large amounts of biomass will be necessary to replace fossil fuels and to meet the future increase of food demand [13] However, the global biomass supply is limited despite biomass being renewable [14,15]. Competition exists between the alternative uses of biomass; i.e., between food, feed, fiber, bio-based materials and energy uses [16], while most planetary boundaries relevant for biomass production have already been exceeded [17]. To cover the increasing food and feed demands of a growing population in 2050, agricultural production has to increase significantly. Today, one out of nine people (820 million people) are hungry, which means they do not consume the adequate amount of dietary energy [18]. More than two billion people suffer from hidden hunger; i.e., they lack key vitamins and other micronutrients, such as iodine, iron and zinc [19]. This affects the health and well-being of the people and, as a consequence, national socioeconomic development [20]. An increasing demand for non-food biomass may impact food security with respect not only to the availability but also to the diversity, stability and access to food. This may lead to an increase in hunger given the disproportionately large energy markets compared to food markets, and the stronger economic position of those demanding more energy versus those being food-insecure [21]. Those potential effects are highly relevant for the compliance with the SDG-2, which aims to eliminate hunger by 2030. The use of biomass poses ecological, social, economic and ethical challenges regarding production, allocation and distribution.

For planning and investment purposes, as well as for governmental policies, it is important to understand how much biomass can be used by humans without putting the ecosystem at risk. In a next step, it has to be determined for what the available biomass should be used (e.g., for food, feed, fiber, materials, energy) and by whom. Several initiatives and projects estimated future biomass availability for bioenergy and came to very diverging results; i.e., they assumed that in 2050 biomass availability could range from 36 to 1458 EJ/a (Exajoule per year) [15,16,22–33]. This large variation has been explained by researchers as being due to differences in the assumptions within the applied models; e.g., regarding land area and use, cropping intensity, yield improvements or population growth [16,22,34]. Though the studies claim that their results consider the future demand for food, it is doubtful how well food and nutrition concepts were integrated in the models. Several authors have critically assessed the studies on biomass availability for bioenergy [16,22,34,35]. However, their emphasis was not on sustainable development from a socioeconomic or a holistic food security perspective.

The four dimensions of sustainable development following Holden et al. [6] can be used as an analytical perspective for examining the biomass estimates and models. The first dimension, i.e., the need for long-term ecological sustainability, is partly addressed in the models or discussed in reviews to a greater or lesser extent [16,34] The second dimension, i.e., the satisfaction of human needs, which includes food security as a human right, has not been explicitly addressed by the research on biomass potentials or the respective reviews. The fulfillment of basic non-food human needs involves housing, energy, water supply, sanitation and health care—all of which directly or indirectly depend on fossil fuels or biomass. An analysis is missing on whether the future non-food biomass supply will be able to cater for all human needs (e.g., materials, chemicals, fiber and energy), or whether certain uses will have to be prioritized. To date, research has concentrated on bioenergy and biomass availability and not on bio-based chemicals or materials [22]. However, the latter might, in future, add significantly to the biomass demand [13,22,36] and should be discussed together with the biomass potentials [13].

The question about who is to use the available biomass and for which purposes has not been part of the discussions on the biomass estimates. This intragenerational equity perspective, reflecting the third sustainability dimension, is also relevant for the SDG 10, regarding the reduction in global and national inequalities of resource use and welfare. Fair distribution and use of resources have been discussed by ethics and philosophy, but these discussions have not been linked to biomass availability. Answers to the above-mentioned knowledge gaps are urgently needed so that governments and other actors can make adequate choices about the kind of society in which we want to live and about the kind of world we want to leave to posterity [7]. Therefore, this research analyses and discusses biomass availability estimates from the perspective of the satisfaction of human needs, especially food security, and intragenerational equity. This research aims:

(i) To understand how food security is reflected in the estimates of biomass potentials;
(ii) To identify to what extent the energetic and material use of fossil fuels can be replaced by biomass, and what this means for resource allocation, distribution and intragenerational equity.

The next section briefly describes the method, definitions and concepts used. The result section shows how far food security aspects are addressed by the estimates of biomass potentials. It identifies to what extent the energetic and material uses of fossil fuels can be covered by biomass, and what this means for the satisfaction of non-food human needs and intragenerational equity. This is followed by a discussion also presenting recommendations for future research, and conclusions with policy implications.

2. Method and Concepts

2.1. The Procedure of the Systematic Literature Review

We conducted a systematic literature review following Jesson et al. [37]. We used the PRISMA guidelines (see http://prisma-statement.org/) but adjusted them slightly for our type of review. For a flow diagram with details of the systematic review procedure see Appendix A. The data search was based on the Thomson Reuters' Web of Science (ISI Web of Knowledge) database. The Web of Science's default settings were used; i.e., time span all years (1945–2018), all indices, all languages and all document types (see Appendix A). The search terms biomass potential(s), potential(s) of biomass, and bioenergy potential(s) returned 745 findings. All titles and abstracts were screened, and the following parameters were used to exclude studies from the further review process: (i) Regionally restricted studies (ii) publications addressing only single energy plants or single biomass sources (e.g., only residues and waste), and (iii) literature focusing merely on chemical processing or economic valorization of biomass. For the remaining 35 articles, a full text analysis was done. Two further exclusion criteria were established: (iv) articles based on reviews and not on own models and estimations, and (v) all publications that did not use 2050 as a reference year for the global biomass potentials. We decided to use the year 2050 as this is when oil resources will be almost depleted and alternative uses will have to be available. Many researchers have also chosen this time frame for their models, and only few studies look at 2030 or 2100. Finally, 14 studies remained for the systematic analysis. Two studies calculated the geographical biomass potential [31,32], one study the sustainable potential [38], and the remaining eleven studies the technical potential [15,22,27,29,30,33,39–43] (see Appendix B for definition of biomass potential types). The (environmentally) sustainable potential includes more assumptions for ecological boundaries, environmental protection and long-term availability of resources.

Data Sources, Scenarios, and Models of the Studies Used in The Review

The primary data source for all reviewed studies is the database of the Food and Agriculture Organization of the United Nations (FAO): FAOSTAT. This database integrates agricultural production and land-use data (including forestry) compiled from single country surveys, satellite imaging data, projections and estimates into one global dataset. Though the quality of the dataset has been contested [44,45], it remains the only comprehensive and standardized global dataset available.

The biomass scenarios and their underlying models provide alternative narratives for how key drivers, e.g., global population, dietary changes (affecting food and feed demand), climate, economic development, crop yield improvements, and available land area, might evolve in the future, and how this might impact other dependent parameters [13]. The most prominent scenarios used in the assessments are those from the Intergovernmental Panel on Climate Change (IPCC) Special Report on Emission Scenarios. The applied modeling approach is usually based on integrating models that combine resource and demand data into a unified modeling approach (such as the Integrated Model to Assess the Global Environment (IMAGE) [31,42,46], Global Land Use and Energy Model (GLUE) [47], IIASA's Basic-Linked System model (BLS) [39]), and 'stand-alone' productivity and crop yield models, like the Lund–Potsdam–Jena model with Managed Land model (LPJmL) [30,48].

To estimate the global biomass potentials, the reviewed studies usually look, roughly summarizing, at available (agricultural) land where biomass can be produced, estimate the food requirements of the population in 2050 and the required amount of land needed for food production, and then estimate how much biomass can be produced on the remaining land. Table A2 provides an overview of the estimated biomass potentials, the type of potential and the biomass sources used in the studies. The studies have different assumptions about the availability of biomass sources; e.g., from agriculture, forestry, waste and about future land-use change. Further differences can be explained by the modeling procedure and the assumptions regarding, for example, diets, population growth and yield increases. For example, population growth projections mainly follow the 'UN medium population forecast' of 9.2 billion in 2050, but values vary from 8.7 to 11.3 billion. Cropland expansion is projected to range between 0.1 and 0.45 Gha, with the majority of the studies providing values in the lower range. Projections of global yield increases can range up to 360% [33]. Assumptions regarding cropping intensification and irrigation are hardly described in the studies but are usually included. Not all studies published details about their assumptions (including nutritional requirements) or their modeling procedure, which may skew this assessment.

2.2. *Definition of Terms and Concepts Used in This Study*

2.2.1. The Concept of Food Security

Being aware that the thinking and consequently definitions around food security have changed over time [49,50], this research uses the international food security definition agreed upon by all states at the World Food Summit in 1996 and again emphasized in subsequent summits and high-level UN meetings: "Food security exists when all people, at all times, have physical and economic access to sufficient safe and nutritious food that meets their dietary needs and food preferences for an active and healthy life" [51]. This definition of food security has been state-of-the-art since the turn of the millennium, and is based on four pillars; i.e., availability of food, access to food, utilization of food and stability [52,53]. The pillar of "food availability" refers to the availability of sufficient quantities of food of appropriate quality at national but also at household level. The pillar of "food access" refers to the physical and economic access of individuals to adequate resources to acquire appropriate foods for a nutritious diet. Physical and economic food access is mainly determined by the income or resource endowment of the population/household, transport and market infrastructure. The pillar of "food utilization" refers to a diet adequate in quantity, quality and diversity, fulfilling all nutritional requirements. Along with food safety, clean water, sanitation and health care, it is imperative to reach a state of nutritional well-being where all physiological needs are met. The term "nutritional requirements" refer to the amount of protein, energy, carbohydrates, fats and lipids, vitamins, minerals and trace elements (such as calcium, iron, zinc, selenium, magnesium and iodine) needed by a human being to sustain a healthy life. The pillar "food stability" refers to the access of a population, household or individual to adequate food at all times, independent of shocks or cyclical events, such as seasonal availability [52,53]. Meeting the nutritional requirements of a human being is only one aspect of food security. Many more conditions need to be met so that a person being described as 'food secure' is in line with the international food security concept which is widely used by the FAO, the UN and many civil society organizations.

2.2.2. The Concept of Allocation, Distribution and Intragenerational Equity

The term "allocation" in this paper refers to how resources (in this case biomass) are divided among different products and product uses; e.g., how much biomass is used for bioenergy or for material use, such as for construction, chemicals, plastics or fibers. This is relevant with respect to the satisfaction of human needs; i.e., one of the four sustainability dimensions [6]. The satisfaction of needs requires that no one suffers from absolute deprivation anymore; i.e., that all basic human needs are met [54]; this is also part of the SDGs. The term "distribution" refers to how goods and services are divided among people of current and future generations [55]. This is relevant for intragenerational equity, another sustainability dimension, which goes beyond the basic needs concept by targeting the relative shares of resource use and deprivation within a generation. To address intragenerational equity regarding biomass use, this research uses an egalitarian approach which entails equal resource use for each person in any society across the world independent of the natural resource base of a country; i.e., everyone gets the same share of biomass allocated for a specific use.

2.3. Estimating Biomass Availability and Uses

The data sources for the calculation of biomass availability and uses are derived from the World Energy Council [56] (see Appendix E, Table A3). The report presents two energy scenarios for 2050 with varying assumptions regarding population growth, income growth, governance and consumption behavior. The Jazz scenario is more consumer oriented and aims to achieve better energy access and affordability through economic growth. The Symphony scenario has a stronger focus on achieving environmental sustainability through coordinated policies and practices by governments. It is important to point out that neither scenario assumes that every person has access to electricity by 2050. The share of households without electricity remains high in Africa and south and central Asia, being higher in the Symphony scenario than in the Jazz scenario.

The following formulas were used to estimate how much of the energy and material requirements in 2050 could be covered by biomass.

The average minimum or maximum biomass potential BP across all studies is determined with

$$BP_{min/max} = \frac{1}{n}\sum_{i=1}^{n} x_i \tag{1}$$

where x_i is the biomass potential of the respective study and i is the reviewed study (i=1, . . . , 14). The minimum, respectively the maximum, value for the biomass availability potential of each study was used. If the study mentioned only one value for biomass availability, this value was used for both the minimum and maximum value.

The average biomass potential per capita BP_{pc} is determined by

$$BP_{pc} = \frac{BP}{WP} \tag{2}$$

where WP is the global population in 2050 as estimated by the World Energy Council [56].

For the following estimations, only those studies that were published in 2010 or beyond were used, as we assume that models improve over time with increasing experience and scientific review (e.g., [34]). The more recent studies only estimate the technical or sustainable potential, which is also more relevant for decision-makers.

The per capita energy demand covered by the biomass potentials ED_{pc} is determined by

$$ED_{pc} = \frac{BP_{pc} \times WP}{WE} \tag{3}$$

where WE is the world energy needs in 2050 as estimated by the World Energy Council [56]. This value includes energy conversion losses, etc., and is therefore higher than the value for actual "final energy consumption." Since conversion losses need to be covered also by energy supplies, for us this is the key value to use in the calculations. For the regional estimates, WE represents the respective regional energy demand in 2050, and WP the respective regional population.

The global per capita material demand covered by the biomass potentials MD_{pc} is determined by

$$MD_{pc} = \frac{BP_{pc}}{RM_{pc}} \tag{4}$$

where RM_{pc} is the regional material use of final energy consumption per capita (GJ/y). Since the World Energy Council [56] does not provide estimates for regional material needs, RM_{pc} is estimated as follows

$$RM_{pc} = \frac{FE}{WP} \times \frac{WM_{pc} \times WP}{FE} \tag{5}$$

where WM_{pc} is the per capita world material need in 2050. WM_{pc} is calculated by dividing the "final energy consumption" FE with the world population WP and then substracting the "final energy consumption per capita, excluding non-energy use." WM_{pc} is 7.6 GJ/y in the Jazz scenario and 6.1 GJ/y in the Symphony scenario, which corresponds to a global share of material uses in final energy consumption of 11% and 12%, respectively.

The estimation of RM_{pc} accounts for the different purchasing power in each region, and hence embraces more inequity in material resource use in 2050; i.e., Africa will be using much less energy for material uses than Europe. Alternatively, one could use WM_{pc} based on the normative aspect to account for the satisfaction of the basic material needs of every person across the world in the same quantity. Given the lack of better data, WM_{pc} is assumed to be a good proxy of what could be desirable as material use of energy. The motivation for this assumption stems from the second and third dimension of sustainable development; i.e., the satisfaction of basic human needs and intragenerational justice. From an intragenerational justice perspective, it is adequate to assume that per capita material demand across all regions should be the same. Despite that, the World Energy Council data estimates already embrace lower per capita energy uses in Africa and Asia than in the rest of the world, and it is not clear whether these assumed levels of energy use for Africa are actually sufficient to meet the basic needs of the whole population or not. The per capita total energy demand covered by the biomass potential after satisfying material needs based on an equal material resource distribution ($EDMD_{pc}$) is determined by

$$EDMD_{pc} = \frac{BP_{pc} - WM_{pc}}{\frac{WE}{WP} - WM_{pc}} \tag{6}$$

Taking regional differences and hence inequity in resource use into account, the per capita total energy demand covered by the biomass potential after accounting for regional difference in satisfying material needs $\left(REDMD_{pc}\right)$ is determined by

$$REDMD_{pc} = \frac{BP_{pc} - RM_{pc}}{\frac{WE}{WP} - RM_{pc}} \tag{7}$$

3. Results

3.1. How Is Food Security Accounted for in the Estimates of Future Biomass Availability?

All reviewed studies follow a kind of "food-first" approach, which means that in their scenarios, no land needed for food production is allocated to bioenergy production. Most studies estimate the amount of agricultural land needed for food production in 2050 by assuming either different "expansion-scenarios" or "non-expansion-scenarios;" i.e., increase or no increase in agriculture land compared to the current situation. These scenarios are mostly based on predictions by the FAO [57]. Some scenarios assume a cropland expansion of 9% and 19% [29,30]. Other scenarios estimate cropland expansion in hectares. Low values range between 0 and 0.1 Gha [33], medium values from 0.2 to 0.5 Gha [43], while high values are more than 0.5 Gha [40]. The projected cropland expansions are then combined in models with other parameters, such as population growth projections, yield projections, and dietary assumptions, to model the need for agricultural land for food production in 2050.

For their biomass availability models, the reviewed studies do not use the encompassing, internationally accepted concept of food security (see Section 2.2.1). However, the studies include some elements from the four pillars of food security (for a general overview, see Table A1).

3.1.1. Food Utilization: Inclusion of Nutritional Requirements in Biomass Models

Only seven out of the fourteen reviewed studies have explicitly presented their assumptions regarding food diets in 2050, and of these seven studies, four provide dietary scenarios. The main distinguishing factors in those scenarios are the total amount of kcal per capita and day and the assumed share of animal protein.

The total caloric intake per capita and day (kcal/cap/d) used as a basis by the first group of studies ranges from 2800–3170 kcal/cap/d [28–30] (Table 1). The second group uses a considerably lower range from 2410 kcal/cap/d in the vegetarian diet scenario up to 2750 kcal/cap/d in the affluent diet scenario [27,32]. The share of proteins from animal products varies considerably between the different scenario groups.

Most of the assumptions about caloric food consumption are around or below the average global food consumption levels at the turn of the millennium, when over 10% of the global population suffered from hunger [58]. The FAO [57] estimated a worldwide per capita food consumption of 2803 kcal/cap/d from 1997–1999, with an average in developing countries of 2681 kcal/cap/d and 3380 kcal/cap/d in industrialized countries. For 2050, the FAO estimates a demand for at least 3070 kcal/cap/d, with consumption of around 3000 kcal/cap/d in developing countries and 3500 kcal/cap/d in industrialized countries [21]. These estimates do not account for the amount of food needed for a food-secure global population but are just scenarios based on what people may be able to afford [21]. Most biomass scenarios include even lower levels of global food consumption than the demand prognosticated by the FAO. For industrialized countries, the models comprise consumption levels 10–30% lower than the demand expected by 2050.

Regarding the nutritional requirements, the necessary protein and energy (calories) are at least addressed by some studies (Table 1). The other nutritional requirements, such as the vitamins and minerals needed for a healthy life are not specifically included; for example, through incorporating horticultural production in the land estimates. The other relevant factors for food utilization, such as the availability of clean water, food safety or health issues, are not discussed or included in the models. All these elements, however, may be linked and negatively affected by agricultural intensification, which is typically one of the biomass model assumptions.

Table 1. Dietary scenarios: Share of animal protein and diet considerations in the reviewed studies.

Scenario	kcal/cap/d	Share of Animal Protein	Diet Considerations
Western high meat scenario; *Rich* scenario [29]	3170	44% of total protein intake; 21% of total nutrient intake.	Rapid acceleration of economic growth and consumption patterns; increases in the share of animal products, sugar and vegetable oil; requires a cropland expansion of 20%.
Current trend scenario; *TREND* scenario; *Business as usual* scenario [29,30]	2990	38% of total protein intake; 16% of total nutrient intake (on global average).	Current growth trends are maintained with strong regional differences in calories and animal product consumption; by 2050, every region is projected to attain the diet level of its country with the highest diet in year 2000; per-capita consumption of sugar and oil crops increases by 19% globally, of animal products by 7%.
Less meat scenario [29]	2990	30% of protein intake; 8% of total nutrient intake.	Total protein levels considered as nutritionally sufficient by the authors. Average protein consumption in North America and Western Europe decreases, and distribution of food categories changes: cereals, roots, pulses, vegetables and fruits categories increase above 1700 kcal/cap/d for all regions, while animal products, sugar and oil crop shares decrease, in particular in rich regions.
Fair less meat scenario; *Fair & Frugal* scenario [29,30]	2800	20% of protein intake; 8% of total nutrient intake.	Protein from animal sources reduced to 20%. Very little diet variation between world regions: richest regions reduce share of animal products, sugar, and vegetable oil. Equal food distribution.
Affluent diet scenario [27,32]	2750	Not specified. High meat and dairy products consumption	Global food requirement of dry weight grain equivalence (gr eq.): 14.4 trillion kg dry weight gr eq. needed. Of this, 73% needed for animal protein production.
Moderate diet scenario [27,32]	2410	Not specified. Some meat and high dairy products consumption.	Global food requirement 8.2 trillion kg dry weight gr eq. Of this 60% needed for animal protein production.
Vegetarian diet scenario [27,32]	2410	Not specified. Only consumption of dairy products, only small share.	Use for the global food requirement 4.5 trillion kg dry weight gr eq. needed. Of this 22% needed for animal protein production.

3.1.2. The Inclusion of Food Availability, Food Access and Food Stability in the Biomass Models

Food availability is addressed in the models through setting aside a specific area of land for food production on a global level. National and local food availability through international trade and food imports to food-deficit countries are considered by many but not by all studies. Six out of fourteen studies include an 'international food trade balance' in their estimations, which means that the gap between regional production and demand for meat and cropland products is balanced by trade; i.e., regions where the demand for primary products like cereals exceeds the regional supply are net importing regions, while regions where the biomass supply is larger than the regional demand are net exporters.

The pillar of food access is hardly addressed by the biomass models. Only two studies include estimates of the development of international food prices. These are relevant for the economic access to food by households. Other elements such as inequality, poverty, land distribution, and the transport and market infrastructure necessary for buying and trading food, are not taken into account.

The pillar of food stability is also only weakly addressed. Stable ecosystems are needed for sustained and continuous food and biomass production and to limit price fluctuations. Climate change is counteracting food security and food stability [59] but is not addressed by most studies. Only two studies use models that consider explicitly climate change and climate-change-induced yield change predictions, while three studies use IPCC scenarios to integrate climate change projections.

3.2. Biomass Availability, Allocation and Distribution

3.2.1. Global and Regional Non-Food Biomass Availability

The estimates for non-food biomass availability in 2050 range widely from 33–1548 EJ/a (Figure 1). The earlier studies tend to show higher estimates than the later studies. Most of the studies come to the conclusion that the future potential for energy from biomass is higher than the current level of around 50 EJ/a. Four studies, however, also estimate that the minimum biomass availability may be below the current usage level of biomass energy.

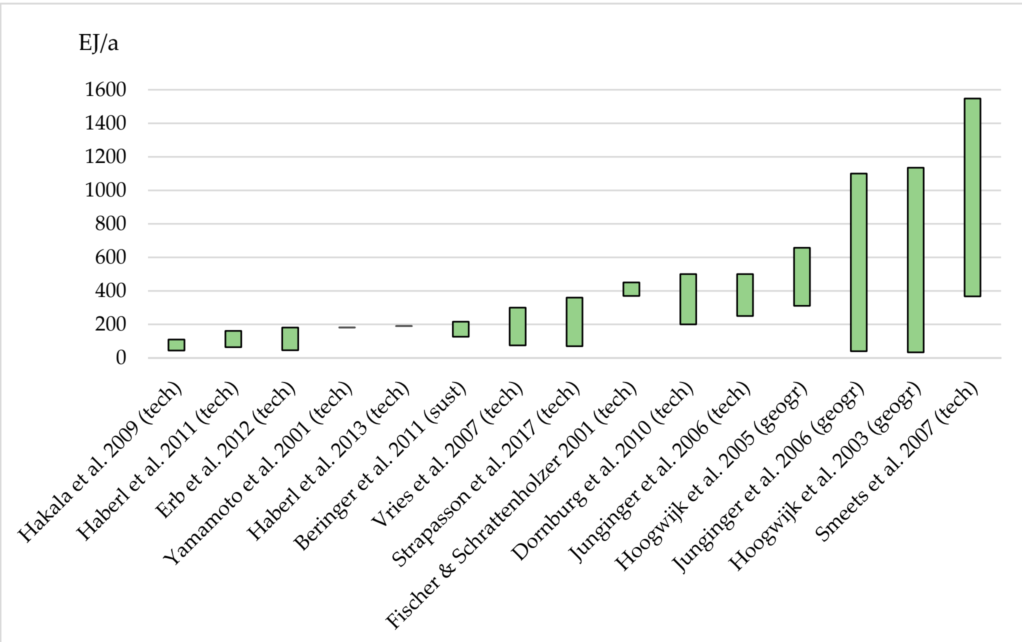

Figure 1. Range of biomass potentials (in EJ/a) and potential type (tech=technological, sust= sustainable, geogr=geographical potential) in the reviewed studies.

The estimates above 1000 EJ/a have to be viewed very critically, as other studies that addressed the planet's maximum capability to produce new biomass concluded that biomass availability cannot be sustained for human use over time. The maximum range for the global energy extraction from biomass is estimated to be between 1080 EJ/a and 1368 EJ/a [14–17]. This is based on the net primary production; i.e., the maximum available biomass for human use, which would include the use of all resources, such as forests, savannah regions and protected areas.

The average minimum availability of biomass across all reviewed studies is 151 EJ/a; highest availability is estimated to be 500 EJ/a. In studies published before 2010, this value is 18% to 35% higher, respectively, and in studies published after 2010, between 23% and 50% lower (Table 2). The assumptions with respect to the minimum and maximum potentials usually vary, regarding, for example, diets, yield improvements, and land and forestry use. The technical or sustainable potentials reveal consistently lower average non-food biomass availability than when the geographic potentials are included.

Table 2. Minimum, maximum and per capita availability of non-food biomass in 2050.

Biomass Potentials	Mean Value (Published Before 2010)	Mean Value (Only Tech or Sust Potential) [1]	Mean Value (Published 2010 or Later)
Minimum biomass potential (EJ/a)	178	148	116
Maximum biomass potential (EJ/a)	674	434	268
Per capita minimum biomass potential (GJ/cap/a)—Jazz scenario	20.4	17.0	13.3
Per capita maximum biomass potential (GJ/cap/a)—Jazz scenario	77.4	49.9	30.8
Per capita minimum biomass potential (GJ/cap/a)—Symphony scenario	19.0	15.8	12.4
Per capita maximum biomass potential (GJ/cap/a)—Symphony scenario	71.9	46.3	28.6

[1] Tech = technical potential, sust = sustainable potential.

Given the estimated global energy needs in 2050 of 879 EJ/a (Jazz scenario) and 696 EJ/a (Symphony scenario), the projected biomass availability shows that energy needs can be covered by anything between 13% and 97% depending on the assumptions about developments in society, agriculture and ecological sustainability and the year of publication (Table 3). The studies published after 2010 show a much lower share, between 13% and 39%, which is more likely to be a realistic one. The range is still considerably large and requires a more in-depth look at the assumptions, as implications for future food security and agricultural systems, as well as impacts on the environment and the society, can be very great.

Table 3. Share of global energy demand which can be covered by biomass in 2050 grouped according to publication year or estimated potential.

	Published Before 2010		Only Tech or Sust Potential [1]		Published 2010 or Later	
	Jazz	Symphony	Jazz	Symphony	Jazz	Symphony
Global energy demand covered by the min. biomass (%)	20.2	25.5	16.8	21.2	13.2	16.7
Global energy demand covered by the max. biomass (%)	76.7	96.8	49.4	62.4	30.5	38.5

[1] Tech = technical potential, sust = sustainable potential.

The projected regional distribution of future biomass availability also shows a wide range of values (Table 4), though most studies do not present regional estimates. Poor data availability at the regional level may also limit the reliability of the data. As an example, the estimated non-food biomass potential for Africa ranges from 25–369 EJ/a, while other studies reveal even lower values, such as 2.5–9 EJ/a [24,60].

Table 4. Overview of regional biomass availability for 2050 (EJ/a).

Source	Min/Max [1]	Africa	Europe	Eastern Eur./CIS [2]	Asia	Oceania/ Pacific	North Amer.	Latin Amer.	Sum All Regions
Fischer & Schrattenholzer 2001	min	100	22	31	58	20	40	83	354
	max	124	27	38	77	26	50	103	445
Haberl et al. 2011	n.a.	24.6	3.59	14.25	20.9	1.89	15.55	23.99	105
Smeets et al. 2007	min	44	15	50	46	42	34	59	290
	max	369	64	205	193	109	193	235	1368
Mean value	min	56.2	13.5	31.8	41.6	21.3	29.9	55.3	249.7
Mean value	max	172.5	31.5	85.8	97.0	45.6	86.2	120.7	639.3

[1] Min = lowest estimate, max = highest estimate. [2] CIS = Commonwealth of Independent States.

3.2.2. Allocating and Distributing Non-Food Biomass to Cover Energetic and Material Demands

Regarding the biomass availability per capita, there is some variation depending on the future societal and energy scenarios (Jazz or Symphony scenarios, see Section 2 for details), but the more recent studies indicate much lower biomass availability for energy and material purposes, ranging from 12–29 GJ/cap/a compared to 17–57 GJ/cap/a using all studies (Table 2). Average global per capita energy needs in 2050 are estimated to be between 74 GJ/a (Symphony Scenario) and 101 GJ/a (Jazz Scenario). The lower estimates for biomass availability would then cover around 13–17% of the global per capita energy demand, and the higher estimates would cover 31–39% (Table 4).

However, the satisfaction of material needs is considered as a top priority of other energy uses, as it is currently hardly possible to replace fossil fuels for material use without using biomass, while technologies to replace fossil fuel energy for industry, electricity or heating with solar, wind or water power are very much advanced. Based on data by the World Energy Council, the global material use of final energy consumption is estimated to be 7.8 GJ/cap/a or 11% in the Jazz scenario for 2050, and 6.1 GJ/cap/a or 12% in the Symphony scenario. The final energy consumption does not take conversion and other losses into account, which amount to 30%. Therefore, a much higher supply of energy in the first place is needed and the presented estimates show the upper bound.

This material demand can be easily covered at the global level by the estimated biomass availability, as there is a surplus of biomass in both the Jazz and the Symphony scenario (Table 5). At the regional level, most regions have no difficulty in fulfilling their material energy requirements if a globally equal biomass distribution exists. An exception is North America, which would not be able to meet all regional material energy needs through biomass, should only the minimum biomass availability be feasible. Europe would just be able to manage in the Jazz scenario, but this would basically leave no leverage for any other biomass use.

The question is now, how much biomass will be available for non-material energy needs when all human material needs are accounted for in the same way; i.e., the amount of material energy distributed to each human being is the same and the unequal regional material consumption levels are not taken into account. At the global level, this is 6–9% for the minimum estimates and 23–30% for the maximum estimates. At the regional level, Sub-Saharan Africa shows the highest values, ranging from 19% to 96%, and North America with the lowest values from 3% to 13% at best, followed closely by Europe (Table 5).

Table 5. Share of Energetic and Material Demand for Fossil Fuels which can be Replaced with Biomass [1].

	Global		Sub-Saharan Africa		Middle East & North Africa		Latin America & Caribbean		North America		Europe		Asia (Incl. Pacific)	
	Jazz	Sym	Jazz	Sym	Jazz	Sym	Jazz	Sym	Jazz	Sym	Jazz	Sym	Jazz	Sym
Per capita energy demand covered by the min. biomass potential in 2050 (%) [a]	13.2	16.7	43.9	52.8	9.3	11.1	11.5	14.6	6.1	7.3	8.1	9.3	14.4	18.7
Per capita energy demand covered by the max. biomass potential in 2050 (%) [a]	30.5	38.5	102	122	21.5	25.6	26.5	33.8	14.1	16.9	18.7	21.4	33.2	43.1
Per capita energy demand for material uses covered by the minimum biomass potential (%) [b]	170	204	548	635	119	131	158	179	81.2	90.7	107	122	182	226
Per capita energy demand for material uses covered by the maximum biomass potential (%) [b]	393	472	1267	1468	275	303	365	414	188	210	248	281	419	522
Per capita total energy demand covered by the min. biomass potential with equal satisfaction of material needs (%) [c]	5.4	8.5	18.1	26.9	3.8	5.7	4.7	7.5	2.5	3.7	3.3	4.7	5.9	9.5
Per capita total energy demand covered by the max. biomass potential with equal satisfaction of material needs (%) [c]	22.7	30.3	75.7	96.1	16.0	20.2	19.8	26.6	10.5	13.3	13.9	16.9	24.8	34.0
Per capita total energy demand covered by the min. biomass potential with unequal satisfaction of material needs [2] (%) [d]	n.a.	n.a.	35.9	44.5	1.5	2.6	4.2	6.5	−1.4	−0.7	0.5	1.6	6.5	10.4
Per capita total energy demand covered by the max. biomass potential with unequal satisfaction of material needs [2] (%) [d]	n.a.	n.a.	93.5	113.6	13.7	17.2	19.2	25.6	6.6	8.8	11.1	13.8	25.3	34.9

[1] using only studies published in 2010 or later. [2] Using estimated regional material needs, which are based on poverty and income developments, population growth, etc., in 2050. [a] corresponds to EDpc, [b] corresponds to MDpc, [c] corresponds to EDMDpc, [d] corresponds to REDMDpc (see Section 2.3).

This picture would look even worse if one were to ask how much of the globally available biomass per person would be available at the regional level for non-material energy uses once all regional material demands predicted in 2050 have been fulfilled. The rich regions would then continue to consume per capita much more than other regions; e.g., North America would consume 6.7 times more material energy than Sub-Saharan Africa, and Europe 5.1 times more. This is especially critical, as it is very likely that poverty and inadequate fulfillment of material needs in Africa and other poor regions would persist given their low income-levels. Based on a projected unequal material resource consumption, Sub-Saharan Africa would be able to cover 36–45% of its non-material energy needs with the minimum biomass share available. North America would not be able to cover any of its non-material energy needs at all, and Europe only around 1–2%. Using the estimates for the maximum biomass availability, Sub-Saharan Africa would be able to fully cover its energetic needs, while North America and Europe could cover around 10% with biomass, and would need other energy sources for the remaining 90% energy requirements.

4. Discussion

The emerging bioeconomies in Europe, North America and elsewhere will require large amounts of biomass in the future. Key questions are, therefore, how much biomass will be available in future for food and non-food uses? For what shall the non-food biomass be used? According to whose needs or national or regional consumption levels? There is increasing research available to answer the first question about availability, but the question of future food security has not been sufficiently addressed in the models of future non-food biomass availability. There is much less research even, on the other questions.

4.1. Limitations Regarding Food Requirements and Food Utilization in the Biomass Scenarios

In the reviewed biomass potential estimates, food security is reduced to mainly the production of calories and proteins through future yield and land-use assumptions. This approach resembles the food security concept used in the 1970s; e.g., by the World Food Conference in 1974, which is now outdated [61]. Given the importance of global food security especially highlighted in the SDGs, and the clear prioritization of food security when moving towards bioeconomies, the limited consideration of the current internationally accepted and standardized food security concept, such as that adopted by the World Food Summit in 1996, is surprising. Even other studies hardly discuss the concept of food security in relation to biomass availability and use; an exception is the report of the German Advisory Council on Global Change (WGBU) with the input study by Faaij [24,46].

The dietary and land-use scenarios used in the biomass models have to be reconsidered with respect to desirability and feasibility from a food security perspective. These studies use diets of 2450–3150 kcal/capita/d, a quantity which is lower than the current food consumption levels in industrialized countries. Therefore, industrialized countries have to reconsider the data they rely on for their bioeconomy strategies when aiming to maintain current food consumption levels. A change in food habits in the OECD countries, as implicit of basically all biomass potentials, is unlikely to materialize. The scenario of a global vegetarian diet is of course creating higher values for non-food biomass availability, but is definitely not an option for policy makers and neither globally nor nationally implementable until 2050. The suggestion of a weekly “meat free day” by the Green Party led to a public outcry in Germany, and significantly decreased the popularity of the party at that time. So how realistic is the implementation of a dietary shift with reducing food calories by 10% to 30% as proposed by the researchers? Which governmental party will explain to its voters that they have to eat less meat to be able to continue their material consumption and drive their cars as they are used to? Biomass availability scenarios should be built on implementable assumptions. It is not at all likely that the above scenario can ever be implemented or is desirable in a society. In a democracy, the state cannot prescribe what and how much to eat, and if food consumption has to be reduced for producing bioenergy or bioplastic, this becomes highly questionable from a moral and equity perspective, as this will be at the expense of the poor.

From the perspective of low-income countries, the question emerges whether the lower range of calories, e.g., 2450 kcal/capita/d, is sufficient, as most employment opportunities involve hard physical labor, especially in the agricultural sector, which is one of the mainstays for most economies. Strauss [62] points out the correlation between caloric input and labor productivity in agriculture, and shows that in developing countries a caloric consumption of over 4500 kcal/capita/d still leads to an increase in labor productivity. A sugar cane harvester in Latin America needs around 3900 kcal/capita/d of food (personal communication, sugar cane plantation manager, 2018). It is very likely that a vegetarian or low meat diet in low-income countries will lead to nutritional deficiencies, as the choice of food is limited there [63] and alternative protein and iron sources are hardly available, extremely costly, often not of good quality, and not a typical part of a diet. For example, around one billion people are anaemic due to iron deficiency; in some countries in Africa over 60% of the population is [64]. The diversity of food sources is also important for a balanced nutrition, so adequate and diverse horticultural production should be integrated in the models to fulfil the requirements for vitamins, minerals and micronutrients.

While some biomass availability scenarios assume the same food consumption level for each individual globally (e.g., some scenarios with less meat, the fair and frugal scenario), other models assume that existing inequalities in consumption will remain in 2050 (e.g., business as usual scenarios), while others do not specify their assumptions (e.g., those that only set a certain amount of land aside for food production). It is likely that the latter are built on maintaining an unequal global food consumption (including undernourishment and malnourishment), as the FAO projections typically estimate future demand for food and not the amount needed to adequately satisfy all food needs of the global population [21]. As the FAO [57] highlights, the higher the inequality in food consumption is in a country, the more calories per person need to be incorporated in future demand estimations if the objective is to reduce or eliminate undernourishment. In other words, for a country with high inequality, even an average per capita caloric consumption of 3100 kcal can still mean that 5% of the population are undernourished.

These estimates of future non-food biomass availability thus imply that in wealthier regions people eat much more than they may need, while in other regions food calories can be below the physical needs of the population. This is a realistic assumption but implies severe conflicts in the future about non-food biomass and global food security. This will be counteracting the efforts to eradicate hunger as globally agreed upon in the SDGs, and is inacceptable from an intragenerational equity perspective. Relying on these studies for future global non-food biomass availability means accepting undernourishment, while at the same time, biomass is used in the rich countries for bioenergy or other uses. If the objective is to achieve global food security before any other biomass use, food caloric availability needs to be much higher than the modeled values, and the FAO data cannot be used, as it assumes that by 2050 poverty and inequality will continue to exist [21].

4.2. Limitations Regarding Food Access, Availability and Stability in the Biomass Scenarios

The pillar of food access would need to better addressed in future models. The development of international food prices has been neglected. Food and biomass prices will be influenced in 2050 by changes in the oil and fossil fuel prices, and there are studies that already claim this relation [65,66]. The latter prices are likely to increase significantly as resources deplete further and alternative energy sources are not developed fast enough to fill the gap [2]. Increasing crop prices are predicted through an expansion of biofuel production along with a net decrease in availability and access to food, especially in Africa [67]. The price developments and effects need to be included in future scenarios, along with poverty levels and inequality in income, land tenure and other resources that affect the physical and economic access to food.

Regarding food availability, the question of international trade of food and non-food biomass and its effects on national availability should be considered in future scenarios. Modeling the future development of the global food and biomass trade is uncertain, as the global agricultural market is influenced not only by subventions and trade barriers [25] but also by the purchasing power of nations. Adding scenarios that depict different market developments and account for purchasing power is needed to better understand the effects of future biomass use on food security by a nation or whole region, especially on low-income, in-food-deficit countries.

The stability of food supplies is at risk due to climate change, environmental degradation, and disease or pest outbreaks [68]. Climate change entails risks and uncertainties for future food security in all its dimensions, as agriculture is sensitive to climate variability and change. Especially in some regions, climate change may slow down the progress towards food security [59]. Therefore, biomass availability models need to integrate climate change effects.

There are also doubts about the effects of agricultural intensification as part of most models. Agricultural intensification is one of the key drivers of biodiversity loss on an unprecedented scale, due to habitat loss and pollution caused by synthetic pesticides and fertilizers, which may also affect ecosystem services, such as food production [69,70]. Whether the agricultural intensification assumptions with their potential effects would be within the planetary boundaries is not certain, but it is rather unlikely, since phosphorus and nitrogen, the key fertilizer elements in agriculture, are far beyond the safe operating space [71]. By definition, the technical potential estimated in nearly all studies does not entail an environmentally sustainable perspective. It is the decision of each researcher how far environmental aspects are considered. It is somewhat surprising that even the more recent research concentrates on the technical and not on the sustainable potential, since ecological sustainability and the need to maintain ecosystem services, especially of rainforests, have already been discussed for decades at the national and international level. Topics also discussed include problems associated with agriculture on peatlands or in biodiversity hotspots, planetary boundaries, land degradation or environmental problems associated with agricultural intensification. Those studies that included an ecologically sustainable potential came to much lower biomass availability levels [24,38]. Ecological sustainability is important not only for food stability but also for the sustainability objective of intergenerational equity to ensure that future generations also have continued and stable access to biomass to fulfill their food and non-food needs. Therefore, the inclusion of ecological sustainable biomass scenarios in addition to technically possible scenarios should become the standard in future studies.

4.3. Large Range of Biomass Availability Estimates

As also indicated by other recent studies, the maximal possible non-food biomass availability will be somewhere around 250–270 EJ/a in 2050 due to biospheric constraints [15,16,35,72]. Searle and Malins [34] derived 60–120 EJ/a as the limit to long-term biomass availability, which is in line with the minimum values of biomass availability of the more recent studies. The range for the technical potential is still large, and implications for future food security, agricultural systems, environment and society can vary greatly. In addition, the reviewed studies insufficiently addressed nutritional requirements and food security, so future available biomass will be lower than the currently technical non-food biomass estimates.

The very high sensitivity of the results with respect to assumptions and modeling techniques implies uncertainties. The assumptions on yields, land use or rehabilitation of degraded land indicate different opinions about what is technically possible, practically feasible or ecologically desirable. They therefore relate to a very different normative perspective of the world; i.e., from a more technologically- and economically-oriented perspective to a more ecological perspective. Any biomass use beyond this range would either mean an expansion of biomass use at the cost of food security, or the conversion of precious, conservation-worthy landscapes like rainforests; or a significant increase in production through irrigation and agricultural intensification far beyond what is estimated to be sustainable, ecologically recommended and practically feasible [24]. The practical feasibility of significant agricultural intensification in low- and lower-middle income countries in the next thirty years needs to be questioned, as these regions lack the necessary socio-economic pre-conditions, such as functional institutions, available infrastructure and financing. They have been affected for decades by problems, such as lack of knowledge among farmers, a dysfunctional extension system, volatile markets, and a lack of roads, marketing infrastructure, and of access to inputs, credits and insurance. Ongoing land degradation [73] and climate change leading to further decreasing yields [56,57] are two additional factors which require a cautious, if not critical look at the estimates of the future potential biomass availability.

4.4. Biomass Availability Is Insufficient to Cover Energy Needs after Satisfying Material Needs

Switching to a (global) bioeconomy "will entail high demand for biomass not only for bioenergy, but also for bio-materials such as plastics that are presently derived from fossil sources" [13].

With a projected depletion of oil stocks by 2050, it is surprising that little attention is paid to the question of where biomass shall come from to substitute fossil fuels. Most research looks at a specific sector, e.g., bioenergy, and every sector claims that there is enough biomass available while ignoring other sectors' needs. For that reason, we think that material/chemical uses of biomass have to be prioritized over energetic uses for electricity or fuel. Our calculations are rough and simplistic but add a new perspective given the strong focus on bioenergy. The data used and the assumptions, especially those using the Jazz and Symphony scenario, will need refining in future research and when better data on material, chemical and other biomass uses is available. While Dornburg et al. [22] suggest that in future, biomass may meet up to 30% of the projected global energy demand, our findings also show that this only may occur if the maximum biomass estimates are used. It could be only 13% based on the minimum values, which is to be expected. This share would be even lower if food security were to be adequately taken into account. There is probably enough non-food biomass available at the global level to fulfill the material energy needs. This is good news, since for material uses, fossil fuels can still hardly be substituted without the use of biomass.

4.5. Intragenerational Equity and Biomass Availability

The industrialized countries will have roughly enough biomass for the predicted material use in 2050 and, depending on the data, equity assumptions and scenarios used, some biomass will remain for additional bioenergy. If resource consumption in Europe and North America continues at the current high levels, basically all available biomass in the future will be needed to fulfill material demands, at least in a world where intragenerational equity is the norm. Hence, any bioenergy consumption higher than the values presented in Table 5 will either require a reduction in consumption levels in North America or Europe, or inevitably lead to an unfair global resource consumption at the cost of biomass availability for poorer nations, and possibly affect global food security via rising prices.

A significant reduction in material consumption in industrialized countries until 2050 is unlikely, since the political agenda is still based on a growth paradigm. Therefore, when prioritizing the fulfillment of material energy needs, there is likely to be no, or only a very small amount of biomass available to fulfill non-material energy needs. Future investments in the bioenergy sector should be kept at a minimum, and the focus for decision-makers, politicians and investors alike would need to be on material uses of biomass.

There is also the threat that biomass use will be increasingly less fair; i.e., that rich countries will consume biomass at the cost of food security or basic material uses of poor countries, when a significant reduction in resource consumption is not taking place at the same time. It is questionable whether market prices will transmit the necessary signals of resource stock depletion in time, as external costs are commonly excluded. Politics needs to address ways to reduce energy usage, be it in production, distribution or consumption [2].

The presented estimations assume either a globally equal share of the material energy needed or a regionally different share with poorer countries consuming less. Both assumptions may be flawed, as in many poorer countries, basic human needs and rights such as adequate housing, food, health, schooling, etc., have not yet been fully addressed. Higher material consumption levels than a globally equal share might be needed to develop a poor region like Sub-Saharan Africa to an acceptable state. Unfortunately, there is no data on how much energy for materials, industry, etc., would be needed to reach an acceptable state.

Several authors conclude that the rise in the use of biomass (biofuels) requires international cooperation, regulations, certification mechanisms and sustainability criteria regarding the use of land, sustainable production and the mitigation of environmental impacts caused by biomass production [16,22,34]. There is a need to go beyond this. Not only does food security need to be ensured in all agricultural production areas and along international value chains, the question about biomass allocation and distribution also needs to be internationally agreed upon.

4.6. Future Research Recommendations

To address food security in biomass availability estimates, future models should integrate several aspects. First, there is the need to include a "zero hunger" target as stated by the SDGs. Second, the advice of global nutrition experts on balanced diets should be integrated taking into account the needs of the population in developing countries that include physically hard-working people, diseases, and health and sanitation problems which may inhibit nutritional uptake. Future research should address the question of how much food will be needed in 2050 if all people are to have stable access to sufficient, nutritious and safe food. The assumption of unequal food consumption levels should always be accompanied by a scenario that assumes a sufficient intake of food. Third, the question of purchasing power, price developments and international trade of food and non-food biomass; and the effects on a global scale, but ideally also at regional and national levels, should be included in future scenarios, especially depicting the effects on low-income, food-deficient countries. To address food stability, climate change effects should always be considered, and more research on the ecological sustainable biomass potential is urgently needed. The key question is really that if all this is considered, how much biomass will be available if food security is appropriately accounted for?

The research presented here could be further strengthened, as it is built on available data and scenarios by the World Energy Council, which constructed plausible future energy scenarios but did not estimate energy scenarios that contain intragenerational equity or the satisfaction of basic human needs. It also may have missed some model assumptions, as not all were explicitly mentioned in the reviewed studies, especially regarding the estimated food requirements, which would have required contacting all authors individually. Also, no solutions to the identified bottlenecks of the models could be offered, as this would have gone beyond the objective of this research. The purpose of the research was to assess the biomass potentials with respect to their inclusion of food security, to show key tendencies and to derive options for future biomass allocation and distribution based on available data, especially from a sustainability perspective. The results are considered to be 'food for thought' about the fair and best uses of biomass for researchers, civil society and among decision-makers.

More research is needed to identify the necessary material energy requirements to satisfy all basic human needs at the global level, and which material energy requirements are required for acceptable outcomes based on human rights. This would involve estimates about global energy needs if all people were to have, for example, access to electricity, water and health services or appropriate housing. These estimates would then be a social boundary that defines the thresholds below which human well-being is endangered. Future research needs hence to identify how much biomass will be available for extra uses (such as bioenergy) if at least all global basic human needs are covered, and global poverty and hunger have been eradicated.

5. Conclusions

A conversion of the current fossil fuel-based economies into bio-based economies is constrained by the overall limited availability of biomass. This systematic review adds a sustainable development perspective on the estimates and models of future biomass availability. The focus is on the satisfaction of human needs through biomass, especially of food security and intragenerational equity, which includes options regarding the allocation and distribution of biomass. Though food security is key for most bioeconomy strategies and international agreements, an internationally accepted concept of food security based on the pillars' availability, access, utilization and stability was not included in the models for estimating non-food biomass potentials. Dietary assumptions were partly based on food consumption levels below the current food consumption in the OECD countries, and partly included globally unequal consumption levels. This has various implications. If the OECD countries were to adjust their economies based on the assumption of high biomass availability, they would have to reduce food consumption—or people in other countries would have to. The dietary assumptions imply that physically hard-working people in low-income countries would not receive sufficient calories for their activities. Unequal food consumption assumptions are very likely to entail the continued persistence of undernourishment until 2050, while biomass is used for material or energetic uses. This is neither acceptable from a sustainable development and intragenerational justice perspective, nor does it meet the SDG targets. It is not certain whether the technical potential can be materialized within the planetary boundaries. Estimates for an ecological sustainable biomass potential are rare and indicate a very low availability of biomass. However, they would be a guiding value to ensure food stability, and thereafter the availability of sufficient, safe and nutritious food over time. In conclusion, if biomass availability estimates had accounted for food security in its four dimensions, the availability of biomass for any use would be even lower than the range 116–268EJ/a of the more recently published biomass potentials.

Material uses of fossil fuel can be replaced by biomass but so far not by other renewable energy sources. Though there is research in this direction, e.g., solar biofuels derived by synthetic biological processes, it is unlikely that energy-efficient technologies that, for example, convert CO_2 from the air into plastic, are ready for the market by 2050. Given the relatively high energy demand for material uses compared to the limited availability of non-food biomass, it does make sense to prioritize the material uses of biomass over bioenergy to fuel cars or generate electricity. However, if this takes place, not much biomass will be left for bioenergy. With increasing development in low- and low-middle income countries, it is likely that material consumption will increase even more than is assumed here. First- or second-generation biofuels may be still an option for land-abundant, fertile countries, but are also questionable from a global distributional perspective. Cascading uses of biomass, and especially the use of waste, for energy generation is much more appropriate. These should be the key element of any bioenergy strategy, and the target for industrial and financial investments.

Increasing energy efficiency is another important element, but despite many calls in the past, progress has been limited. Here, governments need to provide incentives for industry and prevent undesirable behavior; e.g., though taxation. Moreover, new concepts to reduce the total consumption of energy and materials in industrialized countries need to become part of the agenda of politicians, businesses, and civil society, but also of researchers. Policies need to provide many more guiding frameworks for the economic system, including the bioeconomy more than is currently the case, so that economies develop in a sustainable direction agreed upon in the SDGs. If a fairer distribution of biomass use were to become a global norm, the bioeconomy, energy, and economic, climatic and social policies of the OECD countries would need to change significantly to account for at least a limited biomass availability. This implies reconsidering an economic system which, so far, is built on growth, unlimited global availability of inputs, and excludes external costs.

Since the Brundtland report in the late 1980s, it has been reiterated that economy, ecology and society need to be considered and addressed together. Adding a sustainable development perspective to future biomass availability enriches the discussion about what is technically feasible with what may be socially needed. Further research needs to determine how much biomass for bioenergy would really be left if food security and a decent minimum standard of global human well-being were to be incorporated in the estimates. Furthermore, how much biomass would be available if we were to additionally incorporate a stronger environmental sustainability perspective, as envisioned by the SDGs. Other questions are more practically oriented: Which policies and changes are needed at national and multilateral levels to ensure global food security before any other biomass use, given the tremendous income, power, and hence, energetic use differences between nations? Which economic policies and state regulations at the global and national level are needed to ensure the satisfaction of material needs of all humans while powerful economic sectors favor bioenergy? This entails that distribution questions, especially regarding resource use, are raised to the multilateral level and receive more global attention to build a peaceful, sustainable and equitable world.

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Appendix A. Flow Diagram, Search Parameters and Details of the Systematic Literature Search

Search parameters:

- Searched in all databases being part of the Web Of Science database.
- Search terms: TOPIC = (biomass potential), OR TOPIC = (biomass potentials) OR TOPIC = (potential of biomass), OR TOPIC = (potentials of biomass) OR TOPIC = (bioenergy potentials), OR TOPIC = (bioenergy potential).
- Time span: All years (1945–2018).
- Search language = Auto.
- Date last searched: 5 September 2018.

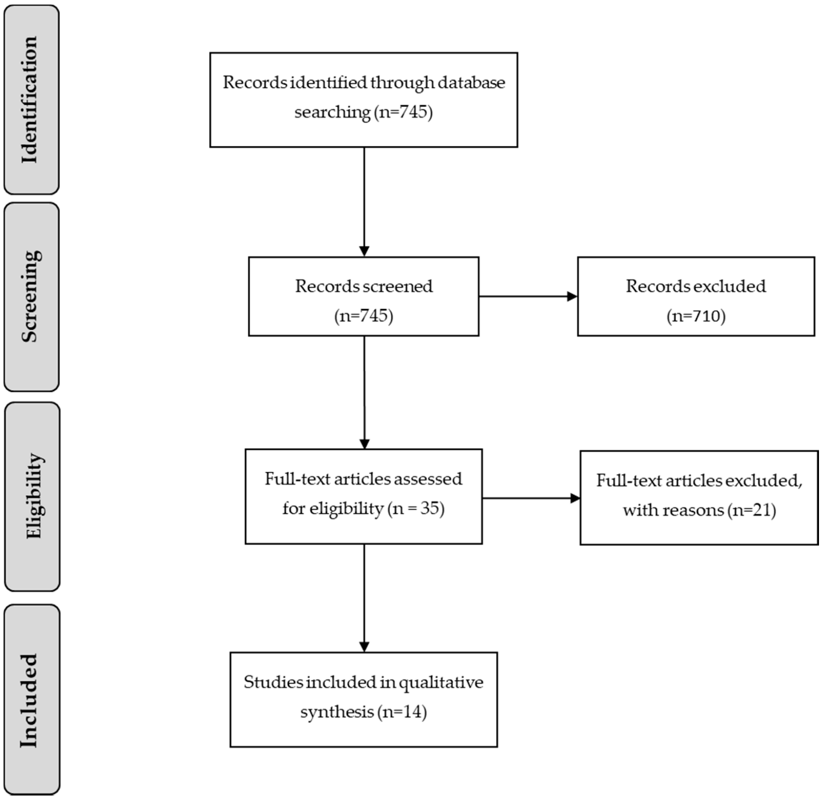

Figure A1. Flow Diagram of the Systematic Literature Search Procedure.

Appendix B. Definitions of Biomass Potential Types

Types of biomass potentials are generally discussed in terms of a hierarchical sequence of the upper limits of energy availability; i.e., theoretical, geographical, technical, economic, implementation/realistic and sustainable potentials. It is to be noted that these terms may be interpreted in different ways by different studies, and this definitional fuzziness hampers transferability and increases the risk of misunderstanding. The most basic potential type is the "theoretical potential". It is limited only by the fundamental physical and biological barriers of the net primary productivity of biomass produced on the Earth's total surface by the process of photosynthesis [24,31,33].The "geographical potential" is the fraction of the theoretical potential limited to the energy stored in terrestrial biomass (i.e., excluding oceans, rivers, etc.) [24,33]. Most studies, but not all, also include 'availability,' 'accessibility' and/or 'suitability' for bioenergy production of terrestrial biomass products as a limiting factor in their definitions. The "technical potential" describes the fraction of the geographical potential that is left after losses from the conversion of the primary energy to secondary energy sources have been subtracted [24,33]. While the terms theoretical and geographical potential are used relatively consistently, the term "technical potential" lacks a universally used definition. In a broad understanding, the "technical potential is the geographical potential reduced by the losses of the conversion of the primary energy to secondary energy sources" [31], which means it is only reduced by conversion efficiency as a result of the level of advancement of agricultural and industrial-energy technology. Other authors include a range of further limiting factors, such as the demand for land for food production, housing and infrastructure, and the conservation of forests (e.g., [33]) The "sustainable potential" is the fraction of the technical potential that remains after considering ecological limitations [24].

Appendix C

Table A1. Use of the food security concept and nutritional requirements in the reviewed studies.

	Food Security Definition	Caloric (Energy) Requirements	Protein Requirements	Vitamin and Micronutrient Requirements	Development of International Food Prices	Role of Governance	International Food Trade Balance Included
Beringer et al. 2011	-	-	-	-	-	-	-
Dornburg et al. 2010	-	-	-	-	yes	-	-
Erb et al. 2012	-	yes	yes	-	-	yes	yes
Fischer & Schrattenholzer 2001	-	-	-	-	-	-	-
Haberl et al. 2011	-	yes	-	-	-	-	yes
Haberl et al. 2013	-	-	-	-	-	-	-
Hakala et al. 2009	-	yes	-	-	-	-	-
Hoogwijk et al. 2003	-	yes	-	-	-	-	-
Hoogwijk et al. 2005	-	yes	-	-	-	-	yes
Junginger et al. 2006	-	yes	-	-	-	-	-
Smeets et al. 2007	-	yes	yes	-	yes	-	yes
Strapasson et al. 2017	-	yes	-	-	-	-	-
Vries et al. 2007	-	-	-	-	-	-	yes
Yamamoto, Fujino et al. 2001	-	-	-	-	-	-	yes

Appendix D

Table A2. Overview of the reviewed studies: Estimated biomass potential type and range, biomass sources and description of assumptions.

	Estimated Biomass Potential Type [1]	Range of Biomass Potential Estimates (Minimum and Maximum) (EJ/a)	Biomass Sources [2]	Assumed Cropland Expansion	Well Described Assumptions for Land Use
Beringer et al. 2011	sust	126–216	EC	10–30%, 142–454 Mha	-
Dornburg et al. 2010	tech	200–500	EC, FR, AR	-	-
Erb et al. 2012	tech	46–181 [3]	EC, AR	9%, 19%	yes
Fischer & Schrattenholzer 2001	tech	370–450	EC, F, AR, W	280 Mha	yes
Haberl et al. 2011	tech	64–161	EC, AR	9.2–19.1%	yes
Haberl et al. 2013	tech	190	-	-	-
Hakala et al. 2009	tech	44–110	EC, AR	-	-
Hoogwijk et al. 2003	geogr	33–1135	EC, FR, AR, W	-	yes
Hoogwijk et al. 2005	geogr	311–657 [3]	EC, AR, FR	-	yes
Junginger et al. 2006	tech	40–1100	EC, FR, AR, W	0–400 Mha	-
Smeets et al. 2007	tech	367–1458	EC, F, AR	100–200 Mha	yes
Strapasson et al. 2017	tech	70–360	EC, F, AR, FW, W, R	12 Mha/a	yes
Vries et al. 2007	tech	75–300	EC	-	-
Yamamoto, Fujino et al. 2001	tech	182	EC, R (+W)	439 Mha	yes

[1] Potential types: sust=sustainable; tech=technical; geogr= geograhical. For a general definition of each potential type see Appendix B. [2] Biomass sources: EC = energy crops; F = forestry; AR = agricultural residues, FR = forestry residues; W = waste; R = general residues (e.g., MSW, etc.); FP = fishery products [3] Total sum is calculated from subtotals provided in the publication.

Appendix E

Table A3. Data sources for our own estimations. As described in Section 2.3, the data is derived from the World Energy Council [58] based on its two different scenarios for the world in 2050; i.e., the Jazz and the Symphony scenarios (details are in the report). The data here stems from the "Regional Summary" (page 249) and the table "The world in 2050" (page 252).

	Scenario	
	Jazz	**Symphony**
World population in 2050 (million)		
Global	**8703**	**9374**
Sub-Saharan Africa	1648	1961
Middle East & North Africa	551	601
Latin America & Caribbean	577	603
North America	594	619
Europe	819	853
Asia (incl. Pacific)	4513	4738
World energy needs (EJ)		
Global	**879**	**696**
Sub-Saharan Africa	50	46
Middle East & North Africa	79	67
Latin America & Caribbean	67	51
North America	130	105
Europe	135	114
Asia (incl. Pacific)	418	314
Final energy consumption (EJ/a)		
Global	**629**	**491**
Sub-Saharan Africa	37	33
Middle East & North Africa	57	49
Latin America & Caribbean	45	36
North America	90	73
Europe	94	75
Asia (incl. Pacific)	306	224
Final energy consumption per capita (GJ/a) excluding non-energy uses		
Global	64.5	46.3

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