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Guest Editors: Ben W.-L. Jang, Roger Gläser, Chang-jun Liu and Mingdong Dong

Bioenergy revisited: Key factors in global potentials of bioenergy

Veronika Dornburg,[a] Detlef van Vuuren,[d] Gerrie van de Ven,[b] Hans Langeveld,[b] Marieke Meeusen,[c] Martin Banse,[c] Mark van Oorschot,[d] Jan Ros,[d] Gert Jan van den Born,[d] Harry Aiking,[e] Marc Londo,[f] Hamid Mozaffarian,[f] Pita Verweij,[a] Erik Lysen[g] and André Faaij†*[a]

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The growing use of bioenergy goes hand in hand with a heated public debate, in which conflicting claims are made regarding the amount of biomass that can be sustainably used for this purpose. This article assesses the current knowledge on biomass resource potentials and interrelated factors such as water availability, biodiversity, food demand, energy demand and agricultural commodity markets. A sensitivity analysis of the available information narrows the range of biomass potentials from 0–1500 EJ/yr to approximately 200–500 EJ/yr in 2050. In determining the latter range, water limitations, biodiversity protection and food demand are taken into consideration. Key factors are agricultural efficiency and crop choice. In principle, global biomass potentials could meet up to one third of the projected global energy demand in 2050.

Introduction

The increasing use of biomass for energy—in particular, the use of biofuels—goes hand in hand with a heated public debate, in which conflicting claims are made regarding the sustainability of such practices. In this debate, the growing concerns about the future growth of biofuel use are roughly of the same order of magnitude as the perceived advantages. For example, it is claimed that biofuels will lead to famine, deplete water resources and destroy biodiversity and soils.[1] Biofuels are often regarded as the cause of the dramatic increases in food prices that have occurred over the past few years. Also, the use of palm oil—of which some 1.5% of the total amount produced in 2007 was used to make biodiesel and generate electricity—is indicated as a key factor in the loss of tropical rainforest in South East Asia, where palm oil production is concentrated. However, biomass is expected to play a major role as a renewable energy carrier in the next few decades, as indicated by a wide variety of policy strategies and scenario studies that address future energy supply and the reduction of greenhouse gas emissions.[2–4]

The current global energy supply is dominated by fossil fuels, which account for approximately 500 EJ per year, while biomass contributes approximately 50 EJ, making it by far the most important renewable energy source.[5] Most of this biomass (70–80%) is used for traditional non-commercial use. Modern bioenergy—that is, large-scale commercial use of biomass for power generation, industrial applications and transportation fuels—is

Broader context

The role of biomass as a sustainable source for energy and materials has been heavily debated in recent years. In 2008, when food prices peaked (just as oil and many other commodities), biofuels were blamed for starving the poor, disturbing markets, making unsustainable use of land and water and, especially due to indirect land use change, resulting in poor or even negative greenhouse gas (GHG) balances. In the meantime a large amount of literature has been produced providing pieces of insight in various fields, but integral analyses on the matter are scarce. This article provides an extensive assessment of what we know and do not know about the possibilities to realize a sustainable resource base for biobased energy carriers and materials. The work looked at energy potentials in conjunction with key factors affecting its sustainability (biodiversity, water, competition with the food production system, soil quality and energy demand) and deployed integrated assessment modelling plus a detailed evaluation of uncertainties. Biomass energy potentials are found to range between 200–500 EJ/yr in 2050. Crucial in these figures is that water limitations, biodiversity protection and food demand are taken into consideration. Improvements of agricultural efficiency and crop choice (especially perennial cropping systems offer the best perspectives) are essential preconditions to reach the higher end of the range.

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[a] *Copernicus Institute, Utrecht University, 3584 CS Utrecht, The Netherlands. E-mail: a.p.c.faaij@uu.nl; Fax: +31 30 2537601; Tel: +31 30 2537643*
[b] *Plant Production Systems, Department of plant Sciences, Wageningen University, 6700 AK Wageningen, Netherlands*
[c] *Agricultural Economics Research Institute LEI - Wageningen University, 2502 LS Den Haag, The Netherlands*
[d] *Netherlands Environment Assessment Agency, 3720 AH Bilthoven, The Netherlands*
[e] *Institute for Environmental Studies, VU University Amsterdam, 1081 HV Amsterdam, The Netherlands*
[f] *Energy Research Centre of the Netherlands, 1755 ZG Petten, The Netherlands*
[g] *Utrecht Centre for Energy Research, Utrecht University, 3584 CS Utrecht, The Netherlands*

† Author contributions: All authors designed research, performed research and wrote the paper.

still growing. In 2007, biomass contributed approximately 6.4 EJ/yr to power generation and industrial applications, and approximately 2.6 EJ/yr to transportation fuels.

One of the main drivers for biomass use is to reduce greenhouse gas (GHG) emissions. Although most biomass chains do have the net effect of reducing GHG emissions, the overall GHG balance depends on the crops used, the agricultural management (*e.g.* application of fertiliser), the co-products, the type of biomass used for energy, the land-use changes that may be involved, and the fossil energy reference system that is replaced by the use of biomass for energy.[6–9] Where land use for biomass leads to land conversion and loss of considerable carbon stocks in soils or above-ground biomass, the use of biomass for energy often leads to net GHG emissions. Searchinger *et al.*[10] demonstrated that indirect land-use changes—that is, moving existing agricultural production to other areas—can similarly result in a 'negative GHG balance' due to bioenergy use. For example, Wicke *et al.* and Reinhardt *et al.*[11,12] have shown that the GHG emission balance of palm oil production and use can be negative where the production involves conversion of forests and/or peatlands, whereas balances can be positive in other land-use cases.

The potential amount of biomass for energy production mainly depends on land availability. In determining the total area of land available, it is essential to consider the growing worldwide demand for food that needs to be met, as well as a wide range of sustainability requirements, including the economic feasibility of biomass production, sustainable management of soils and water reserves, and protection of the environment. To guarantee sustainable production, a variety of certification schemes for biomass production for energy are currently under discussion.[13] Although the available studies give valuable insights into biomass potentials, limited progress has been made in integrating the various scientific fields pertinent to such potentials that the studies encompass. One reason for this lack of integration is that the relationships between the issues are manifold and complex (see Fig. 1).

This article discusses the possible future role of bioenergy and the main uncertainties on the basis of a knowledge assessment and uncertainty modelling.[14] The first section of this article summarises a broad assessment of the knowledge relevant to biomass resource potentials and interrelated areas such as water resources, biodiversity, food demand and production, energy demand and agricultural commodity markets. The next section presents an integrated modelling of the sensitivities. On the basis of the knowledge assessment and the uncertainty modelling, uncertainties and necessary future analyses are then discussed in the following section. Finally, conclusions on the possible future role of bioenergy and the main uncertainties are drawn.

Review of key areas

Biomass potentials

Earlier analyses of biomass potential studies have shown large ranges of energy potentials. These ranges are due to differences in methodologies, as well as assumptions on crop yields and available land.[15] Recent biomass potential studies show a similar picture: the reported biomass supply potentials differ widely as a result of the diverse scenarios considered and methodologies used.[16–23] For example, the highest global biomass potential projected for the year 2050—that is, 1500 EJ—is based upon an intensive, technologically highly developed agricultural system and represents the highest possible technical potential, assuming

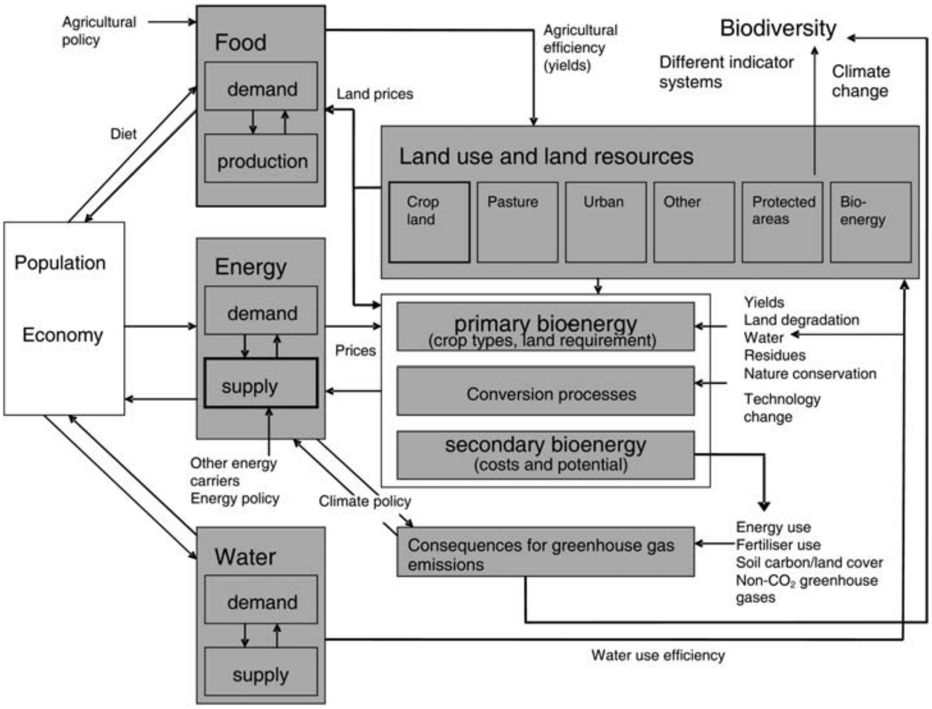

Fig. 1 Overview of key factors affecting potential bioenergy supply.

that food demand is met and nature and forests are protected.[22] In stark contrast, the most pessimistic scenario, assuming high population growth, high food demand and low yielding low-input agricultural production systems, indicates zero potential for energy crops in 2050.[23]‡ Regarding economic potential, the quantity of energy crops that will be available in 2050 at prices below 2 €/GJ (roughly equal to the current price of coal on the world market) has been estimated to be approximately 30–40% lower than the overall technical potentials.[18] In addition to the potential amount of energy crops, residues from forestry and agriculture, secondary residues from processing and tertiary residues from waste are likely to be available. These are estimated by Smeets *et al.*[22] to be approximately 80–100 EJ/yr and by Hoogwijk *et al.*[25] to be approximately 30–180 EJ/yr, assuming that approximately 75% of biomaterials are available as tertiary waste. An estimated 60–100 EJ/yr of surplus forestry could also be available.[22]

To date, none of the biomass potential studies that are covered in this assessment consider the whole range of factors and relationships as presented in Fig. 1. One important factor is whether—and which—degraded and marginal land areas can be used for biomass production. Other issues that, generally, are not considered in sufficient detail are: competition with other sectors for water resources; human dietary trends; development of alternative protein chains and alternative animal production systems; the impact of large-scale biomass production on land use, agricultural commodity prices and agricultural productivity; and the incorporation of specific biodiversity objectives.

Biomass demand

For the purpose of this article, six global and three European studies modelling future energy supply were reviewed.[26–32] In these studies, the scenarios that focus on strong GHG emission reduction show a higher biomass demand than the corresponding reference scenarios that assume a business-as-usual development. The biomass applications indicated by these modelling exercises show a broad range and depend on the extent to which alternative technologies (*e.g.* the hydrogen fuel cell, and carbon capture and storage) are developed. In the year 2050, it is estimated that the global demand for biomass will be between 50 and 250 EJ. Interestingly, the bioenergy demand estimates are generally lower than most supply estimates, mainly due to the competition of bioenergy with other energy sources. This is especially true of bioenergy for power generation. These findings are confirmed by the recent Fourth Assessment Report of the IPCC.[33] Wood and fibre products are the biomaterials that are currently produced in the largest quantities, and in biomass potential studies the demand for wood products is subtracted from the future biomass potentials. Bio-based chemicals and other biomaterials might add significantly to the growing biomass demand, yet they are not usually included in biomass potential or demand estimates. The potential demand for chemicals is, however, much lower than the demand for bioenergy.[34]

In general, these studies have three shortcomings: firstly, the use of biomass as feedstock is hardly elaborated in the models considered; secondly, most of the studies assume relatively constant biomass costs; and, thirdly, the level of detail of technological learning remains ill-defined. The first issue tends to give a higher expected demand for biomass, the second a lower demand, and the third can influence demand in both directions, depending on the learning rates assumed for specific technologies.

Biodiversity effects

Several publications that evaluate the biodiversity effects of crop production for bioenergy give diverse and sometimes even conflicting results.[35–41] This can partly be explained by the various time horizons, spatial resolution and biodiversity indicators used. Most of these publications do not explicitly define their concepts of biodiversity, which range from ‘naturalness’ (*i.e.* the resemblance to a natural ecosystem) to ‘agro-biodiversity’ (*i.e.* the variety of species used in agriculture).

Bioenergy production leads to various trade-offs on biodiversity. At the local level, biodiversity effects depend on crop choice, agricultural management, former land use, and spatial planning. Local biodiversity may benefit from the growing of biomass; for example, when intensive agricultural practices are replaced by low-intensity biomass production systems. In general, mixed cropping systems and perennial woody and herbaceous crops do better than annual agricultural crops at the local level.[42] At the global level, agricultural lands may only become available for biomass production when food production shifts to other areas. Such shifting is likely to lead to biodiversity losses due to changes in land cover; for example, as a result of deforestation.[43] Thus, short-term global biodiversity effects are intimately related to global land-use dynamics. In the long term, biomass production is expected to contribute to a reduction of GHG emissions and, therefore, to a reduction of the effects of climate change on biodiversity. The balance of effects has been analysed in a scenario study in which the ambitious target of mitigating climate change by limiting CO_{2eq} concentration to 450 ppm is met by using mainly woody biomass for large-scale bioenergy production. In this scenario, the ‘positive’ effect is that biodiversity, as indicated by ‘mean species abundance’, would decrease by 10% between 2000 and 2050, compared with 11% in the baseline scenario.[44] However, the overall balance of effects depends on the assumptions on agricultural productivity and expansion.

Water availability and use

Projected industrial and household water use ranges between remaining more or less constant and increasing by 60 to 220% in the period up to the year 2025.[45,46] In the period up to the year 2050, estimates of agricultural water withdrawal range from a moderate increase of 21% to a massive increase of 70–90%, depending on population growth, human dietary trends and agricultural input levels.[47,48] Energy crops are not considered explicitly in most available studies. Berndes[49] shows that

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‡ Also in an assessment by the German Advisory Council on Global Change that assumes a very limited availability of land due to nature protection and high food consumptions with at the same time very low crop yields, only about 70 EJ from residues and about 40 EJ from energy crops are estimated to be available.[24]

large-scale global energy crop production would lead to an increase in evapotranspiration that is comparable to the current evapotranspiration from global cropland. The general trend is decreasing availability of water in most regions, with the largest effects in those regions where water is already scarce. Total ground and surface water requirements and availability, including the environmental water requirements, are shown in a map of water stress, which indicates that on approximately 15% of the total global land, water resources are currently overexploited, with use exceeding availability.[50]

Climate change will increase the variability of rainfall patterns, while increasing temperatures will enhance water transpiration and evaporation. The net effect is difficult to predict, and large regional variations of the net effect can be expected. In particular, semi-arid and arid areas are expected to face reduced water availability.[51,52] Another key factor is the possibility of improving the overall water use efficiency in agriculture and thus increasing the biomass potentials. As water use efficiency depends on many variables, including crop choice, climate, and agricultural management, an analysis at regional-to-local level is needed to further evaluate this possibility. For example, water use efficiencies in g biomass per kg of water are approximately 1.7–2.2 for wheat, 2.5–3.8 for sugar beet, 4.0–6.4 for sugar cane and 1.0–9.5 for lignocellulosic crops.[48]

From the reviewed studies it can be concluded that in some regions the abundance of water provides ample opportunities for energy crop production, whereas in other regions the scarcity of water seriously restricts opportunities for energy crops. However, comparison of the various analyses reveals that they used a coarser spatial resolution than what is required in order to draw reliable conclusions. The large variability in regional climate and hydrology necessitates detailed analysis of the biophysical possibilities for crop production. If the interaction between upstream and downstream water availability and use is to be taken into account, water availability for energy crop production should be determined at the water-basin scale. To date, there have only been incidental studies at this resolution.

Food demand and production

Food production strongly depends on future developments in agricultural technology and economic growth.[22,53] The available literature confirms that producing sufficient food—even for 10 billion people—seems feasible provided that crop yields can be further improved by enhanced crop management and/or genetic modifications.[54,55]

All scenarios that predict global biomass potentials use food demand projections compiled by the FAO.[56] The range of projected demand is wide, as it depends on global population growth and dietary trends. These projections are the best available, though the descriptive data is crude. The estimated reduction of bioenergy potentials from a ‘low’ to ‘high’ food demand scenario as defined in Smeets *et al.*[17] and Hoogwijk *et al.*[22] is about 130–170 EJ/yr. This is due to changing assumptions from an assumed global population of 9 billion to 11 billion and from a ‘low demand’ dietary trend to a ‘high demand’ dietary trend from the FAO projections.

The largest uncertainties with regard to food demand are consumer preferences and the possibility of using alternative protein supply chains. One life-cycle assessment has shown that a transition from animal to plant protein might result in a 3- to 4-fold reduction in the total area of agricultural land required and approximately a 30- to 40-fold reduction in water use.[57] Cultural preferences, however, may hinder the acceptance of alternative protein supply chains.[58,59] Key uncertainties in predicting food production are the achievable crop yields and feed conversion efficiencies in animal production. It should also be noted that food availability and affordability are region-specific, while our current understanding of future distribution of food availability and land-use changes is limited.

Agro-economic models and food prices

The dramatic increases in agricultural commodity prices during the first half of 2007 have raised the question of whether and to what extent the increased use of biomass for energy production is responsible for this price increase. Biofuel production is likely to be only one of the causes, the others being rising food demand, dietary trends, low harvests related to drought, hedge-fund speculation on the commodity markets, agricultural policies and decreases in grain stocks.[60] Estimates of the relative importance of these factors differ widely.[61,62] For example, Rosegrant *et al.*[63] have calculated that approximately 30% of the food price increases in the period 2000–2007 were due to heightened demand for biofuels. This was calculated by modelling prices in the period 2000–2007 with lower demand for biofuels as observed in the period 1990–2000.[64] Nevertheless, other structural factors may have played a role in the observed difference between modelling and reality. The factors determining the rapid recent decline of food prices are so far also hardly analysed.

Recent studies based on agro-economic modelling of future crop prices stress the importance of considering competition and interactions between agricultural markets and bioenergy use. Banse *et al.*[65] estimate that future world prices for first-generation biofuel crops will increase by between 6.5% (for cereals) and 10% (for sugar) in the event of mandatory blending of biofuels with fossil transportation fuels, as called for in the EU Biofuels Directive for 2010. Rosegrant *et al.*[63] estimate that, given current national biofuel plans, by 2020 first-generation biofuel crop prices will increase by 8–26% relative to a baseline scenario with limited biofuel production. In the long term, price increases might stimulate agricultural efficiency, leading to larger potential food and biomass production and less severe price increases. For example, the OECD and the FAO predict that the price of coarse grains will increase by approximately 30% in the short term and approximately 10–20% in the medium term (2010–2016), relative to the 1996 level.[60] At the same time, prices of sugar are projected to increase by approximately 30–40% relative to the 1996 level and then to decrease in the medium term.

To summarise, the results of agro-economic modelling show large variations in price dynamics and still need to be interpreted in terms of future biofuel production. Current agricultural models do not take forestry land and second-generation biofuels into account. Therefore, the impacts of second-generation biofuels on food prices are unclear.

Sensitivity of biomass potentials and demand

All the reviewed studies examine specific aspects only. To give a more integrated picture of biomass potentials, sensitivity analyses have been carried out using existing modelling tools in order to quantify key uncertainties regarding biomass potentials and demand, see also van Vuuren *et al.*[66]

In one of the estimates of global biomass potentials discussed above, Hoogwijk *et al.*[17] are fairly elaborate in that they use an integrated assessment model (IMAGE). It focuses on the geographic and economic potential of woody biofuels, see also ref. 67. For the sensitivity analysis, we applied this modelling framework using the reference scenario of the OECD Environmental Outlook[68] as a baseline. This baseline is a 'medium-development' scenario in terms of population, economic development and agricultural productivity change.§

In order to assess the potential impact of water scarcity on bioenergy potentials, the maps of biomass potentials were overlaid with those of water stress as calculated by the WaterGap model.[45] The WaterGap model uses an index in which a value of 0.2 and higher is defined as moderate water scarcity, while values above 0.4 are defined as severe water scarcity.[50] The overlay exercise indicates that approximately 15% of the total baseline potential for bioenergy crops in 2050 is in areas of severe water scarcity, while an additional 5% is in areas of moderate water scarcity. For all the calculations, rain-fed production conditions were assumed.

In order to estimate the impact of degraded land use on biomass potentials, data from the GLASOD database that classified land worldwide in terms of soil degradation was used.[69] Although this database is rather old and the data is based on expert estimates, it is the only available global dataset on soil degradation to date. It distinguishes three categories of degradation: zero to minor degradation (GLASOD 1–2), serious degradation (GLASOD 3) and severe degradation (GLASOD 4). Inclusion of these data in the modelling shows that approximately 8% of biomass potentials in the baseline scenario are on severely degraded land and another 22% on seriously degraded land.

In the OECD baseline scenario, in order to conserve biodiversity all forest areas and 50% of natural grasslands are excluded from biomass production. To give insight into the impact of enhanced biodiversity protection, biomass potential maps were overlaid with nature protection maps from UNEP-WCMC. These maps cover designated protected areas in the year 2000 and areas projected to become protected under the 'Sustainability First scenario' of UNEP's Global Environmental Outlook.[70,71] This scenario includes most of the biodiversity hotspots and sufficient areas of various eco-regions in order to maintain biodiversity. The resulting impact on bioenergy potential is significant. Excluding protected areas in 2000 reduces the total bioenergy potential by approximately 10%, while excluding the expansion of protected areas by 2050 reduces the potential by another 15% compared to the baseline scenario.

Finally, increasing yields of food and energy crops by approximately 12.5%, which is roughly half of the potential improvement suggested by the International Assessment of Agriculture Science and Technology Development,[53] leads to a 40% increase in biomass potentials relative to the baseline scenario. If agricultural management levels in developing countries could be raised close to current Western European levels, the biomass potentials would even increase by approximately 60%.

To summarise, biomass potential consists of three main categories (see Fig. 2):

1. Together with organic waste, residues from forestry and agriculture represent an energy potential of 30–180 EJ/yr, with

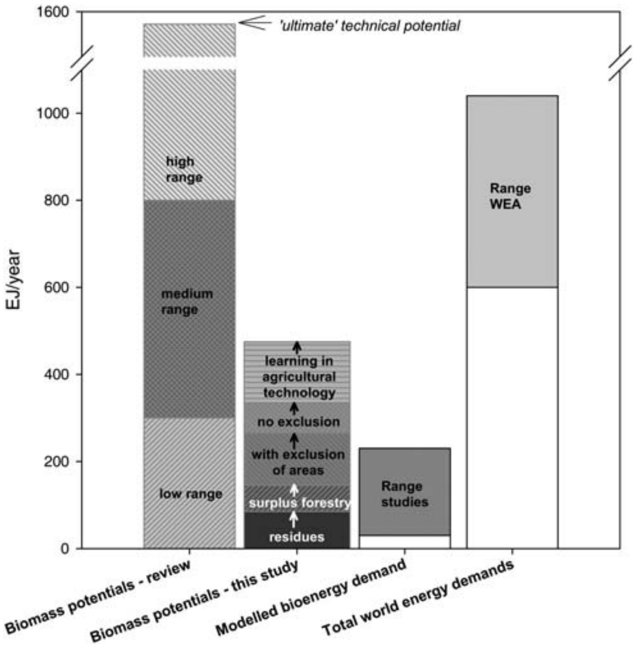

Fig. 2 Comparison of the range of biomass energy supply potentials covered by this review (1st bar from the left), with the lignocellulosic biomass supply potentials from the analysis carried out in this study (2nd bar), the modelled primary bioenergy demands included in this review (3rd bar) and the estimate range for the total global primary energy demand from the World Energy Assessment (71) (4th bar), all by the year 2050. In the second bar from the left, 'residues' include organic waste, and residues from forestry and agriculture and 'surplus forestry' includes net annual increment of forest growth not used for wood products. 'With exclusion of areas' refers to the energy potential of surplus productive land used for biomass production after meeting projected food demand for the OECD baseline scenario (a medium development scenario in the OECD Environmental Outlook (67)) excluding areas with limitations such as water-scarcity, land degradation, and an expanded protected area network. 'No exclusion' represents the energy potential of biomass production on the areas excluded in the latter scenario. The energy potential in 'learning in agricultural technology' represents the additional potential on top of the OECD baseline scenario assuming that more land is available for biomass production due to higher efficiency increases in agricultural production.

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§ Compared to the IPCC scenarios, in terms of most assumptions, the scenario lies in between the A1b (high economic growth) and B2 (medium assumptions) scenarios. The potential for bio-energy on the basis of the OECD baseline scenario in 2050 is around 200 EJ. Using the land use patterns of the IPCC SRES scenarios, but keeping other factors the same as under the OECD baseline scenario, would lead to potentials of 120 to over 325 EJ. Low potentials result in the A2 scenario from high population growth, low yields and little trade, while high potentials occur in the A1 and B1 scenarios as a result of low population growth and rapid yield change.

a mean estimate of around 100 EJ/yr. This part of the potential biomass supplies is relatively certain.

2. The surplus forest growth that is likely to be available amounts to approximately 60–100 EJ/yr.

3. As discussed above, estimates of biomass produced assuming perennial cropping systems show a wide range. A lower estimate for energy crop production, assuming far-reaching exclusion of areas due to water scarcity, land degradation and expansion of protected areas, is approximately 120 EJ/yr. If water-scarce, marginal and degraded lands are not excluded from energy crop production, but are regarded as low-quality land with low biomass yields, their biomass potentials could amount to an additional 70 EJ/yr. Finally, improvements in agricultural management could add an additional 140 EJ/yr to the above-mentioned potentials of energy cropping.

Analysis of factors that determine biomass demand, using the MARKAL energy model based on CASCADE MINTS scenarios,[32] shows that the demand is mainly limited by its marginal cost rather than its supply potential. Similarly, runs with the TIMER energy demand model[28] show that biomass use stabilizes at approximately 130 EJ/yr at taxation levels of above US$100/tonne of carbon. The results of a MARKAL analysis show that shares of bioenergy in total energy supply could vary strongly depending on the learning rates assumed for each technology.

Discussion

In this section, a summary of what we know and don't know concerning biomass potentials are given.¶ Table 1 ranks the main uncertainties regarding biomass potentials and shows the estimated impact on biomass potentials.

1. What drives the economic competitive use of bioenergy and materials?

Feedstock crops such as cereals, oilseeds or sugar cane are in direct competition with food on the consumption side. Such competition is less stringent for biomass crops such as willow or switchgrass, but also such feedstock production competes for scarce resources, especially land. Changes in relative prices between different crops and between different energy sources are key drivers in the future use of biomass and land. Recent work on biofuels clearly shows that apart from direct policy measures, *e.g.* mandatory blending commitments, the price ratio between biofuels and fossil fuels is the most significant driver in the use of biofuels. Dynamics are, however, also important, because shifts in relative prices trigger investments and technical progress in the bioenergy sector. This progress in turn can lower long-term production costs and increase the long-term profitability of bioenergy production.

2. What role might degraded lands play in biomass production?

Another question in determining future biomass potentials is whether degraded lands—of which productive capacity has declined temporary or permanent—can be used for biomass production. At this moment the potential of the large area of degraded soils—classified as light and moderately degraded and covering about 10% of the total land area—to contribute to the production of biomass is not yet clearly assessed. This is because of the unknown impact of two possible drawbacks: firstly the large efforts and long time period required for the reclamation of degraded land and secondly the low productivity levels of these soils. In the integration analysis it has been shown that using severely degraded land would increase biomass potentials from energy crops by about 30–45%, assuming that in principle it would be possible. However, using severely degraded land for annual crop production might require large investments and many attempts at reclaiming degraded land for food production have failed. Other attempts with *e.g.* reforestation and agro forestry might be more promising for biomass production and some projects in the past on *e.g.* saline soils have been successful. Further research on the potential of degraded soils for biomass production is needed. Preferably, other mitigation options (carbon storage in soils and vegetation) and adaptation options should be integrated in the research on the potential of degraded soils for biomass production.

3. What determines biomass yields?

Biomass yields depend mainly on the development of agricultural management and the choice of crops. Most biomass potential studies assume that the efficiency of agricultural production improves in the coming decades assuming low to high technology development rates. Experience, however, shows that deployment of agricultural technologies in developing countries can be a difficult task and implementation strategies need to be studied very well. Moreover, all estimates of future biomass potentials discussed are based on the use of perennial lignocellulosic biomass in 2050. Perennial lignocellulosic crops have in general higher yields than annual sugar, starch and oilseed crops, while perennial sugar and oil crops (*e.g.* sugar cane, palm oil) have high yields, too. However, potentials for annual biomass crops such as maize, might be very low and not sufficient to provide a large part of energy demands.[66]

4. Is water a limiting factor for biomass potentials?

In general, water availability can be a limiting factor for the production of biomass and food. A simple and rough analysis in this study has shown that excluding water scarce areas decreases the biomass potentials by about 15–25% for woody bio-energy crops in 2050, in a scenario with biomass potentials of about 200 EJ/yr (and thus excluding residues and learning in agricultural management). Water availability, however, has not been analyzed on a sufficiently detailed spatial level to estimate regional biomass potentials in water scarce areas. Another remaining point of uncertainty is the possibility to increase water use efficiency in agriculture and as such increase biomass potentials. A regional to local analysis is necessary to further evaluate this possibility. Finally, climate change will increase

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¶ Note that social impacts of biomass use and impacts on energy security—though of large political relevance—have not been an explicit part of this study. Also policies and their effects on biomass potentials have only been analyzed on a very limited level, *i.e.* investigating the effects of carbon taxes on energy demand.

Table 1 Overview of main uncertainties and their impact on biomass resource potentials[a]

Issue/effect	Importance	Impact on biomass potentials compared to	
Supply potential of biomass		*Compared to supply as estimated in recent studies*	*As calculated for the sensitivity analysis in this study*
Improvement in agricultural management	***	↑↓	↑ 40–65%
Choice of crops	***	↓	↓ 5–60%
Food demands and human diet	***	↑↓	n/a
Use of degraded land	***	↑↓	↑ *ca.* 30–45%
Competition for water	***	↓	↓ 15–25%
Use of agricultural/forestry by-products	**	↑↓	n/a
Protected area expansion	**	↓	↓ 10–25%
Water use efficiency	**	↑	n/a
Climate change	**	↑↓	n/a
Alternative protein chains	**	↑	n/a
Demand for biomaterials	*	↑↓	n/a
GHG balances of biomass chains	*	↑↓	n/a
Demand potential of biomass		*demand as estimated in recent studies*	*biomass supply as estimated in TIMER*
Bio-energy demand *versus* supply	**	↑↓	↓ 80–85%
Cost of biomass supply	**	↑↓	n/a
Learning in energy conversion	**	↑↓	n/a
Market mechanism food-feed-fuel	**	↑↓	n/a

[a] Importance of the issues on the range of estimated biomass potentials: *** - large, ** - medium, * - small. Impact on biomass potentials: potentials as estimated in recent studies would: ↑ - increase, ↓ - decrease, ↑↓ increase or decrease— if this aspect would be taken into account. n/a: no quantitative analysis has been carried out for this study.

variability of rainfall patterns. It is expected that in the subtropics and some already water scarce areas rainfall will decrease, while at high latitudes it will increase. For the tropics estimates of future rainfall vary.

5. What is the relation between biodiversity conservation and using bioenergy?

Studies that estimate biomass potentials assume that nature conservation areas are excluded from biomass production. As such estimated biomass potentials consider biodiversity conservation on a base level. Assuming that larger parts of land should not be used for biomass production for reasons of biodiversity conservation, potentials would decrease accordingly. In most cases perennial lignocellulosic crops have lower impacts on biodiversity than annual sugar, starch and oilseed crops and are, thus, better suited for combining biodiversity and biomass production. Important open questions in this area are:

- To what degree is potential energy production on a certain piece of land related to the (potential) biodiversity value of the same piece of land if reserved for nature?
- How to measure biodiversity, realizing different available indicators tell different stories.
- What are the effects of future climate changes on biodiversity (very uncertain) and areas for biomass production (more certain)?

6. What is the effect of biomass use on food prices?

Economic analyses indicate clearly that food prices increase with an increased demand for biomass, but the magnitude of this increase is uncertain. In the long term, price increases might accelerate agricultural efficiency leading to larger potentials of food and biomass production and mitigating price increases. For example, OECD and FAO[60] project a price increase of coarse grain prices of about 30% in the short term and about 10–20% in the medium term (2010–2016) compared to the 1996 level. At the same time, prices of sugar are projected to increase about 30–40% and then even to decrease compared to the 1996 level. Only part of these projected price developments is due to the increase of biofuel production, while other parts are due to low recent harvests and increasing other demands. For annual crops that are used for the production of 1st generation biofuels, the linkage between food prices and biofuel demands is probably larger than perennial lignocellulosic crops used for 2nd generation biofuel production. However, agricultural models currently do not include 2nd generation biofuels and knowledge on the impacts of 2nd generation biofuels on food prices is lacking. Finally, while large amounts of biomass can be used without jeopardizing future global food demands, it should be noted that food availability and affordability are very regional. Further knowledge including the influence of policies and subsidies on food security especially in developing countries is needed.

Overall, an integrated analysis of the most important linkages between the areas of water, food, biodiversity, economic effects, energy demands and biomass potentials is still needed. Important aspects to consider in such an integrated analysis are:

- Drivers and barriers in the food-feed-fuel nexus that could be used to refine modelling and scenario analysis of geographical and economic biomass potentials.

- Linkages between the availability and prices of water, the availability and prices of land, the demand for food and feedstock, the demand for energy and between the cost-supply curves of biomass.
- Regional analysis that analyze the relation between food security, biomass potentials, water availability and land use changes on a spatially explicit level.
- Mechanisms of changes and the implications of policy instruments in different parts of the world

Conclusion

According to our current understanding, total biomass supplies for energy production could be anywhere between approximately 100 EJ using residues only and an ultimate technical potential of 1500 EJ/yr. This assessment analysed the sensitivity of the currently available results, especially with respect to water availability, soil quality and protected areas. This narrows the range of biomass potentials to approximately 200–500 EJ/yr. With energy demand models, the amount of primary energy from biomass that will be used if energy demands are cost-efficiently supplied is estimated to be approximately 50–250 EJ/yr in 2050, whereas the global primary energy use is predicted to be approximately 600–1040 EJ/yr.[72] Thus, this assessment confirms that—in principle—biomass potentials and biomass demands could be very large; that is, up to one third of the global energy demand according to average projections.[71] The estimated potentials are valid for future perennial lignocellulosic crops. The potentials of annual crops that are now used for first-generation biofuels have not been assessed in detail, but analysis with the IMAGE model indicates that they are probably much lower.

The proportion of the total potential which will almost certainly be available—that is, the biomass residues and organic wastes—is only small. Competing applications, however, may push the net availability of these residues and wastes for energy applications to the lower end of the range, and this needs to be better understood in the context of economic demand-side modelling. The greater part of the potential will have to be developed through cultivation and will have to meet a wide variety of sustainability criteria if conflicts relating to land use, water use, protected areas, biodiversity, soil quality and socio-economic aspects are to be avoided.

In general, annual food crops may be less suitable as a prime feedstock for bioenergy than perennial lignocellulosic crops, not only in terms of their potentials but also in meeting a vast array of sustainability criteria. Under certain circumstances, however, annual crops may be a good option. At present, there is only limited experience with sustainable perennial biomass systems for energy production, especially their application in marginal and degraded areas. Therefore, more R&D work and market experience is needed in order to develop feasible and sustainable systems appropriate to a wide variety of settings around the globe.

This assessment indicates that although the development of significant sustainable bioenergy use and biomass production may be possible, many issues still need to be resolved. The biggest challenge in realising the potentials of biomass production is in the design of proper strategies for management and implementation of production and management systems. Such strategies will allow the gradual introduction of crops for bioenergy production in rural areas, at the same time maintaining or even improving the productivity of agriculture.

A successful policy targeting the development of bioenergy use and biomass production should incorporate a variety of targets and boundaries. Clearly, the balance of objectives will be different from setting to setting (compare rural Africa with the EU for example) and in case (regional) trade-offs between various objectives have to be made. Therefore, policies aimed at the development of bioenergy potentials should incorporate multiple objectives with respect to environmental, social and land use issues. Governance and implementation of incentives could then be designed to achieve the necessary performance. If sustainable biomass potentials are to be developed, the main policy implications are as follows:

- Competition between food, feed and fuels could be avoided if the increased production of biomass for energy is balanced by improvements in agricultural management and by growing perennial lignocellulosic crops on degraded and marginal areas.
- At the same time, key environmental concerns, including biodiversity, soil quality and water availability, should be addressed. This can be achieved by selecting appropriate bioenergy systems and applying adequate land use planning.
- Positive GHG balances of bioenergy systems can be secured by choosing suited biomass sources (*e.g.* using residual biomass and perennial crops), while preventing direct and indirect land-use changes that lead to high greenhouse gas emissions.
- Overall sustainability should be guaranteed by implementing suitable policy frameworks that cover the above, for example by means of developing biomass certification schemes.

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