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Assessment of global bioenergy potentials

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Abstract So far, various studies assessed global biomass potentials and came up with widely varying results. Existing potential estimates range from 0 EJ/a up to more than 1,550 EJ/a which corresponds to about three times the current global primary energy consumption. This paper provides an overview of the available research on bioenergy potentials and reviews the different assessments qualitative way with the objective to interpret previous research in an integrated way. In the context of this paper we understand bioenergy as energy from biomass sources including energy crops, residues, byproducts and wastes from agriculture, forestry, food production and waste management. In this review special attention was paid to the difference between residue and energy potentials, land availability estimates, and the geographical resolution of existing potential estimates. The majority of studies concentrate on energy crop potentials retrieved from surplus agricultural land and only few publications assess global potentials separated by different world regions. It results that land allocated to the exclusive production of energy crops varies from 0 to 7,000 ha, depending on land category and scenario assumptions. Only a small number of available potential assessments consider residue potentials as well as energy crop potentials from degraded land. Future energy crop potentials are assumed to vary in the mean from 200 to 600 EJ/yr. In contrast residue potentials are expected to contribute between 62 and 325 EJ/yr. The highest potentials are assigned to Asia, Africa and South America while Europe, North America and the Pacific region contribute minor parts to the global potential.

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1 Introduction

Biomass as commonly defined includes all the existing terrestrial organic matter and means the most important source for food, fodder and fibre production (Sims et al. 2007). Today, biomass contributes roughly 10% to the annual total primary energy demand (International Energy Agency (IEA) 2009). In 2007 approximately 49 EJ out of the total global primary energy supply of 503 EJ were derived from biomass. Hence, biomass today represents the most important renewable primary energy source. However, the largest part of bioenergy is currently used in developing countries for heating and cooking purposes. These applications are often characterized by low efficiencies and strong emission production. A comparably small, but steadily increasing part of biomass use takes place in industrialised countries (United Nations Department of Economic and Social Affairs 2006). Conversion technologies are highly efficient and generate secondary energy carriers of high value that support the establishment of a more sustainable energy system (Hoogwijk et al. 2005).

This modern use of biomass can make substantial contribution to the mitigation of climate change and energy security, particularly in regions where fossil fuel resources are scarce. Moreover, biomass can be used for versatile applications and a variety of commercially available technologies is available to convert biomass into fuel, electricity and heat. Due to these reasons, bioenergy is expected to play a key role in achieving a sustainable future energy system. Several countries all over the world have formulated targets for the contribution of biomass to the national energy supply and introduced policies to promote the increasing application of bioenergy generation. This includes developed countries as well as developing countries (Martinot and Sawin 2009).

Thus, knowledge about the biomass quantities available in the future is of high interest in order to estimate the possible contribution of bioenergy, to establish effective utilisation strategies and reach the set targets. Assessments of global bioenergy potentials have to deal with numerous uncertainties. Thus, the results of available potential estimates can vary significantly, depending on the chosen framework. Major differences of such studies are calculation methodology, chosen timeframe, data sources, regional scale, and the specification of crucial parameters. Furthermore, the available studies provide different definitions of the term bioenergy and the biomass categories they refer to in their assessments often deviate from those assessed by others. One major and unanimously exercised distinction can be made between residual materials and energy crops. Residual materials include residues, by-products and wastes released from production processes of agriculture, forestry, food production and waste management. Energy crops in contrast are purpose grown crops, usually cultivated on plantations, which are determined to be used for the production of energy. Energy crops in particular are designated to contribute a substantial part to the worldwide primary energy supply but their potential primarily depends on the available cultivation area. Residues form a more secure resource base as the generated amounts are driven by the demand for different primary products. When it comes to long-term availability of biomass resources, they generally are assigned a smaller potential than energy crops. Residual materials can be assigned to several sub-categories referring to their origin, type, or characteristics. It has been found appropriate to concentrate on major residue fractions rather than assessing each possible residue fraction potential within assessments of global bioenergy potential.

Table 1 provides an overview and classification of the most important residue types. However, it has to be noted that there is no consensus on how to define and assign residue fractions to different categories.

The objective of this paper is to provide a comprehensive overview of the current research on global bioenergy potentials in order to allow improved evaluation of the results of potential studies. In this context major challenges and specifications of crucial parameters of potential estimates shall be identified.

2 Definitions of biomass potentials

The assessment of bioenergy potentials is a complex and multidimensional task and much dependent on the underlying assumptions. It is hence relatively difficult to compare different estimates and get an idea about the order of magnitude of the resource availability.

A recently published literature review (Berndes et al. 2003) analysed 17 studies that reported bioenergy potentials, all published in the 1990s except one (Fischer and Schrattenholzer 2001) which became available in 2001. The analysed studies differ in complexity of approach, observed timeframe, analysed type of potential and geographic resolution. Beyond that, one can distinguish between demand-driven and resource-focused assessments. The latter can be described as feedstock analyses of different biomass resources with consideration of competing uses while demand-driven assessments rather focus on the possible contribution of bioenergy within the overall energy system. Supply analyses are considered to better portray the resource availability, as they are more capable of covering competing uses and certain sustainability criteria. Therefore, recent potential studies largely took the form of a supply-driven assessment (see for example (Hoogwijk et al. 2003, 2005; Smeets et al. 2007)).

The literature distinguishes between different types of biomass potential. The associated definitions often differ from publication to publication making it even more complicate to compare results (Thrän et al. 2006). The following classification is based upon a recently published paper (Smeets et al. 2007) that already summarized the definitions made in other publications (Hoogwijk 2004; World Energy Council 2004).

- **Theoretical potential:** The upper limit of bioenergy production that is limited by fundamental physical and biological barriers, including biomass from land, rivers, seas, oceans or, in other words, all biomass produced through photosynthetic reaction.
- **Geographical potential:** The fraction of the theoretical potential that is limited by the area of land and excludes marine biomass.

Table 1 Definitions of major residue categories

	Harvest residues	Process residues	Wastes
Vegetable residues	Straw, leaves, haulm, etc.	Molasses, bagasse, pomace, etc.	Decayed food products
Wood residues	Logging and thinning residues, (unused annual increment)	Sawn wood, saw mill wastes, pulp & paper production	Waste wood (demolition & construction wood, etc.)
Other		Dung, manure	Organic parts of municipal solid waste

- **Technical potential:** The fraction of the geographical potential that is limited by the demand for land for food production, housing and infrastructure, and the conservation of forests. Furthermore, it is based on the level of advancement of agricultural technology.
- **Economic potential:** The fraction of the technical potential that can be produced at economically profitable levels.
- **Implementation potential:** The fraction of the economic potential that can be implemented within a certain timeframe, taking into account institutional and social constraints and policy incentives.

So far, most studies assessed technical potentials. The estimation of technical potentials bases on relatively stable parameters that are less fluctuating than for example economic conditions like costs and prices. However, one needs to be aware of the fact that the meaning of technical potentials is sometimes seen critical. For example, in comparison to economic potentials, Verbruggen et al. (2010) argues that technical potentials of renewable energies are less suitable for creating specific deployment strategies and supporting policy processes. Nevertheless, in this paper, we focus on technical potential assessments only as the existing database enables the most meaningful comparison of results and methodologies.

3 Available potential estimates

Global bioenergy potentials were assessed by various studies. In addition to detailed and comprehensive potential assessments, there are also studies that presented results without further informing about their calculation procedure, and collections of different potential estimates.

Table 2 shows the distribution of 19 studies that assessed global technical bioenergy potentials. The majority of publications concentrate on the long-term energy potential of biomass. The best information base exists for 2050, but also for 2100, several publications could be found. Three out of the 19 studies reported potentials for both 2050 and 2100. Another three studies give information about the potentials to be expected within the short and mid-term perspective (2020 and 2030).

Most studies come to the result that the potential of bioenergy is significantly higher than the current level of biomass use. Figure 1 shows estimates of global bioenergy

Table 2 Overview of studies included in the literature review

Evaluation period	No year	2020–30	2050	2100
Number of studies	3	3	11	6
Studies with regional disaggregation	2	2 (3)	4 (5)	1
Studies considering both residues and energy crops	2	2	6	2
Studies considering only energy crops	1	0	4	4
Studies considering only residues	0	1	1[a]	0
Studies with regional disaggregation that consider both energy crops and residues	2	1(2)	2	0

Numbers in brackets also include partially disaggregated studies

[a] This study only considers the potential from annual forest growth

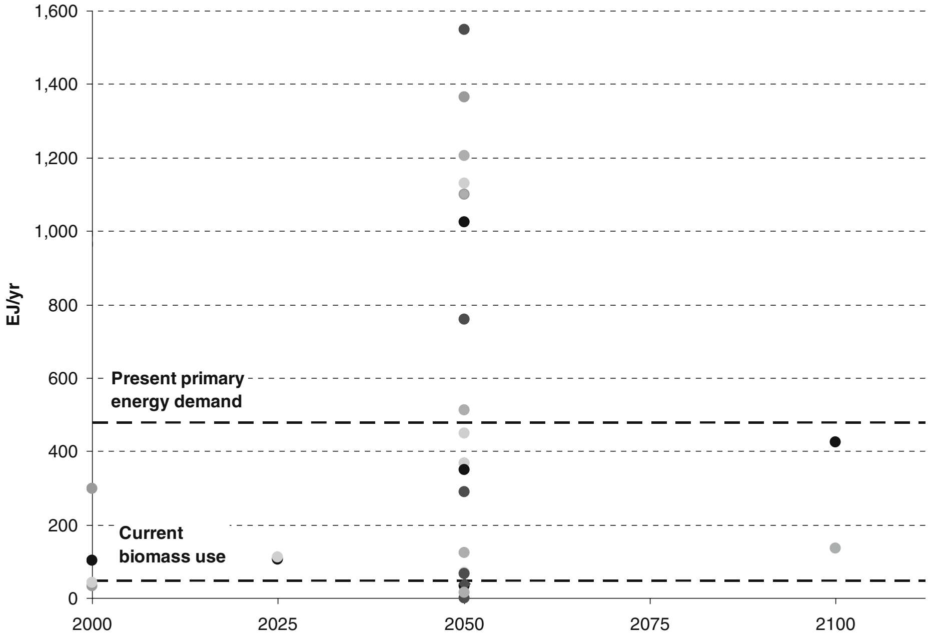

Fig. 1 Global bioenergy potential as reported in 19 studies (Sims et al. 2007; Hoogwijk et al. 2003, 2005; Smeets et al. 2007; Bauen et al. 2004; Campbell et al. 2008; Dessus et al. 1992; Faaij 2007; Fischer and Schrattenholzer 2001; Hall et al. 1993; Johansson et al. 2004; Kaltschmitt et al. 2009; Moomaw et al. 2001; Moreira 2006; Smeets and Faaij 2007; Swisher et al. 1993; Wolf et al. 2003; Yamamoto et al. 1999; Yamamoto et al. 2001)

potentials as identified by recently published studies. The more optimistic estimates equal several times the present global primary energy production. In the most favourable scenario, the potential reaches 1,548 EJ/yr. This is equivalent to more than three times the present global primary energy supply. However, it also has to be pointed out that a substantial part of assessments comes out with numbers being below the current usage level of bioenergy. Thus the overall range between biomass potential estimates is extremely wide and future contribution of bioenergy strongly relies on certain prerequisites relevant for the specification of crucial parameters.

Most estimates of future bioenergy potentials rely on a scenario approach. Creating scenarios initially requires the identification and definition of scenario drivers that have an impact on the target value. One could differentiate between exogenous and endogenous drivers, whereas exogenous drivers describe independent variables that are not altered within the scenario context. They have effects on the endogenous drivers which can also be referred to as dependent variables. A distinction between dependent and independent variables in the context of bioenergy potential assessments seems rather difficult. Some publications even claim that for instance food and material demand were taken as exogenously defined variables in previous assessment studies. The bioenergy sector was assumed to have evolved in parallel to the food or material sector, neglecting potential interactions (Berndes et al. 2003).The choice of scenario drivers is closely linked to the scenario design and its objective. Consequently, each study identified different parameters making it difficult to assess the most relevant ones.

Thrän et al. (2006) figured out six fundamental drivers mainly affecting the available land for energy crop production and hence the energy crop potential. Three of them are also considered to influence the potential supply of residues. Table 3 lists the referring drivers and the way they are addressed by different studies.

3.1 Resource fractions

Bioenergy resources can be divided into two major groups, namely energy crops and residues. In recent times, potential estimates put more emphasis on analysing the potential of energy crops than that of residual materials (Dornburg et al. 2008). Generally, residue potentials are within a much smaller range than energy crop potentials. Taking into account all estimates prepared with for the timeframe 2050 residue potentials vary between 62 and 325 EJ/yr, while energy crop potentials range from 0 to 1,272 EJ/yr.

Figure 2 shows a boxplot diagram including various different assessments of energy crop potentials in 2050. It has to be noted that the significance of such statistical means is limited in this case, as the basis data used here is far beyond from anything like an objective series of measurements. In fact, numerous uncertain parameters determine the potential of energy crops. Nonetheless, some conclusions regarding the potentials to be expected can be drawn from this analysis. Accordingly, half of the estimates came out with a number between 162 and 297 EJ/yr, equalling less than one quarter the overall resulting range. Moreover, 75% of the reported energy crop potentials are below 657 EJ/yr. In contrast, the highest estimates are almost twice as high, boosting the impression that these extreme values represent some kind of optimum estimates, which are only feasible under extraordinarily favourable conditions. Presumably, the availability of energy crops in 2050 will range between round about 200 and 600 EJ/yr, according to current potential assessments. Furthermore, there is evidence that the sustainable potential of energy crops is rather situated at the lower end of this range and even below it, as demonstrated by the latest potential assessments (Campbell et al. 2008; Teske et al. 2008).

Table 3 Fundamental scenario drivers affecting the bioenergy potential (Thrän et al. 2006)

Parameter	Affects	Scale of parameter in 2050			
		(Hoogwijk et al. 2003)	(Hoogwijk et al. 2005)	(Smeets et al. 2007)	(Fischer and Schrattenholzer 2001)
Population growth (in billion)	E, R	8.7–11.3	8.7–11.3	8.8	10
Per capita consumption (in MJ d^{-1})	E, R	10.1–11.5	n. s.	13.8	n. s.
Yield increase through breeding	E	n. s.	Taken into account	Taken into account	Taken into account
State of the art of food production	E	Varying	Varying	Varying	Constant
Impact of climate change on available land area	E, W, R	Excluded in all scenarios			
Reduction of agricultural land	E, (W)	Partial consideration of single aspects (e.g. reforestation), however disregard of the important driver "soil degradation"			

E energy crops; *R* residues; *W* wood from forests

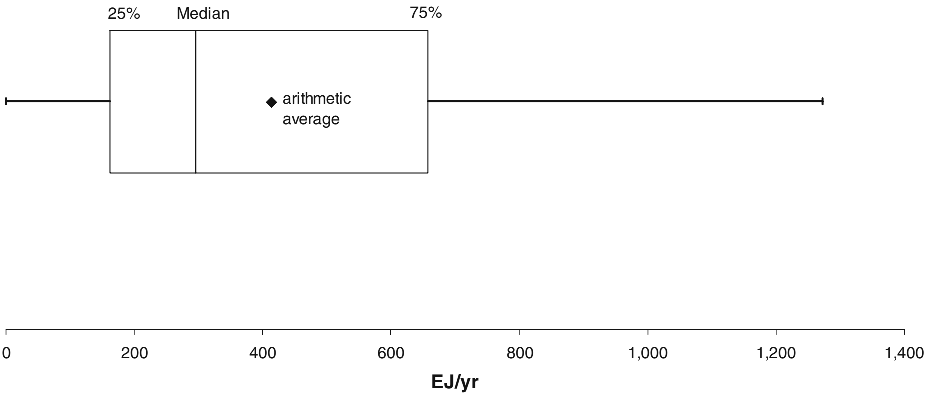

Fig. 2 Box-plot diagram of energy crop potentials reported for 2050

The general approach of deriving residue potentials involves estimating the production quantities of food and wood and multiplying these with a residue generation factor and an energy recovery factor. All three parameters are critical for the available residue potential. The development of the food and wood production is associated with uncertainties as well as the development of residue generation factors. It is for example assumed that in the future yield increases achieved in the food production sector will result in a decreasing residue production, relative to the production of the primary product. The recoverable fraction of the produced residues depends on the amounts of residues required for alternate uses. Except applied for energy production, residues are also used as industrial raw materials, animal feed, animal bedding and traditional fuel. Furthermore, in case of crop harvest residues like straw, a share of residues has to remain on the field for reasons of erosion prevention and soil quality conservation.

Table 4 shows recoverability factors that were used in different studies. The ratios are presented for different types of residues released at different stages from the biomass production chain. Harvest related residues here mainly comprise straw and forest removals while process related residues include materials resulting from industrial processing (e.g. sawn wood or residues from the food industry). Finally, wastes refer to organic wastes like

Table 4 Energy recovery factors as assumed in different studies

Stage of release	Type of residue	(Smeets et al. 2007)	(Hoogwijk et al. 2003)	(Dessus et al. 1992)	(Hall et al. 1993)	(Yamamoto et al. 2001)
Harvest	Crops	0.25	0.25	0.3–0.5	0.25	0.25–0.67
	Wood	0.25	0.25–0.5	0.5–0.7	0.25	0.5
Process	Crops	1	1	–	1	1
	Wood	0.75	0.33–0.75	–	0.75	0.42–0.75
	Animal	–	0.125–0.25	0.3	0.125	0.25
Waste	Crops	1	–	–	–	–
	Wood	0.75	–	–	–	–
	Organic waste	–	0.75	0.1	–	0.75

decayed food products or waste wood. The mentioned figures indicate the part of a certain type of residue generated that becomes available for energy generation. There can be seen some kind of agreement among the studies because in most cases the same ratios were applied. In some cases however, differences occur that principally relate to the respective methodology applied. For instance, one study (Dessus et al. 1992) only assumed a recoverability rate of 0.1 for organic wastes while others took a factor of 0.75. The number presented by Dessus et al. (1992) however takes the total waste production as a base while others only refer to the organic parts of municipal waste. Referring to wood ratios, some studies make distinctions between developing and industrialised countries and further roundwood production of industrial applications and for woodfuel.

3.2 Land availability

The most crucial parameters when assessing the potential of energy crops are the available land area and attainable crop yields (Berndes et al. 2003). Both factors are highly dependent on underlying assumptions made by the respective study, which explains the widely differing estimates. Land types considered suitable for energy crop plantations mainly include surplus agricultural land and degraded or marginal land, also referred to as abandoned agricultural land. Surplus agricultural land is usually defined as the remainder after subtracting the land required for food and feed production from the total existing agricultural land. Most studies focussed mainly on energy crop potentials from surplus agricultural land. However, few studies also observed potentials from degraded land or abandoned land. The spatial extent of available degraded and marginal land suitable for energy crops cultivation is of particular interest as it allows a biomass production largely unaffected by utilisation competitions. Quantifying the biomass potentials from degraded or abandoned land and estimating attainable yields of energy crops is however a challenging task (Campbell et al. 2008). One major problem is the limited availability of data, another is that these land categories are not clearly defined and often used synonymously. Consequently, only few potential assessments carried out the potential of biomass cultivation on degraded, marginal or abandoned land. Table 5 shows area potentials as calculated by seven potential assessments. Four studies do not explicitly state the category of land they investigated to be usable biomass cultivation. However, it can be assumed that these estimates can be largely classified as surplus agricultural land. Degraded land, defined as “areas where human activities have induced soil and/or vegetable degradation” (Hoogwijk et al. 2003), is assumed to have a potential between 0 and 580 Mha. The pessimistic estimate results from assumptions concerning financial, political and social

Table 5 Land availability as estimated by different potential studies [Mha]

	(Smeets et al. 2007)	(Hoogwijk et al. 2003)	(Campbell et al. 2008)	(Fischer and Schrattenholzer 2001)	(Hall et al. 1993)	(Moreira 2006)	(Wolf et al. 2003)
Degraded land	0–430	430–580					
Abandoned land			385–472				
Surplus agricultural land	729–3,585	0–2,600					
W/o specifying land category				3,300	890	2,380	0–7,000

restrictions. The biomass potential of abandoned land was recently quantified by Campbell et al. (2008) based on geographical information system data. The authors define abandoned land as areas that have been abandoned to crop and pasture due to a relocation of agriculture and due to degradation from intensive use. According to this definition, abandoned land overlaps with degraded land. In fact, Campbell et al. (2008) compared their potentials of abandoned land with previous estimates of degraded land potentials (primarily the findings of (Smeets et al. 2007)). Abandoned land available for the production of energy crops according to Campbell et al. (2008) varies between 385 and 472 Mha. Both degraded land and abandoned land, irrespective of overlapping definitions of these land categories, form a minor area potential compared to surplus agricultural land, which is assumed to range between 0 and 7,000 Mha in the most extreme case. Moderate estimates of surplus agricultural land are between 2,000 and 3,000 Mha, which still represents an area, ten times as high as degraded or abandoned land.

Additional aspects effecting the potentially available area, but have only marginally been addressed by the analysed potential estimates, include water scarcity, land degradation or biodiversity concerns. Taking into account these factors can lead to a considerable reduction of the originally calculated potential. van Vuuren et al. (2009) re-evaluated their own potential estimate and found out that one third of it was assigned to areas that are suffering from severe water scarcity, severe land degradation or are potential nature reserve areas.

3.3 Regional distribution

Information about the regional distribution of potentials is of great meaning as it indicates from where large amounts of resources can be expected to be supplied in the future. This is essential, for example concerning the establishment of biofuel trading structures or bioenergy resource procurement. However, only few publications analysed the allocation of the potential onto different world regions. In Table 6 the available figures are illustrated. Comparing these results, it is striking that all potential estimates expect the largest part of the bioenergy potential to be distributed among developing countries. However, the African or Asian potential move within a wide range indicating large uncertainties concerning the magnitude of these potentials. Usually potential assessments for these parts of the world are extremely critical as they usually have to cope with lacking data and thus may only represent a rough estimate. However, also the potentials of industrialised regions like North America move within a relatively wide range indicating that large uncertainties concerning the derivation of bioenergy potentials prevail in all world regions.

4 Discussion of methodological approaches

The previous assessments of bioenergy potentials base on different methodological concepts. The first estimations were carried out in the 1990s. These largely relied on bottom-up calculations taking into account literature values, accompanied by expert judgment. Then, there was a trend towards top-down approaches that resulted in the development of complex integrated models like the Global Land Use and Energy Model (GLUE) or the Integrated Model to Assess the Global Environment (IMAGE) (Smeets et al. 2006). One of the latest comprehensive potential estimates (Smeets et al. 2007) relies on bottom-up calculations that are characterised by a high level of transparency and reproducibility.

Integrated assessment models provide the opportunity to combine knowledge from different disciplines. Models used for simulating bioenergy potentials for example include

Table 6 Regional potentials as reported in different studies for different time perspectives in EJ/yr

World region	No year		2020–2030		2050			
	(Hall et al. 1993)	(Kaltschmitt et al. 2009)	(Dessus et al. 1992)	(Bauen et al. 2004)	(Smeets et al. 2007) (low)	Smeets et al. 2007) (high)	(Fischer and Schrattenholzer 2001) (low)	(Fischer and Schrattenholzer 2001) (high)
OECD[a] North America	40.7	19.9	16	21.8	34	193	40	50
OECD[a] Europe	15.2	8.9	8	11.2	15	64	22	27
OECD[a] Pacific	19.7		2	3.5	42	109	20	26
C.I.S.[b] and Non-OECD[a] Europe	49.8	10	14	76.0	50	205	31	38
Caribbean and Latin America	55.9	21.5	27		59	235	83	103
Asia	59.9	21.4	22		46	193	58	77
Africa	55.5	22.1	17		44	369	100	124

[a] OECD: Member states of the Organisation for Economic Co-operation and Development

[b] C.I.S.: Member states of the Commonwealth of Independent States

modules like energy system, land cover, agricultural economy and terrestrial vegetation to simulate for example land use patterns. Integrated assessment models can be powerful tools as they incorporate a variety of different parameters and quantify linkages between them. However, the complexity of such integrated models can also be disadvantageous as the calculation procedures are hard to be comprehended making an evaluation of the results difficult. The choice of scenario drivers for instance is crucial for the generated output and the set-up of drivers differs significantly among different types of integrated models used for the calculation of bioenergy potentials. The transferability of results achieved with these models is limited as the algorithms used in such models are only partially documented so that full traceability is hardly possible. From the methodological point of view, a bottom-up approach offers the highest level of transparency and traceability and seems to be an appropriate basis for further assessments.

5 Conclusion

In this paper, we analysed the global bioenergy potential by comparing different previous research. Various studies could be made available that analysed the bioenergy potential and came out with widely differing assumptions on the size of the potentials. Considering the large number of uncertainties, the available research on bioenergy potentials allows an evaluation of the existing and resource base and also gives useful information about the possible future development. However, the evaluation of global biomass potential figures requires getting insight into the framework and assumptions of the respective research. As has been demonstrated, reasons for large differences in outcome are manifold so that an independent analysis of how these potentials were estimated is required to interpret the respective outcomes. Aspect to be considered include

First, the comparison of different potentials as reported in the studies involves certain difficulties. For example, studies refer to diverse definitions of some biomass resource fractions. The identification of the resource type considered includes itself an understanding of the respectively applied methodology in order to be comparable, which is particularly significant in reference to forest-derived biomass.

Most potential studies focus on estimating energy crop potentials based on an estimate of available surplus agricultural land. Only a few studies give detailed potentials of residues or energy crops on degraded land. Particularly the debate regarding the effect of energy crops cultivation on the price of food products has induced rising concerns about the energetic use of biomass. Cultivating energy crops on degraded land that is unsuitable for food production as well as an increased use of residues are approved means for minimising biomass utilisation competitions. If residues were included within a potential estimate, largely only selected fractions were considered, not allowing a sufficient overview of the entire resource. Additionally, the classification of residues observed was often not clearly stated. Most studies mention a potential for crop residues that is often solely based on harvest residues like straw, whereas process-related residues of crops were not assessed at all. Therefore, comparing different publications it is nearly impossible to identify the total potential of residues available worldwide. As information on crucial parameters such as recoverability factors, conversion factors, and residue-to-product ratios is often insufficient, residue potential calculations are largely based on conservative assumptions and thus are likely underestimated.

Thus, the following major conclusions can be made.

- The existing research on bioenergy potentials shows that bioenergy has the potential to contribute a major part to the global primary energy supply in the future.
- The research provides useful information about the evaluation of the magnitude of the potential, however the definite size of the potential is unclear and estimates are widely varying.
- Comparisons of the results of different studies are only possible to a limited degree. Different methodologies partly only traceable with difficulties, different data and uncertainties concerning the specification of crucial parameter values together cause widely ranging outcomes.
- Land availability is a crucial parameter for bioenergy potential assessments and its quantification is confronted with various uncertainties. Available estimates range from 0 to 7,000 Mha. Depending on the land category observed the potential of land can be in a much smaller range. Estimates about degraded or marginal land are between 0 and 580 Mha. In contrast to bioenergy cultivated on surplus agricultural land, the use of degraded or marginal land for biomass production is largely unaffected by utilisation competitions. Another promising option in the context of minimising utilisation competitions is the use of residues. Potentials of residual materials are estimated to range from about 62 to 325 EJ/yr. However there are only few studies that allow an evaluation of the complete residue potential.
- Furthermore, the impact of factors like water scarcity, biodiversity concerns, and land degradation have often not been included within potential estimates. However, the results of studies that took into account these factors indicate that they could lead to a substantial reduction of the potential.

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