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The contribution of biomass in the future global energy supply: a review of 17 studies

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Abstract

This paper discusses the contribution of biomass in the future global energy supply. The discussion is based on a review of 17 earlier studies on the subject. These studies have arrived at widely different conclusions about the possible contribution of biomass in the future global energy supply (e.g., from below 100 EJ yr^{-1} to above 400 EJ yr^{-1} in 2050). The major reason for the differences is that the two most crucial parameters—land availability and yield levels in energy crop production—are very uncertain, and subject to widely different opinions (e.g., the assessed 2050 plantation supply ranges from below 50 EJ yr^{-1} to almost 240 EJ yr^{-1}). However, also the expectations about future availability of forest wood and of residues from agriculture and forestry vary substantially among the studies.

The question how an expanding bioenergy sector would interact with other land uses, such as food production, biodiversity, soil and nature conservation, and carbon sequestration has been insufficiently analyzed in the studies. It is therefore difficult to establish to what extent bioenergy is an attractive option for climate change mitigation in the energy sector. A refined modeling of interactions between different uses and bioenergy, food and materials production—i.e., of competition for resources, and of synergies between different uses—would facilitate an improved understanding of the prospects for large-scale bioenergy and of future land-use and biomass management in general

Keywords: Biomass energy; Bioenergy; Potential; Global; Regional; Assessment; Scenario; Review

1. Introduction

Climate change is one of the most serious environmental problems. The United Nations Framework Convention on Climate Change (UN 1992, article 2) calls for a ...“stabilization of greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system...”. Concentrations of CO2 in the atmosphere will continue rising unless major changes are made in the way fossil fuels are used to provide energy services [1].

Biomass has the potential to become one of the major global primary energy sources during the next

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century, and modernized bioenergy systems are suggested to be important contributors to future sustainable energy systems and to sustainable development in industrialized countries as well as in developing countries [2–10]. Energy crop production on land included in set-aside schemes to reduce the food surplus presents an opportunity to make productive use of such land,[1] and the conversion of excess cropland to profitable energy crop production is suggested as a path towards a phase-out of agricultural subsidies [15].

Many studies have been undertaken to assess the possible contribution of biomass to the future global energy supply. The conclusions from these studies differ significantly. This paper reviews a selection of 17 studies discussing the future global use of biomass for energy.[2] The main objective is to discuss the diverging conclusions about the future contribution of biomass energy, by analyzing and discussing the underlying assumptions and methodologies that are used in these studies.

The paper is structured as follows. A brief overview of the reviewed studies is given in Section 2. The findings of the studies regarding the contribution of biomass in the future global energy system (and the sources for this biomass supply) are summarized in Section 3. In Section 4, we discuss how parameters most critical for the outcome are treated in the different studies (A more detailed account is given in Appendix A). Finally, conclusions and some remarks are given in Section 5.

2. Overview of the reviewed studies

The reviewed studies are presented in Table 1, where also the acronyms identifying the studies throughout the paper are given. Table 2 gives a characterization of the reviewed studies according to general approach, timeframe and geographical aggregation used (see also Fig. 1).

The biomass energy potential depends on both competition between biomass resource uses and competition between alternative energy technologies and primary energy sources. In the sense of economics, the term potential corresponds to a supply curve (supply as a function of price), and actual supply (and demand) would then be the result of intersecting the supply curve with a demand curve (demand as a function of price). The ideal study would therefore take into account the whole chain in Fig. 1. However, most studies focused on either the supply side or the demand side. Two main categories of general approach are therefore referred to in this paper:

- demand-driven assessments that analyzed the competitiveness of biomass-based electricity and biofuels, or estimated the amount of biomass required to meet exogenous targets on climate-neutral energy supply (demand side),
- resource-focused assessments that focused on the total bioenergy resource base and the competition between different uses of the resources (supply side).

Demand-driven assessments were often accomplished without actually specifying what sources of bioenergy are used. Bioenergy options were instead characterized in terms of performance of related energy technologies and biomass availability at specific costs. However, most demand-driven assessments included a feasibility evaluation of the bioenergy supply that implicitly involved consideration of specific sources via reference to other studies of the possible future contribution of biomass for energy.

Population growth and economic development are principal factors behind overall energy end-use. Assumptions about technology development, energy system transformation and changes in the energy intensity of economic activity influence the translation of energy end-use into the demand for different primary energy carriers. In addition to development of bioenergy technologies, also development of non-bioenergy technologies is crucial for the ultimate

[1] Extensification of agricultural production is an alternative approach to control overproduction, which at the same time can reduce pollution and promote biodiversity [11–13]. Environmental policy priorities and local seriousness of environmental problems will determine what strategy is considered preferable from an environmental point of view [14].

[2] See Table 1 for full references. A detailed account of the treatment of biomass in the studies is provided in [16].

Table 1
The studies included in this review

	Main reference[a]
WEC[b]	WEC, New Renewable Energy Resources: World Energy Council. Kogan Page Ltd., 1994.
IIASA-WEC[c]	Nakicenovic, N., A. Grübler, and A. McDonald, Global energy perspectives: International Institute for Applied Systems Analysis/World Energy Council. Cambridge University Press, 1998.
FFES	Lazarus, M., L. Greber, J. Hall, C. Bartels, S. Bernow, E. Hansen, P. Raskin, and D. von Hippel, Towards a Fossil Free Energy Future. 1993, Stockholm Environmental Institute - Boston Center: Boston.
EDMONDS	Edmonds, J.A., M.A. Wise, R.D. Sands, R.A. Brown, and H. Kheshgi, Agriculture, land use, and commercial biomass energy: A preliminary integrated analysis of the potential role of biomass energy for reducing future greenhouse related emissions. 1996, Pacific Northwest National Laboratory.
SWISHER	Swisher, J. and D. Wilson, Renewable energy potentials. Energy, 18(5), 437–459. (1993).
USEPA	Lashof, D.A. and D.A. Tirpak, eds. Policy options for stabilizing global climate. 1990, Hemisphere Publishing Corporation: New York, Washington, Philadelphia, London.
SØRENSEN	SØrensen, B., Long-term scenarios for global energy demand and supply: Four global greenhouse mitigation scenarios. 1999, Roskilde University, Institute 2, Energy & Environment Group, Denmark.
HALL	Hall, D.O., F. Rosillo-Calle, R.H. Williams, and J. Woods, Biomass for Energy: Supply Prospects, In: T.B. Johansson, et al., Editors. Renewable Energy: Sources for Fuels and Electricity, Washington, D.C.: Island Press, 1993 p. 593–651.
RIGES	Johansson, T.B., H. Kelly, A.K.N. Reddy, and R.H. Williams, A renewables-intensive global energy scenario (appendix to Chapter 1), In: T.B. Johansson, et al., Editors. Renewable Energy: Sources for Fuels and Electricity, Washington, D.C.: Island Press, 1993 p. 1071–1143.
LESS/BI	Williams, R.H., Variants of a low CO2-emitting energy supply system (LESS) for the world: Prepared for the IPCC Second Assessment Report Working Group IIa, Energy Supply Mitigation Options. 1995, Pacific Northwest Laboratories.
LESS/IMAGE	Leemans, R., A. van Amstel, C. Battjes, E. Kreileman, and S. Toet, The land cover and carbon cycle consequences of large-scale utilizations of biomass as an energy source. Global Environmental Change, 6(4), 335–357. (1996).
BATTJES	Battjes, J.J., Global options for biofuels from plantations according to IMAGE simulations. 1994, Interfacultaire Vakgroep Energie en Milieukunde (IVEM), Rijksuniversiteit Groningen, Nijenborgh 4, 9747 AG Groningen, The Netherlands.
GLUE	Yamamoto, H., K. Yamaji, and J. Fujino, Evaluation of bioenergy resources with a global land use and energy model formulated with SD technique. Applied Energy, 63, 101–113. (1999).
FISCHER	Fischer, G. and L. Schrattenholzer, Global bioenergy potentials through 2050. Biomass and Bioenergy, 2001. 20: p. 151–159.
DESSUS	Dessus, B., B. Devin, and F. Pharabed, World Potential of Renewable Energies: Actually Accessible in the Nineties and Environmental Impact Analysis. 1992, la Huille Blanche No. 1, Paris.
SHELL	Shell International, The evolution of the world's energy system 1860–2060. 1995, Shell Center: London, U.K.
SRES/IMAGE[d]	IPCC, Special report on emission scenarios. Cambridge: Intergovernmental Panel on Climate Change. Cambridge University Press, 2000.

[a] [47] is complementary to GLUE. [48] is complementary to SRES/IMAGE.
[b] WEC explores two scenarios: "Current Policies" and "Ecologically Driven" (ED). Only ED is included in this review.
[c] Six scenarios. A (3 scenarios): extensive technological improvements and high economic growth. B: less ambitious technological improvements, more intermediate economic growth. C (2 scenarios): an ecologically driven future. Substantial technological progress, international cooperation centered explicitly on environmental protection and international equity.
[d] Two IMAGE 2 simulations from the IPCC SRES scenarios were included since they were accessible within deadlines for reports that are the bases for this paper.

bioenergy demand. For example, solar and wind energy systems account for a rapidly increasing share of primary energy supply from 2030 up to 2100 in the FFES study. This relieves the demand for other non-fossil, non-nuclear primary energy supply such as bioenergy. The two ecologically driven C scenarios in the IIASA-WEC study explore widely different paths for nuclear power—and consequently different demand for other primary energy sources such as bioenergy.

Table 2
Approach, time-frame, and geographic aggregation used in the reviewed studies

	Approach	Time-frame	Geographic aggregation	Resource focused	Demand driven
WEC	Expert Judgment and per capita forecasting based on present consumption	1990–2020	9 regions		x
IIASA-WEC	Energy Economy model, six scenarios	1990–2100	11 regions		x
FFES	Energy Economy model based on Edmonds and Reilly, IPCC-based scenario with focus on fossil free energy system in 2100. Nuclear phased out by 2010	1988–2100	10 regions		x
EDMONDS	Integrated land use/energy-economy model (Edmonds and Reilly), IPCC based scenario	1995–2095	11 regions		x
SWISHER	Literature-based bottom-up calculation. Based on DESSUS and data from Hall who authored HALL	2030	20 regions	x	
USEPA	Non-integrated land use/energy-economy model based on Edmonds-Reilly	1985–2100	6 regions	x[a]	x
SØRENSEN	Bottom-up maximum limit calculation, energy-economy model	2050		x[a]	x
HALL	Literature based bottom-up calculation +expert judgment	1990	10 regions	x	
RIGES	Bottom-up energy supply construction. Biomass part based on HALL. Energy demand from somewhat adjusted high growth variant of IPCC Accelerated Policies Scenario	1985–2050	11 regions	x[a]	x
LESS/BI	Scenario extension of RIGES, using updated oil and gas resource estimates and including CO_2 sequestration	1990–2100	11 regions	x[a]	x
LESS/IMAGE	Integrated land use/energy-economy model. Energy demand from LESS/BI	1990–2100	13 regions		x
BATTJES	Integrated land use/energy-economy model + expert judgment	2050	13 regions	x	
GLUE	Land use/energy-economy model based on Edmonds-Reilly. Further bottom-up calculation of resources	1990–2100	10 regions	x	
FISCHER	Bottom-up calculation by using land use model of IIASA, with complementary data from DESSUS	1990–2050	11 regions	x	
DESSUS	Literature-based bottom-up calculation +expert judgment	1990–2020	22 regions	x	
SHELL	Not documented	2060	world		
SRES/IMAGE	Integrated land use/energy-economy model, IPCC scenario	1970–2100	13 regions		x

[a]These studies have an upper limit of biomass energy availability for their demand driven scenario, based on a resource assessment.

Resource-focused assessments took the form of inventories of potential bioenergy sources, with an evaluation of possibilities to utilize the sources for energy purposes. Food and material demand, and land-use efficiency in agriculture and forestry, determine land requirements for food and materials production—and hence availability of land for other purposes, such as energy crop production. The food and material demand and technologies for harvesting and processing biomass into

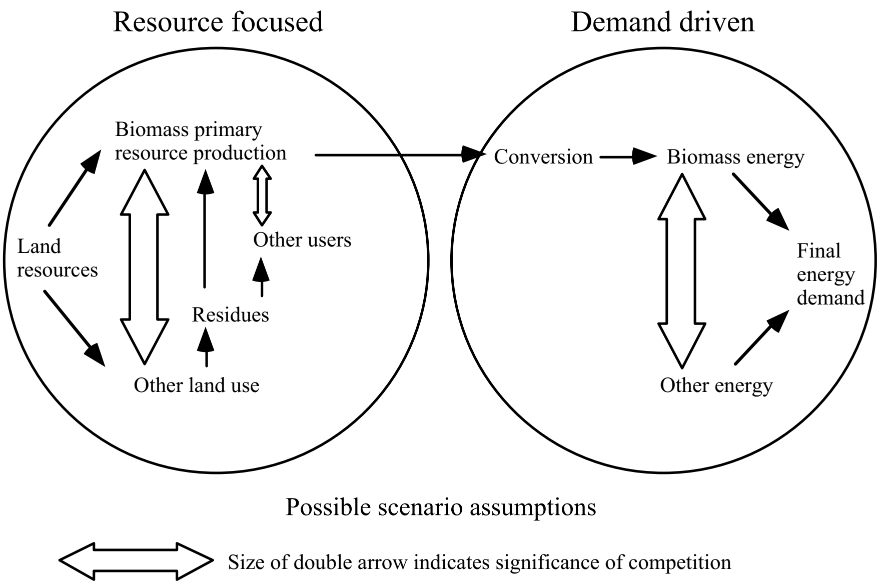

Fig. 1. The classification used in this paper. See text for a characterization of demand-driven and resource-focused studies.

products also determine the availability of residues and by-products for use as feedstock in bioenergy production.

Four studies are indicated as being both resource-focused and demand-driven in Table 2. However, the estimates of the bioenergy potential in these studies do not correspond to the intersection of a supply curve with a demand curve as described above. The resource assessments did not result in supply curves, only information about maximum levels for the bioenergy supply. The bioenergy potential was instead estimated based on a prescribed energy end-use demand and characteristics of non-biomass energy technologies and resources. Thus, the four studies can be characterized as demand-driven assessments, with resource-focused assessments attached in order to ensure physical feasibility. For example, the contribution of plantation biomass 2025 in LESS/BI is only around 20 percent of the level in RIGES, although the two studies are based on identical energy end-use demand and the same bottom-up energy supply construction. The reason is that LESS/BI uses estimates of remaining oil and gas reserves that are significantly higher than those that RIGES is based on.

3. Global and regional bioenergy potentials: results of the studies

In this section, the results reported in the 17 studies are summarized. The absolute and relative contribution of biomass to the global primary energy supply over time is presented, as well as the bioenergy supply over regions. An account of the relative importance of different sources of biomass for energy is also given.

3.1. Global bioenergy supply, and relative importance of biomass in the future global primary energy supply

The reported potential future bioenergy supplies are presented in Fig. 2. The present global primary energy consumption is included for comparison. Fig. 3 presents the contribution of biomass to total global primary energy supply in the demand-driven studies. The resource-focused studies are not included in Fig. 3 since they do not relate their bioenergy supply to the total energy supply.

The more optimistic resource-focused assessments report a future bioenergy potential of similar size as, or even larger than, the present global

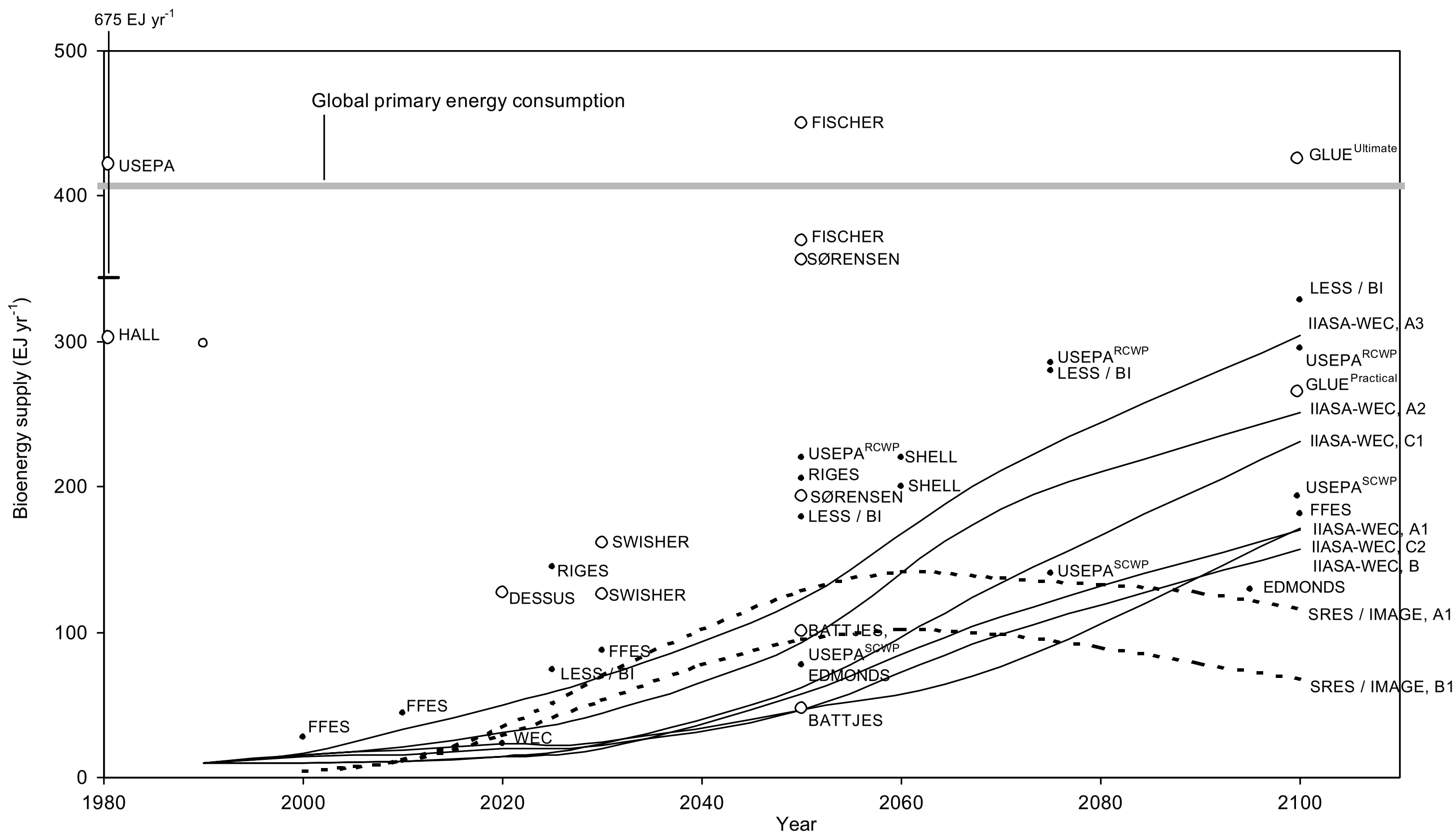

Fig. 2. Potential biomass supply for energy over time. Resource-focused studies are represented by hollow circles and demand-driven studies are represented by filled circles. USEPA and HALL, who do not refer to any specific time, are placed at the left side of the diagram. IIASA-WEC and SRES/IMAGE are represented by solid and dashed lines respectively, with scenario variant names given without brackets at the right end of each line. The present approximate global primary energy consumption is included for comparison. (The global consumption of oil, natural gas, coal, nuclear energy and hydro electricity 1999–2000 was about 365 EJ yr^{-1} [43]. Global biomass consumption for energy is estimated at 35–55 EJ yr^{-1} [44–46].)

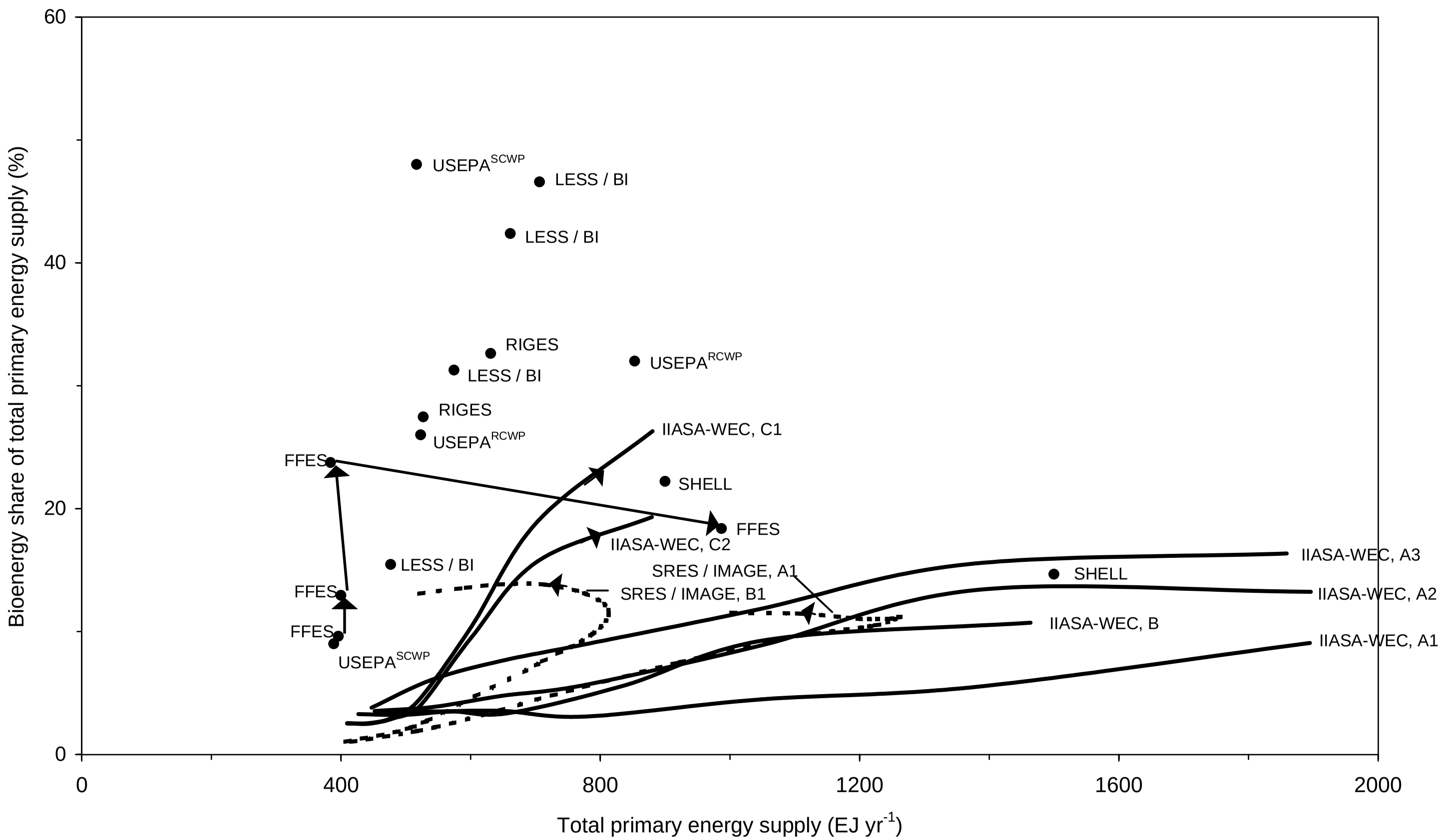

Fig. 3. Total primary energy supply, and share provided from biomass in demand-driven studies. Where no indication of development is made for a particular study, the changes over time are towards increasing total primary energy supply and bioenergy share. IIASA-WEC and SRES/IMAGE are represented by solid and dashed lines, respectively, with scenario variant names given without brackets at the right end of each line.

primary energy consumption.[3] However, there are also resource-focused assessments that report much lower bioenergy potentials. For example, the lowest estimate for the year 2050 (BATTJES: 47 EJ yr^{-1}) is almost ten times lower than the highest year-2050 estimate (FISCHER: 450 EJ yr^{-1}). Nevertheless, the resource-focused assessments in aggregate appear to justify the levels of bioenergy use that are reported in the demand-driven studies.

From Fig. 2, it is apparent that most demand-driven studies report an increasing bioenergy supply over time. SRES/IMAGE is the exception, reporting a peak in bioenergy use around 2060 and declining use thereafter. As can be seen from Fig. 3, the declining bioenergy use in SRES/IMAGE is more due to decreasing total energy use than decreasing competitiveness of biomass relative to other primary energy sources.

The A2 and A3 scenarios in the IIASA-WEC study illustrates the fact that the future bioenergy demand can be high even in the absence of policies directly addressing climate change. The two A scenarios (characterized by high economic growth and technological development) reach higher levels of bioenergy demand than the ecologically driven C1 scenario in the same study, which explores the technical and economic feasibility of meeting low stabilization targets for atmospheric CO_2 (Fig. 2). The modest relative contribution of biomass to total energy supply in the two A scenarios as compared to the C1 scenario (13–16% of total primary energy supply vs. about 26% for C1) is outweighed by the much higher total energy demand in these scenarios (Fig. 3). The two scenarios from USEPA (SCWP and RCWP)[4] represent a similar case. Both scenarios include policies addressing climate change. The $USEPA^{SCWP}$ scenario reaches a larger biomass share in total primary energy supply, but the $USEPA^{RCWP}$ scenario reaches a larger absolute biomass energy supply, due to much higher total energy demand.

The evolution of bioenergy (and other primary energy sources) in the FFES study is also noteworthy. In FFES, total global primary energy supply changes slowly (and even decreases 2020–2030), and the bioenergy share steadily increases up to 2030. After 2030 the growth in energy supply from solar and wind technologies abruptly changes and total global primary energy supply increases linearly (ca 85 EJ per decade) up to 2100, while supply from biomass increases slowly, hydro is constant, and fossil fuels are completely phased out.

3.2. Regional bioenergy supply

The reported distribution of bioenergy supply between industrialized and developing countries[5] is presented in Fig. 4. Developing countries are expected to contribute the major share of the global bioenergy supply in most of the studies, especially in the longer term. Note that the regional bioenergy supply in Fig. 4 does not necessarily reflect the regional bioenergy demand in the demand-driven studies. For example, in RIGES, Africa produces about 13 and 22 EJ yr^{-1} of methanol (using about 22 and 34 EJ yr^{-1} of biomass) in 2025 and 2050, respectively, but only one fourth and one third of this methanol is consumed in the region. The rest is exported to other regions. Biomass-derived fuels are traded also in LESS/BI (the extension of RIGES to year 2100), while biomass production was assumed to occur in the region of biomass demand in WEC, IIASA-WEC and FFES. Based on Fig. 4, it appears that the resource-focused studies indicate that substantial volumes of biomass can be made available for energy in developing countries, but that large-scale export of biofuels to industrialized countries may be required for this potential to be realized since the bioenergy demand in the developing countries will be too low (at least during the coming decades).

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[3] The resource assessment part of the USEPA study holds an exceptional position, reporting a maximum potential at 675 EJ yr^{-1}. The reason is that USEPA assumes that very high energy crop yields can be reached in the future. The maximum potential assume yields that range from 46 Mg DM ha^{-1} yr^{-1} in temperate areas to 99 Mg DM ha^{-1} yr^{-1} in tropical areas (DM=dry matter). The global average yield levels (on 556 Mha) range from about 30 Mg DM ha^{-1} yr^{-1} for the low estimate to 60 Mg DM ha^{-1} yr^{-1} for the high estimate. There is no justification for such yield levels from present experience in agriculture and silviculture (see also Fig. 6). It should be noted however, that the bioenergy production envisioned in the scenarios in the USEPA study is constrained to levels far below those reported from the resource assessment.

[4] Slowly changing world with policies addressing climate change (SCWP), and rapidly changing world with policies addressing climate change (RCWP).

[5] Using the distinction between industrialized and developing countries in today's sense, Africa, Middle East, Latin America, and non-OECD countries in Asia & Oceania are designated developing countries.

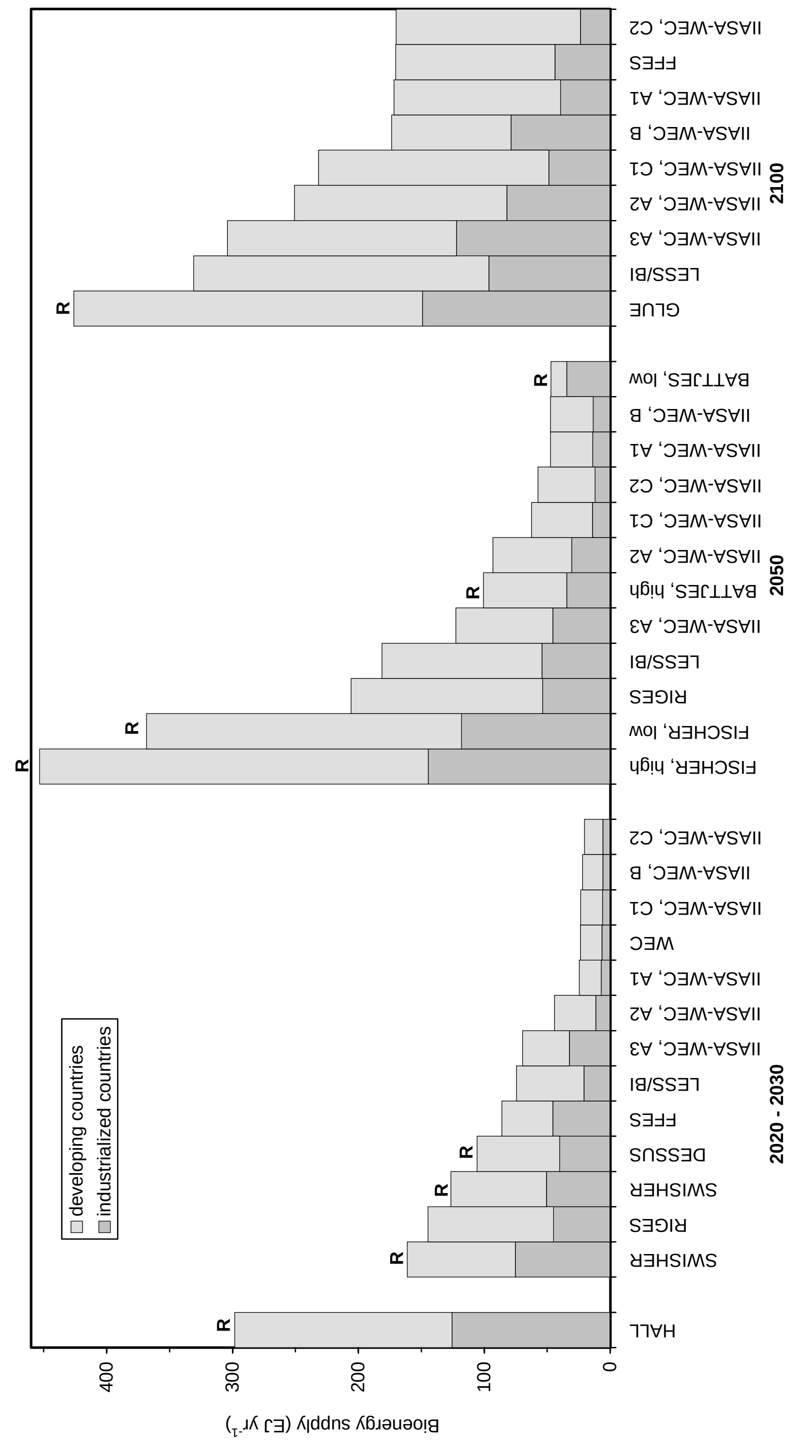

Fig. 4. Contribution of industrialized and developing regions to total bioenergy supply. Studies that are characterized as resource-focused are indicated with R. HALL does not refer to any specific time period. EDMONDS, USEPA and SHELL are not included since they only report results on the global level.

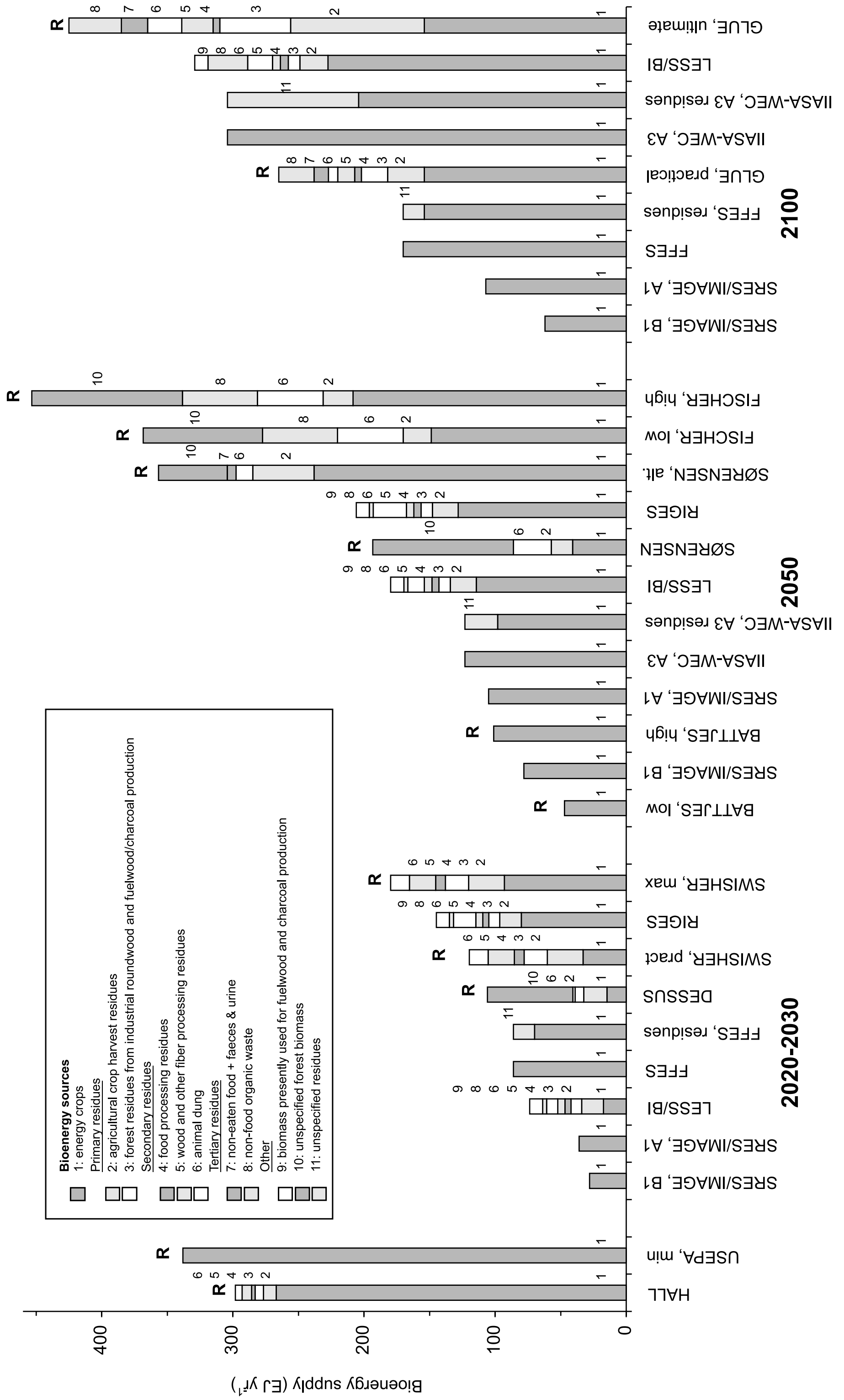

Fig. 5. The contribution of specific sources to the total bioenergy supply. The number sequence to the right of the bars corresponds to the sequence of bioenergy sources in each bar. Studies that are characterized as resource-focused are indicated with R. The IIASA-WEC study is represented by the bioenergy-intensive A3 variant. The non-specified residue potential in SWISHER is distributed between residue categories 2–6 according to HALL, since SWISHER use data from David Hall who also produced the HALL estimate.

3.3. Contribution of specific biomass sources to the total bioenergy supply

Fig. 5 presents the contribution of the specific biomass sources to the total bioenergy supply in the studies.[6] It is evident from Fig. 5 that most studies consider biomass plantations as the most important source of biomass for energy. In some cases the reason is simply that other potential sources of biomass for energy have not been considered. But also studies presenting more complete assessments of the bioenergy resource base give prominence to biomass plantations. The major role of biomass plantations as suppliers of biomass for energy implies that assumptions about land availability and biomass yields are central for the total bioenergy potential. It is clear from Fig. 5 that there are widely different opinions among the studies what regard these two crucial parameters.[7]

It is also clear from Fig. 5 that forest biomass is a potentially major source of biomass for energy, and that the studies differ dramatically in their conclusions about the availability of forest biomass for energy. The main reason for the divergence is that some studies calculate the forest biomass potential based on the estimated wood flow in the forest sector. Thus, the bioenergy potential is restricted by the projected future demand for sawnwood, wood-based panels and paper. Other studies do not make this restriction (this is further discussed in the next section).

Dung and food crop residues (mainly cereal residues) are the two major bioenergy sources in the agricultural sector.[8] Thus, assumptions about future production and availability of dung and cereal residues are more important in defining the future contribution of biomass for energy in the agriculture sector, than consideration of all the different residue flows in agriculture.

[6] WEC, EDMONDS, and SHELL did not explicitly report the contribution from different sources, and are therefore not included. Demand-driven studies are included when they explicitly report the biomass supply sources.

[7] For demand-driven estimates though, a low supply from plantations may reflect limited bioenergy demand rather than constrained biomass plantation supply. However, also when excluding demand-driven studies at the lower end, the range is substantial: from 15 to 86 EJ yr^{-1} in 2020–2030, 41–238 EJ yr^{-1} in 2050, and 154–304 EJ yr^{-1} in 2100.

[8] Presently, dung and cereal residues constitute more than 70 percent of the total residue flows in the agriculture sector [17].

In the next section, the methodologies and underlying assumptions that are used in the reviewed studies are discussed. Appendix A provides more detailed information about approaches in the different studies.

4. Discussion of approaches and results in the studies

4.1. Biomass plantations

As was shown in Fig. 5, the contribution of biomass plantations is crucial for the total bioenergy supply in almost all of the reviewed studies. Consequently, land availability and yield levels in energy crop production are among the most critical parameters for the outcome of the studies. Fig. 6 presents the global average yield levels and amounts of land that were assessed as available/required for energy crop production in the studies. Some additional data are also included in Fig. 6 in order to put the assumptions about land availability and average yield levels into perspective:

- the global tree plantation area in 2000 is indicated along the X-axis,[9]
- the average yield levels for Pinus and Eucalyptus plantations (globally, the two main species [18]) in selected countries are indicated along the Y-axis,[10]
- the harvested area and yield in global cereal production in 180 countries,[11]

[9] About 187 Mha. Asia accounts for 62 percent of the total, Europe 17 percent, N. & C. America 9 percent, S. America 6 percent, Africa 4 percent, and Oceania less than 2 percent [18].

[10] Yield data reported from tree plantations presently managed for fiber and fuelwood production are highly variable, and low yields are often found to be caused by factors other than growth-factors such as soil and climate. Wrong matching of species/provenances to site and lack of tending operations are reported principal factors behind low yields, rather than inferior growing conditions. Lack of integrated planning—matching demand with supply—and of incentives for local participation and plantation promotion are additional factors behind low yields [19–21].

[11] 1990–1999 average. Data downloaded from the FAOSTAT online database (www.fao.org), assuming an average dry matter content of cereal grains at 85 percent. Given similar crop growth potential, climate- and soil conditions, and tending management, energy crops can be expected to have higher average annual yields than cereals due to a longer growing season (especially for non-annual energy crops) and higher harvest index (around 0.7–0.9 [22–25] as compared to regional averages for cereals at typically 0.25–0.5 [17]).

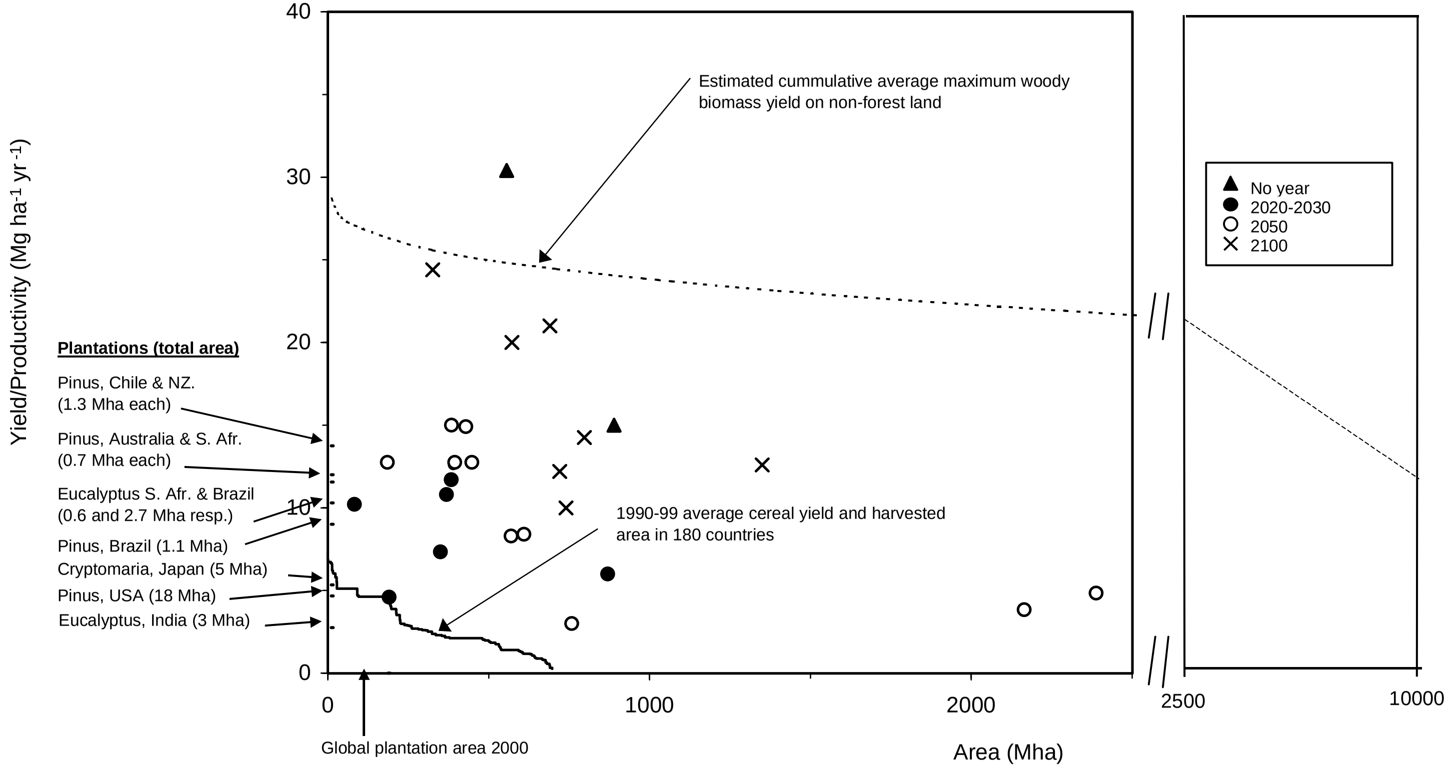

Fig. 6. Land use and yield levels in future energy crops production. Dots represent suggested plantation area and average yield levels in the studies. Lines represent suggested maximum woody biomass yield on non-forest land, and harvested area and yields in global cereal production. The global tree plantation area in 2000 is indicated on the X-axis. The average yield levels for Pinus and Eucalyptus plantations in selected countries are indicated along the Y-axis. The specific yields and plantation areas used are given for each study in Appendix A.

- the potential cumulative average maximum woody biomass yield on global non-forest land. [12]

First of all, it can be concluded that the reported plantation areas and yield levels in energy crop production vary substantially between the studies, and this leads to widely different conclusions about the bioenergy potential of biomass plantations (Fig. 5). At the same time, a comparison with the 1995 global industrial plantation area reveals that even a plantation establishment corresponding to the more modest land availability assumptions would imply a substantial increase in the overall global plantation area. It also implies very ambitious planting rate goals. Presently, 4.5 Mha yr^{-1} are planted globally, with about 3 Mha estimated to be successful [18]. In order to reach 500 Mha bioenergy plantations in 2050, an average of 10 Mha of plantations would have to be established annually—in addition to the plantations established for industrial roundwood production and other non-industrial purposes. [13]

When considering yield levels, USEPA [14] stands out in Fig. 6, suggesting global average yield levels substantially higher than the other studies, and also higher than the indicated maximum woody biomass yield level. Note also that cropland and permanent pastures—presently ca 1.5 and 3.4 Gha, respectively—are included in the non-forest areas in Fig. 6. Thus, unless bioenergy plantations are established on the more productive land, maximum woody biomass yield levels on the right side of Fig. 6 is the relevant comparison. SØRENSEN and FISCHER [15] are found in the other end of the yield range, having yield levels almost ten times lower than the USEPA study.

Not all studies documented how the reported yield levels were estimated. Those who did can be categorized either as (i) model based estimates, where yield levels were obtained as a function of model parameters influencing productivity (e.g., soil type, climate, agronomic practice), or (ii) case study based estimates, where the yield levels where set based on present experience of biomass plantations.

Both approaches have weak points. The use of yield records from small scale field trails or individual plantations as a basis for estimates of what can be achieved on large scale, obviously introduces speculation. Model based yield estimates rely on widely accepted crop models, but the reliability and quality of the soil-, climate- and other data used as modeling input is uneven across regions [26]. In addition, the approach includes the use of parameters that specify the difference between simulated potential and actual yields. The definition of how such parameters will evolve over the coming 50–100 yr introduces speculation of similar degree as in case study based yield estimates.

Several of the yield estimates in Fig. 6 appear to be very optimistic when compared to present average tree plantation yields (given along the Y-axis), and also to cereal production (global average is about 2.4 Mg dry matter/ha and year). However, the highest yield levels in Fig. 6 refer to the year 2100, i.e., 100 years of plant breeding efforts and cultivation development from the present situation. There are yet large differences between actual and potential yield levels in agriculture, in silviculture, and for energy crops [27–29]. Generally, new energy crops have a larger yield increase potential than traditional crops since less efforts has been

[12] Calculated as 80 percent of the simulated theoretical rainfed yield level (based on climate and soil conditions) obtained from the Integrated Assessment Model IMAGE 2.1. A scaling factor of 0.8 corresponds to calibration factors used for modeling plantations with high inputs, such as sugarcane plantations. Although such modeled data on maximum yield levels have limited usefulness for predictions of what yield levels that could be reached in practice over large areas, they can provide insights regarding upper limits. Land classified as forest in IMAGE 2.1 (about 2.9 Gha) was excluded since the studies commonly reject large-scale deforestation with subsequent plantation establishment as a way of implementing large-scale bioenergy production.

[13] In addition to fuelwood supply, non-industrial purposes include providing soil and water conservation, wind protection, biological diversity conservation and other non-commercial purposes. To some extent, biomass plantations can be established and managed so as to provide both bioenergy and additional environmental services.

[14] The representation of USEPA in Fig. 6 refers to the lowest average yield level (25–49 Mg ha^{-1} yr^{-1}). Suggested medium and high yield levels are 37–74 and 49–99 Mg ha^{-1} yr^{-1}, respectively. As already mentioned, the bioenergy production envisioned in the four scenarios in USEPA is constrained to levels far below that resulting from suggested yield levels and land availability for energy crops.

[15] The large area and low yields in FISCHER are due to the method used to account for grazing requirements. Grazing was accounted for by reducing the simulated bioenergy yield on grassland instead of subtracting grassland area needed for grazing.

put into plant breeding and cultivation method development. In addition, increasing CO2 concentrations and climatic changes—including changes in temperature and precipitation regimes, and thus changes in prerequisites for both bioenergy and food crop production [16] —makes it even more difficult to evaluate the feasibility of the stated future yield levels.

Where should the plantations be established? The approaches to answering this question include: (i) rough regional-level calculations based on the assumption that certain shares of the present crop-, grass, and forest land could be converted to plantations; (ii) calculations based on estimates of the extent of surplus cropland in industrialized countries and/or degraded lands in developing countries; and (iii) modeling approaches based on geographically explicit land use/land cover databases.

Several studies suggest that biomass plantations in developing countries can be major future suppliers of bioenergy, although other studies indicate a relative small contribution from this source (Fig. 7). The plantation biomass supply from developing countries—as envisioned in the more optimistic studies—is much larger than the present and suggested future plantation contribution to industrial roundwood production. The present global annual industrial wood production from plantations is around 330 million m^3, or roughly 3 EJ [33]. The present potential fiber availability from plantations in developing countries corresponds to around 1 EJ, and stated optimistic assumptions suggests that 4–5 EJ could be available in 2050 [34]. This can be compared with the bioenergy supply from plantations in Fig. 7, which range from 7 to 56 EJ yr^{-1} in 2020–2030, from 26 to 146 EJ yr^{-1} in 2050, and from 122 to 182 EJ yr^{-1} in 2100.

None of the reviewed studies presents an autonomous assessment of the actual extent of degraded land that is suitable and available for plantation establishment. Instead, reference is made to other studies of the extent and suitable management of degraded land [35–37]. However, the studies referred to did not focus on availability of degraded land for plantation establishment, but discussed land use and terrestrial carbon management in a broader perspective. Approaches other than large-scale plantation establishment were often viewed as suitable for the reclamation of degraded land. For example, protection, assisted regeneration, and agroforestry—rather than large-scale plantation establishment—were recommended for areas subject to temporary forest clearance and selective logging.

Also, the land degradation studies referred to focused on the physical availability of land. The practical land availability can be expected to be limited to lower levels due to political and socioeconomic factors [17] [40]. Land reported to be degraded is often the base of subsistence for the rural population. One example is forest fallows with shortened rotation periods in shifting agriculture owing to population pressure. Reforestation attempts will likely meet strong objection unless advantages to the traditional user are secured. The need to integrate bioenergy production with food/feed production and rural development programs in general are most often acknowledged in the reviewed studies, but the suggested bioenergy yield levels appear to refer to large-scale plantations rather than agroforestry systems for integrated food/bioenergy production.

To sum up, it is not possible to make any clear-cut conclusion regarding the feasibility of the suggested extent and performance of biomass plantations. It is clear however, that the more optimistic suggestions represent ambitious targets regarding total extent of plantations, average yield levels and plantation establishment rate. Indeed, given that the more optimistic suggestions materialize, biomass plantations will become '...a human use of photosynthesis that is comparable in scale to that for agriculture or forestry' [41].

4.2. Utilization of forest wood for energy

The studies take different positions when it comes to defining the basic drivers behind forest biomass extraction. Several studies restrict the energetic use of forest biomass to the utilization of discarded

[16] The results of analyses of food crops are still very uncertain, partly because of uncertainty in climate models. Present knowledge and modeling efforts suggest that climate change will increase yields at high and mid-latitudes and lead to decreases at lower latitudes [30–32].

[17] Nilsson and Schopfhauser [38] estimated for example that 41, 27, and 20 Mha out of 535, 740, and 162 Mha of suitable land in Latin America, Africa, and Asia, could be available for plantations. Trexler and Haugen [39] estimated the land availability for plantations at around 25, 8, and 40 Mha in Latin America, Africa, and Asia, respectively.

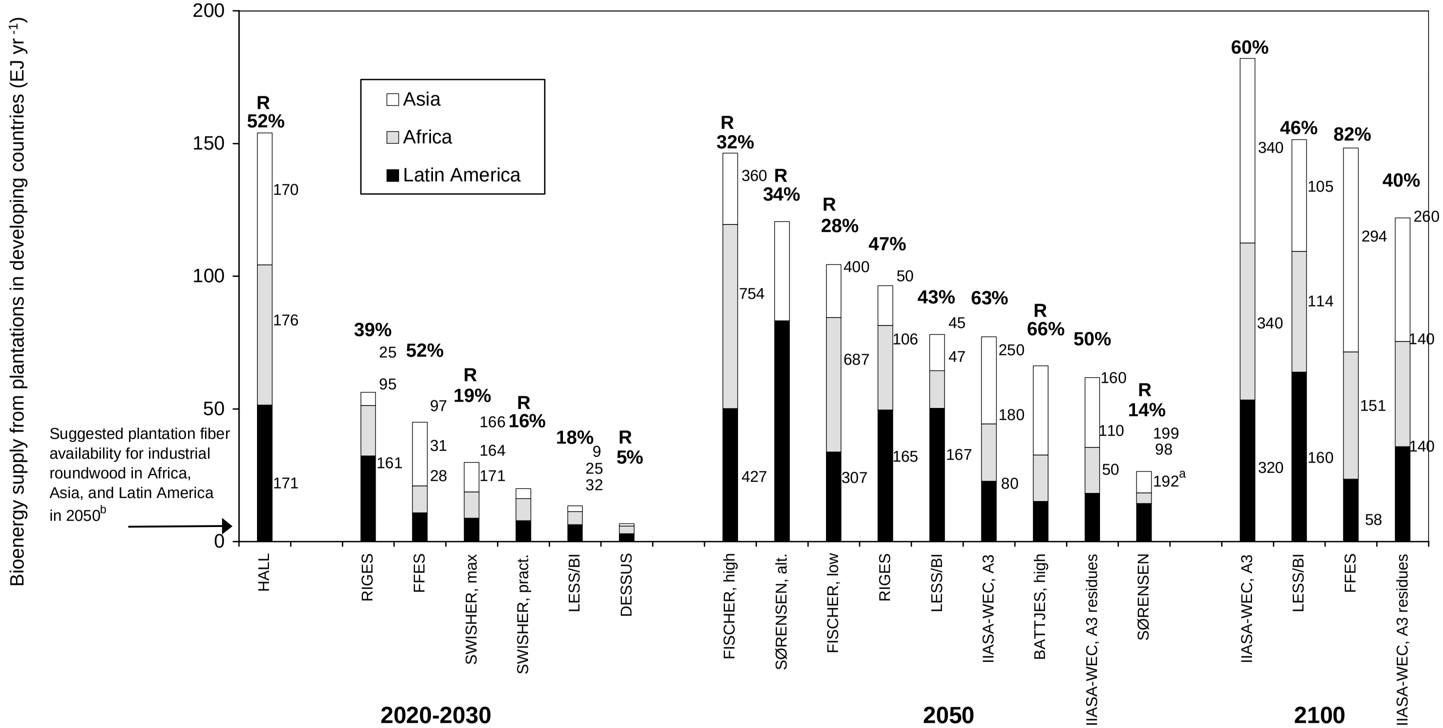

Fig. 7. The production of plantation biomass for energy in developing countries. Studies that are characterized as resource-focused are indicated with R. The percentage data above bars refer to the contribution of the plantations to the total global bioenergy supply. The numbers at the right side of bars are the plantation areas in respective region. Latin America and SE Asia “Tigers” are grouped together in SØRENSEN.

wood-based products, or primary and secondary residues in the forest sector (e.g., felling residues, sawdust and pulping liquors). Thus, the bioenergy demand is assumed to operate together with industrial roundwood demand as a joint driver behind forest biomass extraction, and the forest bioenergy potential is ultimately restricted by the anticipated future industrial roundwood demand. [18]

Three studies (SØRENSEN, FISCHER AND DESSUS) estimated the bioenergy potential of forests based on forest biomass growth rather than forest product demand. Region-specific shares of the total forest biomass growth are estimated to be available for energy uses, based on overall accessibility of forest resources and competition with other uses. These studies report much larger potentials of forests, and forest biomass is even emphasized as the largest source of biomass for energy by SØRENSEN and DESSUS (see Fig. 6).

The estimated wood energy potentials in the three studies are presented in Fig. 8, where also the present industrial roundwood and wood fuel production is given for comparison. It is clear from Fig. 8 that the wood energy potentials correspond to a much larger wood extraction than the present industrial roundwood and wood fuel production. Although the studies use different regionalization, it is also clear that the regional distribution of this wood energy potential is quite different from the present distribution of industrial roundwood and wood fuel production. [19] SØRENSEN refers to biofuels production from forestry residues (wood industry scrap, discarded wooden items and forest management residues). Thus, the forest bioenergy potential in SØRENSEN presumes a dramatic expansion—and regional redistribution—of global industrial roundwood production. DESSUS and FISCHER do not elaborate on how the estimated forest bioenergy potentials would be realized in practice.

4.3. Residue generation and recoverability

It is clear from Fig. 5 that the total amount of residues that are generated in the food and forest sectors is substantial in a global energy context. For example, the ultimate potential of residues in the year 2100 is estimated in GLUE at about 270 EJ yr^{-1}, or three quarters of 1999–2000 global commercial primary energy consumption (oil, natural gas, coal, nuclear energy and hydro electricity).

With the exception of the ultimate potential estimate in the GLUE study and the estimate for dung by FISCHER, the data in Fig. 5 refer to the amount of residues that are estimated to actually be available for energy. The predominant approach in estimating the potential future availability of residues for energy was to combine statistics or projections on food and fiber production with residue multipliers, i.e., factors that account for the amount of residues that is generated per unit primary product delivered. Recoverability fractions were then used to estimate the practical residue potential. Thus, both choice of residue multipliers, recoverability fractions and assumption about the future demand for food and forest products are critical for the bioenergy potential of residues.

FISCHER considers the use of crop residues for animal feeding and also uses decreasing residue multipliers, referring to expected increases in the harvesting index of crops. Otherwise, no study made any comprehensive assessment of residue generation or alternative residue uses (e.g., soil conservation and C sequestration, animal feeding and bedding, and paper/board production) in order to arrive at the residue multipliers and recoverability fractions used. Instead the studies used constant residue multipliers and recoverability fractions over the scenario period, and without differentiation between regions. In addition to the lack of assessment of alternative residue uses, land-use consequences of meeting the future food and forest products demand (and consequently the residue generation in the food and forest sectors) are commonly only roughly outlined. The approaches to

[18] In RIGES and LESS/BI, part of the wood presently used for charcoal and fuelwood is also assumed to be available as a future source of biomass for energy. This bioenergy source, which adds about 10 EJ yr^{-1} to the wood flows associated with industrial roundwood production and processing, is defined by the present fuelwood and charcoal production. It does not grow over time, so the relative importance of this bioenergy source gradually decreases (e.g., in LESS/BI it decreases from about 14 percent of the total biomass supply in 2025 to about 3 percent in 2100).

[19] For example, the estimated wood energy potentials range from 16 to 26 EJ yr^{-1} for Latin America and 17–23 EJ yr^{-1} for Africa, while the 1996 industrial roundwood + fuelwood & charcoal production was about 3.5 and 6 EJ yr^{-1}, respectively.

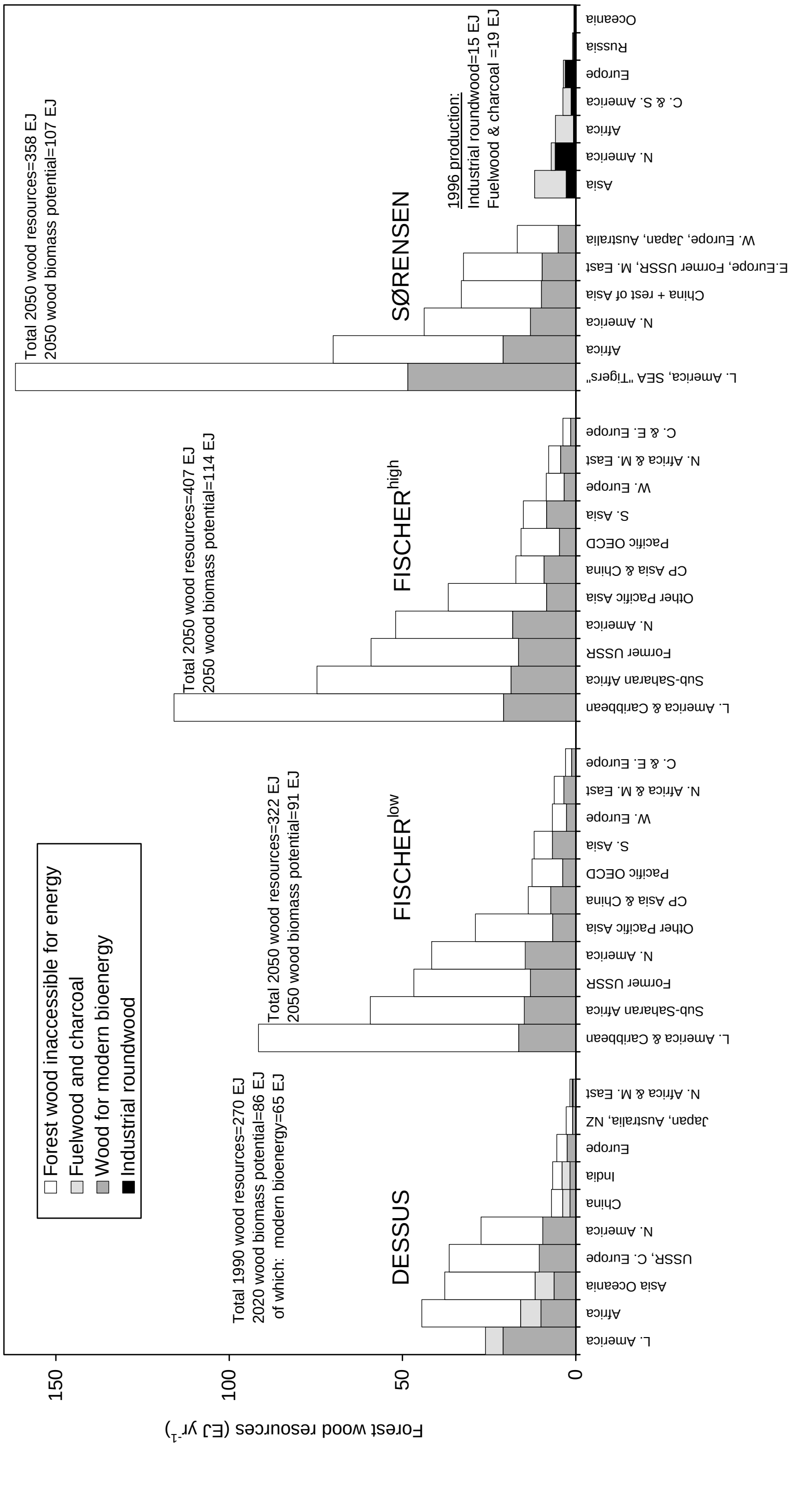

Fig. 8. The estimated bioenergy potential of forest wood. Note that the three studies use different geographic aggregation.

treating future land use in relation to the assessed bioenergy potentials are further discussed in the next section.

4.4. Interactions with other biomass and land uses

Of course, most studies ensure that the presented bioenergy potentials are physically possible and avoid inconsistent land use.[20] However, the development of the food and materials sector is exogenously defined in most studies, and the bioenergy sector evolves in parallel, utilizing residues and land not required for food or materials production. Thus, even though residue flows in the food and materials sectors are guided to bioenergy uses and land is used for energy crops production, the expanding bioenergy sector does by definition not affect the food and materials sector. Consequently, the studies do not provide much insight in how the expanding bioenergy sector will interact with other land uses, and in the socioeconomic consequences of realizing the reported bioenergy potentials. Also, the environmental consequences of large-scale bioenergy supply are not considered in detail. Environmental concerns are emphasized as reason for stated conservative assumptions about the availability of forest wood, residues and land, but it is unclear how such conservative levels were settled.

The IMAGE 2 model that was used in the LESS/IMAGE, BATTJES, and SRES/IMAGE studies, and the AGLU module in MiniCAM 2.0 used by EDMONDS are exceptions. Both models offer possibilities to analyze the interaction between the bioenergy sector and other land uses.[21] However, inter-sectoral competition has not been carefully analyzed in any of these studies. EDMONDS modeled how prices drive land allocation between food and bioenergy crops, but only scenarios in which no CO2-abatement occurred were explored. This means that the energy price does not increase to the point where bioenergy becomes more competitive for land than food. Bioenergy land is 77 percent the size of other cropland in 2095, but the expansion of bioenergy was acknowledged as implying continued pressure on forests and unmanaged ecosystems, rather than competing with food production. LESS/IMAGE found a clear competition for land availability in Africa and some of the Asian regions, while there were no strong competition between food and bioenergy in other regions. Sensitivity analyses also revealed that the energy crop production in the LESS/IMAGE scenario could have far reaching consequences for environmental issues such as deforestation, land degradation and threats to biodiversity.

The findings suggest that closer attention need to be paid to the economics of scarce land resources and the competition for land between food and energy crop production under stringent CO2 control policies.[22] Also, restrictions on bioenergy expansion, other than land claims of the food and forestry sectors, are hardly investigated in the studies. Biodiversity, soil and nature conservation, and carbon sequestration considerations do not imply an explicit land demand.[23] The attractiveness of climate change mitigation options depends on how well they harmonize with other environmental and socioeconomic goals. Future studies should therefore avoid assessing the prospects for bioenergy in isolation, but instead adopt a broader approach where several land-use based mitigation options are treated simultaneously and under consideration of also other environmental and socioeconomic goals.

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[20] The GLUE study is somewhat flawed by the assumption that 756 Mha of degraded land could be converted to arable land by 2100. A close reading of the source behind the 756 Mha estimate [35] suggests that this implies deforestation of 224 Mha selectively logged tropical moist forest and montane forests—although forest protection is postulated in GLUE—and also double counting of land resources—since more than 40 percent of the 756 Mha degraded land is already cropland.

[21] Although, the possibilities to analyze inter-sectoral competition in IMAGE 2.1 is somewhat restricted due to lack of feedback mechanisms from the land use-module to the energy module, and no modeling of competition for residues.

[22] For example, preliminary modeling suggests that with high enough carbon taxes there would be substantial profits in the bioenergy sector and farmers would have incentives to cultivate energy crops rather than food [42]. Under such conditions bioenergy plantations might successfully compete for scarce land resources in several regions of the world. Such competition might induce increasing food prices, with mixed socioeconomic consequences; e.g., farmers might benefit whereas poor urban populations might suffer.

[23] The land allocation approach in EDMONDS involves the possibility to withhold land from exploitation for biomass harvest, but no land was assigned to this protected category in the analysis.

5. Conclusions and discussion

It can be concluded from the demand-driven studies that bioenergy demand may increase to several hundred exajoules per year in the future. It can also be concluded that the bioenergy demand is sensitive not only to biomass supply potentials, but also to total energy demand and competitiveness of alternative energy supply options. At the same time, the reviewed resource-focused studies have arrived at widely different conclusions about how much biomass that can be made available for energy in the future. For example, the highest estimate for the year 2050 is 9 times larger than the lowest estimate. To some extent the difference can be explained by the exclusion of potentially major biomass sources in the lowest estimate, but the major reason for the divergence among the studies is that the two most crucial parameters, land availability and yield levels in energy crop production, are very uncertain. For example, the biomass supply from plantations in 2050 ranges from 47 to 238 EJ yr^{-1}.

The conclusions about future availability of forest wood and of residues from agriculture and forestry also vary substantially among the studies. Especially, the use of forest wood has been identified as a potentially major source of biomass for energy in several studies (up to about 115 EJ yr^{-1} in 2050). Other studies have on the other hand presented a less prominent role of forest wood in supplying biomass for energy. Here, the divergence can be explained by different approaches to estimating the bioenergy potential of forest wood: the lower end estimates restrict the bioenergy potential to certain shares of the wood flows in the forest sector (and thus to the future forest product demand), while the higher end estimates does not make such restrictions.

The studies have illustrated what a future large-scale bioenergy supply (several hundred exajoules per year) could look like. They have also shown that such a supply is indeed technically feasible. However, based on this review, it is not possible to establish whether such a large-scale biomass supply for energy is an attractive option for climate change mitigation in the energy sector. There are two main reasons for this:

First, the studies do not provide much insight into how the expanding bioenergy sector will interact with other land uses. Development of the food and materials sector is exogenously defined in most studies. The bioenergy sector evolves in parallel and does not affect the food and materials sector. It is therefore not possible to conclude much about the socioeconomic consequences of a global large-scale expansion of biomass use for energy.

Second, the environmental consequences of a realization of the assessed bioenergy potentials are insufficiently analyzed. It is therefore unclear to what extent the assessed potentials harmonize with other environmental goals such as biodiversity and nature conservation.

Integrated land-use/energy-economy models such as the IMAGE and MiniCAM models stand out as most suitable for a more comprehensive assessment of the prospects for biomass in a future sustainable global energy supply. The LESS/IMAGE study also provides some insights into the potential environmental and socioeconomic consequences of a global large-scale bioenergy supply. However, these issues need more attention in future studies. Biodiversity, soil and nature conservation, and carbon sequestration considerations need to be parameterized and integrated into modeling frameworks as competing uses of residues, land, water, and other resources.

A closer consideration of the issues discussed above need not necessarily result in reduced bioenergy potentials. It may well be that earlier assessments have been over-cautious when considering restrictions (e.g., on yield levels and availability of residues) that they have had insufficient information about. Regardless of the outcome, a refined modeling of interactions between biodiversity, soil and nature conservation and bioenergy, food and materials production—i.e., of competition for resources, and of synergies between different uses—would facilitate an improved understanding of the prospects for large-scale bioenergy and of future land-use and biomass management in general.

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Appendix A.

Table 3 gives an overview of the various bioenergy sources considered in the reviewed studies. All studies focused on terrestrial biomass sources for energy. Aquatic biomass was not considered in any study. Few of the studies consider all biomass flows as potentially available for energy use. In some cases, exclusion of certain bioenergy sources is explicitly motivated (e.g., municipal waste is excluded in FFES, with reference to concerns about toxic emissions from incinerators and insistence on material reuse and reduction policies). In other studies bioenergy sources are excluded without motivation.

Table 4 provides information about bioenergy plantation area and yield levels in the reviewed studies, and how those were estimated. Studies that used geographically explicit modeling obtained yield levels as a function of model parameters influencing productivity (e.g., soil type, climate, agronomic practice) anddistribution of energy crop production over suitable areas. The other studies made assumptions about yield levels based on present experience in fiber and energy crop production, and on projected yield increases over time.

Availability of land for energy crop production was estimated differently among the studies. Some studies did not assess land availability as input in the modeling. Instead, land requirement for bioenergy was calculated based on assumptions about total bioenergy demand, plantation contribution, and yield levels in energy crops production. Several studies suggested that a certain share of present crop-, grass-, and/or forest land could be used for energy crop production. In many studies, surplus cropland in industrialized countries and degraded land in developing countries are suggested to be targeted for bioenergy plantations.

The approaches to assessing the bioenergy potential of biomass flows in the food and forest sectors are presented in Table 5. The predominant approach was to combine statistics or projections on future food and fiber production with residue multipliers, i.e., factors that account for the amount of residues that are generated per unit primary product delivered. Recoverability fractions were then used to estimate the practical residue potential. Three studies (SØRENSEN, FISCHER, DESSUS) estimated the bioenergy potential of forests based on the estimated forest biomass growth instead of forest product demand. Specific shares of the total growth are estimated to be available for energy, based on overall accessibility of forest resources and competition with other uses.

Table 3
Overview of various bioenergy sources, and their inclusion in the reviewed studies[a]

	Energy crops	Primary residues		Secondary residues			Tertiary residues		Non-residue forest biomass	Unspecified forest biomass	Unspecified biomass
	1	2	3	4	5	6	7	8	9	10	11
WEC	X										X
IIASA-WEC	X										X
FFES	X										X
EDMONDS	X										X
SWISHER	X	X	X	X	X	X					
USEPA	X										

Table 3
(*continued*)

	Energy crops	Primary residues		Secondary residues			Tertiary residues		Non-residue forest biomass	Unspecified forest biomass	Unspecified biomass
SØRENSEN[b]	X	(X)	(X)	(X)	(X)	(X)	(X)	(X)		(X)	
HALL	X	X	X	X	X	X					
RIGES	X	X	X	X	X	X	(X)[c]	(X)[c]	X[d]		
LESS/BI	X	X	X	X	X	X	(X)[c]	(X)[c]	X[d]		
LESS/IMAGE[e]	X	(X)	(X)	(X)	(X)	(X)	(X)	(X)	(X)		
BATTJES	X										
GLUE	X	X	X	X	X	X	X	X			
FISCHER	X	X				X		X		X	
DESSUS	X	X				X	(X)	(X)		X	
SHELL[f]											
SRES/IMAGE	X										

[a] 1 = energy crops; 2 = agricultural crop harvest residues; 3 = forest residues from silvicultural treatments and fellings; 4 = food processing residues; 5 = wood and other fiber processing residues; 6 = animal dung; 7 = non-eaten food, faeces and urine; 8 = non-food organic waste.

[b] Several residue types are mentioned as potentially available for energy, but they are not assessed explicitly. Instead, the potential of residues is calculated as certain shares of estimated energy flows in the food and forest sectors. In an alternative estimate, energy crops and selected food sector residues (2, 6, 7) are explicitly assessed. The bioenergy potential of forest sector residues are estimated based on residue factors in HALL and assuming the per capita industrial roundwood production in 1989 prevails in 2050. See also Table 5.

[c] Categories 7 and 8 are implicitly considered via inclusion of urban refuse.

[d] Biomass presently harvested for fuelwood and charcoal production is assumed to be available for modern bioenergy as the "traditional" uses are phased out.

[e] Bioenergy sources other than energy crops are assumed to be readily available at volumes given in LESS/BI. See also Table 5.

[f] No documentation.

Table 4
Bioenergy yield levels and extent of land used for energy, with description of how yields and areas were estimated in the reviewed studies[a]

	Plantation area (Mha)	Comment	Global average yield levels ($Mg\ ha^{-1}\ yr^{-1}$)	Comment
WEC		Illustrative calculations are presented to show that there is enough land to provide the bioenergy. Focus on surplus cropland in industrialized countries, while various land types are considered in developing countries. Reference to studies of David Hall, including HALL reviewed in this paper.		Various yield levels (e.g., 150 $GJ\ ha^{-1}\ yr^{-1}$ on surplus cropland in industrialized countries and 30–300 $GJ\ ha^{-1}\ yr^{-1}$ in developing countries depending on soil and climatic conditions.) are discussed and used in the assessment of possibilities of providing the biomass used for energy in the scenario.
IIASA-WEC Scenarios	A 2050: 390/610 2100: 690/1350	Land demand calculated based on total bioenergy demand, share supplied from plantations and specified yields. Land demand is then compared with estimates of future surplus land [1] in a post-scenario feasibility check.	2050: 12.6/8.4 2100: 21/12.6	Yield levels taken from LESS/BI.

Table 4
(*continued*)

	Plantation area (Mha)	Comment	Global average yield levels (Mg ha^{-1} yr^{-1})	Comment
FFES	2030: 158/384 2100: 326/721	Land use for plantations results from biomass demand for energy and regional yield levels used. Indicates degraded tropical land might be targeted. Refers to land availability estimates of David Hall and also to DESSUS and USEPA.	2030: 23.4/11.7 2100: 24.4/12.2	Regional yields calculated based on distribution of bioenergy land over three land types with specified yields: 10 Mg DM ha^{-1} yr^{-1} in temperate regions; 20 Mg in moist/irrigated tropical regions, and 4 Mg in semi-arid tropical regions. Yield levels stated to be conservative so as to consider possible water, nutrient and ecological restrictions on very high yield levels. The doubled yield level is introduced to illustrate the potential decrease in land use requirements given productivity improvements.
EDMONDS	2025: 350 2050: 570 2095: 740	Land allocation among competing uses, including biomass production for energy, is obtained as model outputs from land use module AGLU (a dynamic market equilibrium model).	1990: 6 2095: 10	Output of land-use module. In the version used, all variables affecting productivity other than technology (climate, conc. of atm. CO_2, fertilizer application) are kept constant at their initial values. Technology change is exogenously defined.
SWISHER	2030: 870 (Max)	Basic assumption: 10% of global crop, forest and woodland area (based on David Hall). Adjusted to larger areas in USA and the Nordic countries with reference to case studies. Marginal land in developing countries assumed to be targeted. Practical Potential estimate adopts DESSUS estimate for energy crops.	2030: 6 (Max)	8 and 4 Mg DM ha^{-1} yr^{-1} in industrialized and developing countries respectively. Based David Hall.
USEPA	(No year): 556	10% of global crop, forest and woodland area.	(No year) Low: 30 Medium: 46 High: 61	Low: 25 and 49; Medium: 37 and 74; and High: 49 and 99 Mg ha^{-1} yr^{-1} in temperate and tropical regions respectively. Yield levels calculated based on specified yield increase rates.
SØRENSEN	2050: 752	10% of cropland in regions expected to have surplus cropland (Americas, W. Europe, Japan, Australia, SE Asian "Tigers"). 50% of rangeland in all regions.	2050: About 3 (54 GJ ha^{-1} yr^{-1})	Region-specific yields correspond to specified shares (0.16–0.4) of simulated productivity of mature natural ecosystems in areas assumed to be used for energy crops production.
HALL	(No year): 890	Assumes 10% of global crop, forest and woodland areas are used for bioenergy plantations. Refers to FAO estimates of extent of non-used potential cropland, and shows that such areas will be available both for the bioenergy plantations	(No year): 15	Various yield levels are discussed as a basis for suggesting one uniform yield level for all regions. Draws on both fundamental aspects of photosynthesis and biomass productivity, and on experience with agricultural

Table 4
(*continued*)

	Plantation area (Mha)	Comment	Global average yield levels (Mg ha^{-1} yr^{-1})	Comment
		and expanded cropland for increased food supply. Refers also to estimates of the extent of surplus cropland in industrialized countries and of degraded land in developing countries that are suitable for reforestation.		crops, field trails of plantation crops, and to some extent large-scale plantations.
RIGES	2025: 369 2050: 429	Degraded land in developing countries, and excess cropland in industrialized countries.	2025: 10.8 2050: 14.9	Based on HALL, but uses two different yield levels. 2025: 15 Mg ha^{-1} yr^{-1} in USA and OECD Europe and 10 Mg ha^{-1} yr^{-1} in the rest of the world. 2050: 15 Mg ha^{-1} yr^{-1} in all regions but Canada where yield level is assumed to be 10 Mg ha^{-1} yr^{-1}.
LESS/BI	2025: 83 2050: 385 2100: 572	See RIGES.	2025: 10.2 2050: 15 2100: 20	As in RIGES, with the exception that the average yield in Canada is 15 Mg ha^{-1} yr^{-1} from 2025 to 2100. From 2075, all regions except Canada have an average yield at 20 Mg ha^{-1} yr^{-1}.
LESS/IMAGE	2025: 191 2050: 448 2100: 797	In IMAGE 2, demand for biomass from plantations is determined in an Energy/Industry system model and entered into an agricultural economy model, where the demand is automatically satisfied. There is no feedback mechanism that limits the bioenergy use on the basis of land availability. Future changes in land use and land cover are computed based on demand for food, feed, timber, and biofuels. If abundant productive land is available both food and bioenergy crops occur on these lands. If not, bioenergy crops are driven towards the more marginal land (where food crops cannot be produced), often replacing pasture. In this specific study, demand for biomass from plantations is exogenously set to be identical to LESS/BI.	2025: 4.6 2050: 12.75 2100: 14.25	Output of land-use model. Yield levels obtained as a function of model parameters influencing productivity (e.g., soil type, climate, agronomic practice) and distribution of energy crop production over suitable areas.
BATTJES	2050: 185/395	Set aside land, with addition of 10% of agricultural area in developing regions in the high estimate.		See LESS/IMAGE.

Table 4
(*continued*)

	Plantation area (Mha)	Comment	Global average yield levels ($Mg\ ha^{-1}\ yr^{-1}$)	Comment
GLUE		Arable land is used for energy crops to the extent that such is available after land allocation for cereal production (for use in the region and export to other regions). 68 Mha of fallow land in developed regions is assumed to be converted to arable land by 2025. In developing countries, 30% of deforestation area is diverted to arable land (no year specified), and 756 Mha of degraded land is converted to arable land by 2100.		Based on IMAGE 2.0 Conventional Wisdom Scenario, the crop productivity in developed regions is assumed to increase to 1.74 and 1.77 times the 1990 level in 2050 and 2100 respectively. In developing regions, the crop productivity increases to 2.19 and 2.49 times the 1990 level in 2050 and 2100 respectively.
FISCHER	2050: 2165/2388	Grassland. Estimates are consistent with land use changes in a global scenario of agricultural development up to 2050 (IIASA's Basic Linked System of Models, a business-as-usual global agricultural scenario of overall economic and agricultural development).	2050: 3.8/4.8	Yields for the year 1990 were estimated using FAO's agro-ecological zones methodology. It was then assumed that the bioenergy potential of grasslands will grow up to 2050 at rates similar to those of agricultural productivity (low and high estimate at 0.8 and 1.25%, respectively).
DESSUS		Depends on population density. Max 10% of cultivated land in areas where density is low		Based on recorded productivity of sugarcane and short rotation bushes.
SHELL		Not documented.		Not documented.
SRES/IMAGE		See LESS/IMAGE.		See LESS/IMAGE.

[a]Not all studies report plantation areas/yield levels explicitly. Several studies provide more than one area and/or yield estimate. E.g., for the IIASA-WEC A scenarios year 2050, two plantation areas and yield levels are given: 390/610 Mha and 12.6/8.4 $Mg\ ha^{-1}\ yr^{-1}$, respectively. Then, the average yield level is 12.6 $Mg\ ha^{-1}\ yr^{-1}$ on 390 Mha, alternatively 8.4 $Mg\ ha^{-1}\ yr^{-1}$ on 610 Mha.

Table 5
Approaches to assessing the bioenergy potential of biomass flows in the food and forest sectors

	Approach to assessing the bioenergy potential of biomass flows in the food sector	Approach to assessing the bioenergy potential of biomass flows in the forest sector
WEC		
IIASA-WEC A Scenarios	No own estimate. Reference to LESS/BI.	No own estimate. Reference to LESS/BI.
FFES	No own estimate. Reference to studies of David Hall who produced HALL.	No own estimate. Reference to studies of David Hall who produced HALL.
EDMONDS	Crop residues are assumed to be available up to a maximum share, at a cost rising linearly up to the full harvest of residues. Maximum share not presented.	

Table 5
(*continued*)

	Approach to assessing the bioenergy potential of biomass flows in the food sector	Approach to assessing the bioenergy potential of biomass flows in the forest sector
SWISHER	No own estimate. Reference to studies of David Hall who produced HALL	
USEPA	Does not include residues in the assessment.	
SØRENSEN	Availability of vegetable residues in the food sector is set to 25% of vegetable food produced in all regions. It is assumed that animals being fed fodder from crops will be in situations where collection of manure is feasible. Available energy in manure, combined with slaughterhouse wastes, is assumed to equal 51% of the energy in fodder fed to animals.	Thirty percent of the total forest biomass production in all forests in the world is assumed to be used for bioenergy. The estimated potential is assumed to be realized within using residues and forest products. Emphasizes that rainforests and other preservation-worthy forest areas are not suggested to be touched, but that more than 30% should instead be possible to use for energy in other regions.
HALL	25% of all residues generated in production of cereals, vegetables and melons, roots and tubers, and sugar beets are assumed to be available for energy. For sugar cane, all bagasse and 25% of tops and leaves are assumed to be available. 12.5% of estimated global dung generation is assumed to be available.	75% of milling and manufacturing wood wastes (set equal to the amount of wood in final products) and 25% of forest residues (set to 40% of total biomass cut when trees are harvested) are assumed to be available.
RIGES	25% of all cereal residues are assumed to be available for energy. For sugar cane, all bagasse and 66% of tops and leaves are assumed to be available. 25% of global dung production is assumed to be available. More food sector wastes are implicitly considered available via the assumption that 75% of the energy in urban waste in OECD countries is used for energy	75% of mill residues and 50% of forest residues associated with industrial roundwood production are assumed to be available. Based on data for USA in the late 1970s, mill+forest residues is set to equal 65% of industrial roundwood production for all regions. It is also assumed that roundwood production for fuelwood and charcoal generates residues with availability set to equal 32% of roundwood produced for fuelwood and charcoal. During 2025–2050, roundwood production for "traditional" applications such as cooking is assumed to be largely phased out, and 75% of the 1985 production level is instead used for modern bioenergy.
LESS/BI	See RIGES.	See RIGES.
LESS/IMAGE	Since the purpose was to perform an alternative estimate of the land use consequences of the plantation biomass supply in LESS/BI, it was assumed that other biomass sources such as residues was just readily available.	See food sector approach.
BATTJES	Does not include residues in the assessment.	Does not include residues in the assessment.
GLUE	The "Ultimate bioenergy potential" includes all forms of biomass residues except material-recycled portions of forest sector residues. Residue volumes estimated using residue factors, based on RIGES and other sources. The "Practical bioenergy potential" is estimated by using recoverability fractions, reflecting what is considered the realistic maximum rates of energy use of biomass residues.	See food sector approach.

Table 5
(*continued*)

	Approach to assessing the bioenergy potential of biomass flows in the food sector	Approach to assessing the bioenergy potential of biomass flows in the forest sector
FISCHER	Based on a BAU scenario of overall economic and agricultural development. Dynamic, region-specific crop residue factors and availability fractions are used. Bioenergy potential of animal waste is defined as the non-digestible part of animal-feed inputs.	Regional wood energy yield per hectare calculated based on 1990-data from DESSUS. High and low wood energy yields for 2050 were then estimated based on 1.25% and 0.8% annual growth rates of wood yields from 1990 to 2050. Referred to "...the sustainable use of forest products...", but did not present any information regarding the implications of this concept for forest wood availability.
DESSUS	Residue multipliers and recoverability fractions for the major agricultural products are combined with production data. Urban waste is considered available for energy, and the per capita urban waste generation in developing countries is assumed to be 60% of the 1990 level in Europe.	Based on estimates of area and average productivity of specific forest types in different world regions. Regional wood energy reserves were defined as specific shares (50–70 percent) of regional forest wood production. The bioenergy potential was then estimated from assumptions about accessibility (25–80 percent) of the wood energy reserve.
SHELL	Not documented.	Not documented.
SRES/IMAGE	The use of residues for energy is not included as an option in the IMAGE 2 model.	See food sector approach.

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