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Exploration of the ranges of the global potential of biomass for energy

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Abstract

This study explores the range of future world potential of biomass for energy. The focus has been put on the factors that influence the potential biomass availability for energy purposes rather than give exact numbers. Six biomass resource categories for energy are identified: energy crops on surplus cropland, energy crops on degraded land, agricultural residues, forest residues, animal manure and organic wastes. Furthermore, specific attention is paid to the competing biomass use for material. The analysis makes use of a wide variety of existing studies on all separate categories. The main conclusion of the study is that the range of the global potential of primary biomass (in about 50 years) is very broad quantified at $33-1135$ EJy^{-1}. Energy crops from surplus agricultural land have the largest potential contribution (0–988 EJy^{-1}). Crucial factors determining biomass availability for energy are: (1) The future demand for food, determined by the population growth and the future diet; (2) The type of food production systems that can be adopted world-wide over the next 50 years; (3) Productivity of forest and energy crops; (4) The (increased) use of bio-materials; (5) Availability of degraded land; (6) Competing land use types, e.g. surplus agricultural land used for reforestation.

It is therefore not "a given" that biomass for energy can become available at a large-scale. Furthermore, it is shown that policies aiming for the energy supply from biomass should take the factors like food production system developments into account in comprehensive development schemes.

Keywords: Biomass energy; Bioenergy; Potential; Global; Bio-material

1. Introduction

Biomass is seen as an interesting energy source for several reasons. The main reason is that bioenergy can contribute to sustainable development [1]. Biomass energy is interesting from an energy security perspective. Resources are often locally available and conversion into secondary energy carriers is feasible without high capital investments. Moreover, biomass energy

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can have a positive effect on degraded land by adding organic matter to the soil. Furthermore, biomass energy can play an important role in reducing greenhouse gas emissions, since when produced and utilised in a sustainable way, the use of biomass for energy offsets fossil fuel greenhouse gas emissions. Since energy plantations may also create new employment opportunities in rural areas in development countries, it also contributes to the social aspect of sustainability. At present, biomass is mainly used as a traditional fuel (e.g. fuelwood, dung), contributing to about 38 ± 10 EJy^{-1}. Modern biomass (e.g. fuel, electricity) to about 7 EJy^{-1} [2]. In this study we include both traditional and modern biomass energy.

Many energy scenarios suggest large shares of biomass in the future energy system (e.g. [3–6]). The availability of this biomass is not always separately analysed. Furthermore, large-scale utilisation will have large consequences for land demand and biomass infrastructure, which should be assessed. Many studies have been undertaken to assess the future biomass energy potential, e.g.: [4,5,7–20].

To get insight in the main assumptions that have been made in these studies we have conducted an analysis of the approaches used to assess the global biomass energy potential (see also [21]). Overall, it has been concluded that the results vary widely. Furthermore, most of the investigated studies do not include all sources of biomass in competition with other land use functions. The studies are not always transparent in the procedure for calculating the energy potential. Insight in the factors that are of main importance of realising the investigated potential is therefore not always presented. Finally, many studies tend to neglect the competition between various land use functions and between the various applications of biomass residues [21]. Therefore, in this paper, we consider a different approach of exploring the biomass potential.

The main objectives of this paper are: (1) To gain insight in the factors that influences the potential of bioenergy in the long term. (2) To explore the theoretical ranges of the biomass energy potential on the longer term in a comprehensive way, including all key categories and factors. (3) To evaluate to what extent the potential of biomass supply can be influenced. This analysis focuses on a global scale. The chosen timeframe for this exercise is the year 2050.

In this paper we first describe the methodology applied (Section 2). Next, in Sections 3 and 4 the potential production of biomass is assessed. In Section 5, the potential future demand of biomass for production of materials is taken into account by evaluation of utilization, and applying economic projections, and resulting growth in demand, for the long term. Finally, the ranges found for land availability; biomass productivity levels, availability of biomass residues and the availability of organic wastes are translated into primary energy supply potentials (Sections 6 and 7).

2. Methodology

2.1. Biomass categories

First we define the concept 'potential' that is used in this paper. We are interested in an upper limit of the amount of biomass that can come available as (primary) energy supply without affecting the supply for food crops. This is defined as the geographical potential. As timeframe we take the longer term (2050 y).

We define our biomass supply system by dividing biomass production and use into different categories. These categories make the competition and synergy of the separated biomass flows more transparent, see Fig. 1. The scheme presented in Fig. 1 is a simplification of the real system, and hence not complete. E.g. one could also think of aquatic biomass from the fresh water or oceans. Furthermore, the land use category 'other land' includes all kind of land types such as desert, semi-arid land, ice, etc. This scheme also implies that biomass supply from protected nature conservation areas is not included in this study. Also competing land use functions like recreation and human settlements are excluded. Nevertheless, residues from forest areas are included in this study. Fig. 1 also shows the total surface per land use type. Out of the total land surface of 13 Gha, 5 Gha is used for food production [22]. (to some extent the figures very among different studies, e.g. [10] takes a figure of 5.3 Gha).

In the system defined (Fig. 1) there is on one hand competition for land, for the production of energy, food and materials, i.e. farmers may compete with foresters or energy producers on the use of land for their products. Furthermore, competition exists

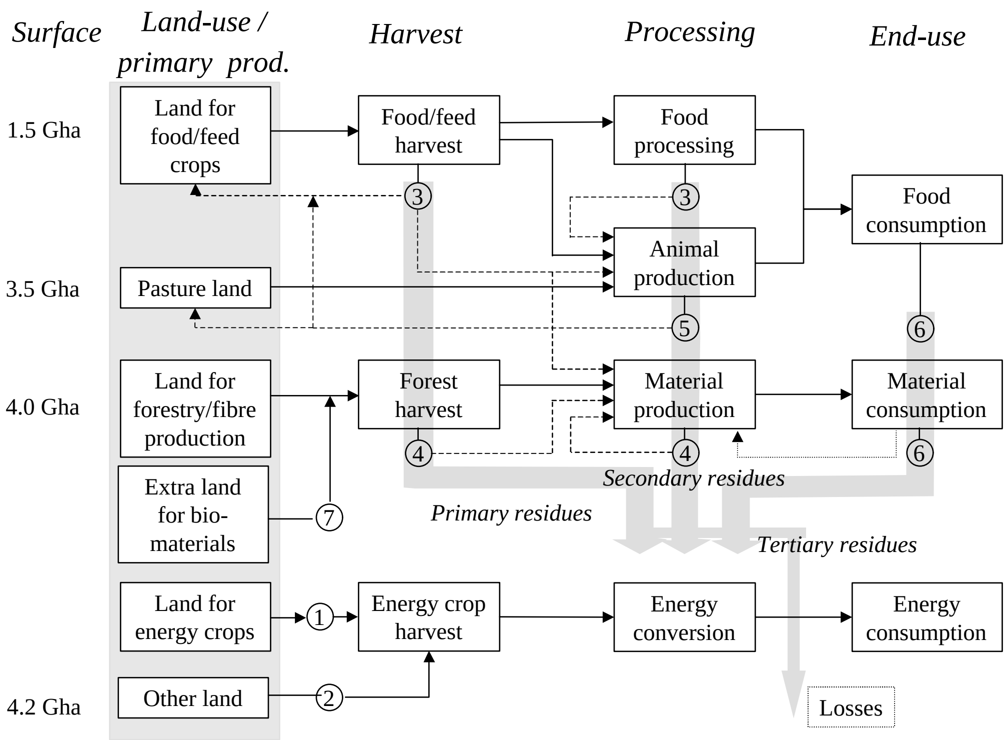

Fig. 1. Overview of various types of biomass flows and the global land surface (Based on: [1,22]). The black arrows indicate the main product flows, whereas the dotted lines show potential non-energy applications of various residue categories. The gray arrows represent the potential energetic use of the resources (1 = energy crops, 2 = energy crops at degraded land, 3 = agricultural residues, 4 = forest residues, 5 = animal manure, 6 = organic waste, 7 = bio-material).

between the use of residues (dotted lines). Residues can be used for energy purposes, but also for e.g. fiber, fertilizer or fodder. On the other hand, synergies occur between energy and food material production (the end-use options, right part of the figure), since residue flows increase with increasing food production and these flows can also be utilized for energy purposes.

To explore the ranges of biomass potential for energy that includes all those flows and applications we define (based on Fig. 1) seven categories of biomass (Table 1). The land for energy crops from Fig. 1 are divided in two categories (here referred to as categories I and II): surplus agricultural land and degraded land. The degraded land is included in the land use category 'other land' in Fig. 1. The primary and secondary residues, as shown in Fig. 1, are merged due to lack of disaggregated data. This is done for both agricultural residues (Category III) and forest residues (Category IV). The use of biomass for material applications (such as solid products or fiber or wood for pulp), which may increase in the future, and should be subtracted from the biomass production for energy applications on surplus agricultural and degraded land. However, after a delay of time (which can cover a time period between several weeks (paper) up to decades (construction wood), this biomass becomes, at least partly, available as waste and adds to Category VI (organic waste).

2.2. Approach

The potential supply of the various categories in Table 1 is assessed using the results of existing studies. For the assessment of the biomass produced on surplus agricultural land (Category I), the demand for land required for food is assessed. Therefore various population scenarios, three different diets and two different food production systems are assumed. The potential of

Table 1
The biomass resource categories distinguished to assess the theoretically available potential of biomass for energy use

Category	Description
Category I: biomass production on surplus agricultural land	The biomass that can be produced on surplus agricultural land, after the demand for food and fodder is satisfied
Category II: biomass production on surplus degraded land	The biomass that can be produced on deforested or otherwise degraded or marginal land that is still suitable for reforestation
Category III: agricultural residues	Residues released together with food production and processing (both primary and secondary)
Category IV: forest residues (incl. material processing residues)	Residues released together with wood production and processing (both primary and secondary)
Category V: animal manure (dung)	Biomass from animal manure
Category VI: organic wastes	Biomass released after material use, e.g. waste wood (producers), municipal solid waste
Category VII: bio-materials	Biomass directly on used as a feedstock for material end-use options like pulp and paper, but also as feedstock for the petrochemical industry

Category II is mainly based on an overview of studies with the objective to assess the amount of degraded land available for reforestation. The potential biomass productivity at both surplus agricultural and degraded land is estimated using a grid cell based crop growth model. The potential assessment of residues (Category III–VI) is based on various potential assessments. The approaches of the assessments are compared and similar assumptions and results combined to construct a lower and upper limit of the potential. The demand for bio-materials (Category VII) is based on scenarios on the future economic development, production figures and share of bio-materials in the total material production. The results of the separated categories are combined to give an overall estimation of the upper and lower ranges of primary biomass supply.

3. The potential for energy farming on agricultural land

3.1. Availability of surplus agricultural land (Category I)

To assess the land areas available for production of biomass for energy use on surplus agricultural land, the future demand for land for food and fodder production has to be estimated. In order to do so, we use a study from Luyten that explores the potentials of food production on a global level [23], as the basis for the assessments. Several adaptations are made to the Luyten study, mainly regarding the land areas included. The adaptations can be done since the study by Luyten has been reported transparently. While Luyten considers all land that can be used in principle for food production (e.g. including current forests), we limit ourselves to the current 5 Gha in use for food production (see also Fig. 1). At present (forest) land is converted into agricultural land, and so, the agricultural land is increasing. If more land is required for food production, there is no land available for energy crops. We assume that the land area that is abandoned is included in the second category of biomass sources (energy crops on degraded land). The first category only includes (high quality) surplus agricultural land. Furthermore, more recent insights on population growth scenarios are used [3]. We assess the potential future world food demand assuming three population projections and three food consumption patterns. To assess the required land to supply this demand, two types of food production systems are assumed, based on very different input levels of fertilizers and pesticides and more intensified

Table 2
Global average daily consumption per adult for three different diets expressed in MJ day^{-1} and as grain equivalents in kg dry weight/day (Source: [23])

	Current global situation	Vegetarian diet	Moderate diet	Affluent diet
Energy intake (MJ d^{-1})	9.4	10.1	10.1	11.5
Plant prod. (gr eq, kg^{-1} d^{-1})		1.05	0.90	1.13
Meat prod. (gr eq, kg^{-1} d^{-1})		—	0.22	1.91
Dairy prod. (gr eq, kg^{-1} d^{-1})		0.28	1.23	1.16
Total (gr eq, kg^{-1} d^{-1})	2.3	1.3	2.4	4.2

management techniques and thus different intensities of farming [23]. Hence, 18 different food scenarios are produced.

3.1.1. Future demand for food

Total food demand depends primarily on population and average diet. Three average food consumption patterns are considered, taken from Luyten [23]: a vegetarian diet with little or no animal protein, a moderate diet as well as an affluent diet with a large share of meat and dairy products (Table 2). The diets are composed of different shares of plant, dairy and meat products. To make the diets comparable, they are expressed in grain equivalents (gr. eq.). Grain equivalents are universal measures for the amount of dry weight in grains used directly or indirectly (as raw material for other food products e.g. milk or meat) in our food consumption. In this approach also some crops, which are not cereals, such as fruit, are translated to grains [23]. Losses when converting grains and grasses to dairy and meat products are taken into account. It should be noted that such losses are considerable. Luyten assumes conversion efficiencies of 33% for dairy and 11%, for meat. [3] The three diets are all sufficient with respect to daily caloric intake and daily protein requirements, but differ strongly with respect to their composition and thus daily consumption per adult in grain equivalents (see Table 2). The conversion factor that converts the diets to grain equivalents, are weighted averages of the conversion factors of each separate product consumed in the diet, respectively 0.92, 1.45 and 2.77 kg grain eq/kg product, for the vegetarian diet, moderate and affluent diet [23].

Population projections are taken from recent scenario studies of the Intergovernmental Panel on Climate Change [3]. Projections for 2050 vary between 8.7 and 11.3 billion, compared to the present (2000) figure of 5.9 billion global citizens. Combined with the three average diets described, and assuming the entire world population adopts those diets, this results in the total future food demands for the three diets as indicated in Table 3. Hence, it can be concluded that the total global demand (represented in grain equivalents) can, in principle, vary between 4.1×10^{12} and 17.3×10^{12} kg dry weight, which is 80% up to 350% of the current demand for food.

3.1.2. Future supply of food

Two fundamentally different production systems are defined to assess the future supply of food: a High External Input (HEI) system and a Low External Input (LEI) system [23]. These systems differ mainly in the way diseases and plagues are combated and in the use of fertilizers.

HEI production system. The HEI production system is based on the concept of 'best technical means': crop production is maximized, and realized under optimum management, in with an efficient use of resources [24,23]. Nutrient requirements are fully covered by fertilizer application. The crop production is only limited by the availability of water if no irrigation water can be applied. The most effective methods of weed, pest and disease control are used to avoid yield losses

[3] Taking into account an annual increase of productivity of about 2%, these data compare reasonably with present production efficiencies as studied by Wirsenius. Wirsenius mentions a variation of conversion efficiency from corn (in corn equivalents) between 5.2 and 19%, for cattle milk and dairy products respectively. For meat production a range is given of 0.58–1.8% for beef, 2.8–6.4% for pork meat, 4.1–8.3% for chicken and 10–18% for eggs [22].

Table 3
Population projections for 2050 (in 10^9 people) and the food requirement in grain equivalents (in 10^{12} kg dry weight) for three population scenarios (L = low, M = medium and H = high)

	Current	Vegetarian diet			Moderate diet			Affluent diet		
	situation	L	M	H	L	M	H	L	M	H
Population size 10^9 people	5.9	8.7	9.4	11.3	8.7	9.4	11.3	8.7	9.4	11.3
Global food requirement in 10^{12} kg dry weight gr eq.	5.0	4.1	4.5	5.4	7.6	8.2	9.9	13.3	14.4	17.3

Table 4
Potential area, potential yields and total potential food production

	Area (Gha)		Global mean yield Gr eq in ton ha^{-1}		Potential production Gr eq in Gton	
	HEI	LEI	HEI	LEI	HEI	LEI
Irrigated	0.75	0.75	14.3	4.1	10.7	3.1
Rainfed	0.75	0.75	5.9	2.1	4.4	1.6
Grassland	3.5	3.5	5.9	2.1	20.5	7.4
Total	5	5			35.6	12.0

and there are no restrictions in biocide use. Typical yields are 14.3 tonnes dry matter of gr gr eq ha^{-1} y^{-1} for irrigated areas and 5.9 tonnes dry matter of product in gr eq ha^{-1} y^{-1}, for non-irrigated areas [23]. These figures are relatively high (about a factor 2) compared to the present yield figures (2000) of cereal crops in Western Europe, of 5.7 tonne ha^{-1} y^{-1}, and a world average figure of 3.1 tonne ha^{-1} y^{-1} [25].

LEI production system. The LEI system aims at an agricultural system that minimizes the environmental risks. Within this system, no chemical fertilizers and biocides are applied. Fertilization is only obtained through biological fixation and is kept in the system by recycling animal and crop residues. Potassium and phosphorous availability to the crop are assumed optimal, but production is limited by both water and nitrogen availability. Herbicide application is replaced by mechanical weeding and the control of pests and diseases is carried out by means of prevention. This results in an average yield of 4.0 tonnes dry matter of gr eq ha^{-1} y^{-1} for irrigated areas and 2.2 tonnes dry matter of product in gr eq ha^{-1} y^{-1} [23]. These figures are close to present global average cereal yields of 3.1 tonne ha^{-1} y^{-1} [25].

Luyten has calculated the rainfed crop production for the two systems with a simple crop growth model. Calculations are done for grid cells of $1^\circ \times 1^\circ$ (with site-specific climate and soil conditions) over the globe [23]. We use the global mean irrigated and non-irrigated yields as assessed by Luyten and presented in Table 4.[4] The assessed yields are applied at the 5 Gha agricultural land, divided into grassland (3.5 Gha) and cropland (1.5 Gha) (see Table 4).

The total food supply is assessed for the actual agricultural area of 1.5 Gha cropland and 3.5 Gha grassland. We assume that with both systems, 20% of the agricultural land area are irrigated, and that on grassland no irrigation is applied.[5]

[4] Luyten has used the following values for the Harvest Index (ratio between of harvested part and total crops), being representative for current major cereals: 0.4 (LEI, grain), 0.45 (HEI, grain), 0.7 (LEI, grass) and 0.6 (HEI, grass) [23].

[5] Currently 20% of the present arable land in developing countries and 13% in developed countries is irrigated. In 2030 the share of irrigated versus non-irrigated land in developing countries is estimated to be 22% [26].

Table 5
Ratio between the potential global food production and global food requirement (in 2050) calculated for two production systems (HEI and LEI) using three population scenarios (low, medium, high)

	Vegetarian diet			Moderate diet			Affluent diet		
	Low	Medium	High	Low	Medium	High	Low	Medium	High
HEI	7.7	7.1	5.9	4.2	3.9	3.2	2.4	2.2	1.8
LEI	2.7	2.5	2.1	1.5	1.3	11	0.8	0.8	0.6

Table 6
The area available for energy plantations agricultural land area (5 Gha)—using a food security factor of 2

	Vegetarian diet			Moderate diet			Affluent diet		
	Low	Medium	High	Low	Medium	High	Low	Medium	High
HEI	3.7	3.6	3.3	2.6	2.4	1.9	0.8	0.5	0
LEI	1.3	1.0	0.2	—	—	—	—	—	—

Table 7
The fraction of the total global area available for energy plantations—using a food security factor of 2

	Vegetarian diet			Moderate diet			Affluent diet		
	Low	Medium	High	Low	Medium	High	Low	Medium	High
HEI	74%	72%	66%	52%	48%	38%	16%	9%	3%
LEI	26%	20%	3%	0%	0%	0%	0%	0%	0%

3.1.3. Future land requirement for food production

The ratio between global food production and global food requirements (see Table 5) is used to calculate the fractions of agricultural land needed for food production. It is assumed that the remaining fraction in principle can be used for the production of biomass for energy. The demand is only fulfilled under optimal infrastructure to match supply and demand. However, food production between years and regions may vary, and unequal income distribution may keep food inaccessible to the poor if food supply is limited. Furthermore various transportation and distribution losses require a higher production compared to the consumption. Therefore, we work with a ratio of 2 to guarantee food self-sufficiency. This assumption is based on discussions among several experts [23,27]. It is stressed that the value is rather arbitrary, as it depends on a large set of factors (e.g. unequal spatial distribution of demand and supply, variation among years and losses in transport).

The fraction of agricultural land that may be used for biomass production and the total area available for biomass production are given in Tables 5–7.

3.2. Availability of marginal/degraded land for energy farming (Category II)

To investigate the potential availability of marginal/degraded land for energy farming, we have analysed a selection of studies that assess the land availability for forest-based climate change mitigation strategies (see [28–30,12,13]). The approach in these studies is first to identify areas where human activities have induced soil and/or vegetation degradation. The identified areas are subsequently evaluated in order to estimate availability for reforestation. In this context biomass energy plantations offer one of several possible land use options. Forest replenishment and agroforestry systems are alternative strategies for reclamation of degraded land. The studies attempt to

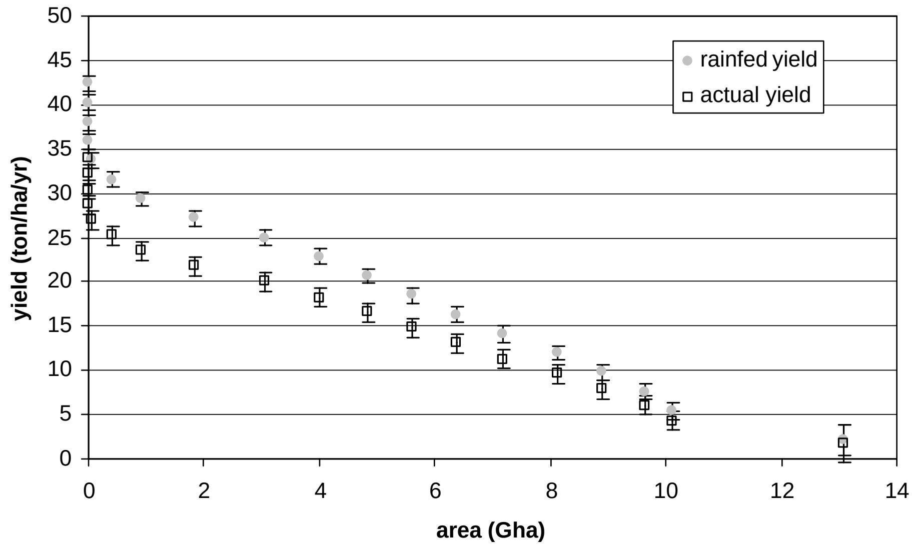

Fig. 2. Global average biomass yields of woody short rotation crops (based on [32]).

refine the reforestation concept in order to evaluate the feasibility for specific reforestation strategies. Otherwise, it is difficult to evaluate the feasibility of establishing biomass production for energy purposes on degraded land identified as potentially available for forestry based climate change mitigation strategies. The reason is that land availability assessments within the context of bioenergy plantations establishment require a more restricting set of evaluation criteria than if the assessment is employed within the context of forestation strategies in general. Hence, the land availability estimates are uncertain.

Hall [12] assumes that out of the 760 Mha of degraded land as mentioned by Grainger [30], about 430 Mha can be used for energy crops. US-EPA [13] assumes an amount of land available for reforestation of 380 Mha. Houghton [28,29] estimates 500–580 Mha. However, a pessimistic scenario by Houghton [29] gives a figure of 0 Mha. This pessimistic scenario was described to state that, due to financial, policy and social aspects, the effort for this deforestation could also be zero. However, as we do not include these aspects in this study, the range taken in this study, based on above references is 430 –580 Mha of degraded area potentially available for energy crop production. The lowest figure applies to the scenario when competing land use options are chosen. The upper limit assumes high priority input and marginal competing options. However, one should be aware that these figures are difficult to quantify and so the values are highly uncertain.

3.3. Productivity of energy crops and primary energy potential of energy crops

In this study the species of energy crop is not specified. For the productivity assessment we restrict the energy crop to woody short rotation crops, like eucalyptus and willow. Energy crop productivity depends on environmental conditions (i.e. climate, soil, etc.) and management (i.e. crop protection, nutrient supply, irrigation, etc.) and can therefore vary considerably among different areas. We distinguish two types of biomass cultivation for energy. The first type of cultivation is reforestation on degraded land; characterized by (more) extensive management and often on less productive land. The second category is “dedicated fuel supply systems”, with a more intensive management methods, (e.g. eucalyptus, grasses, willows). The latter is assumed to have a higher productivity. The value of this future productivity is difficult to assess, as well as the difference in productivity among both production systems. We have studied the productivity of energy crops, using the crop growth model of the IMAGE 2.1 model (see Fig. 2). This crop growth model is similar to the one used by Luyten to estimate the food productivity. It includes climatic and soil characteristics and is applied at grid cell basis. To convert the theoretical yield to actual yield, a management factor is introduced. This management factor can be seen as a weighting factor for the losses due to non-optimal biomass agricultural practices, and is based on empirical values as described in literature [31,32]. For the simulation of the management-based productivity, a constant management factor of 0.7 is assumed in this study, see Fig. 2.

The graph in Fig. 2 shows decreasing yields with decreasing soil and climate quality. So the highest productivity is assumed to be found for energy plantations of the "dedicated fuel supply systems", the lower for plantations at degraded land. Taking Fig. 2 as a basis for the yield assumptions on both surplus agricultural land and degraded land, a range of 10–20 tonne ha^{-1} y^{-1} for surplus agricultural land and 1–10 tonne ha^{-1} y^{-1} for degraded land is used in this study for the year 2050. These figures are consistent with future yield assessments presented in literature [12,17,5,18].

3.4. Summary of the potential of energy crops

It is shown (see Tables 6 and 7) that the range of the area potentially available for energy crop production range from 0 and 3.7 Gha to 2.6 Gha could be available on a global scale for the moderate diet in a low population growth scenario. This may be a reasonable set for establishing the upper limit and is used in the final figure in Section 6 and likely more realistic than the vegetarian or the affluent diet applied on a global scale. The degraded area potentially available for energy crop production may lie between 430 and 580 Mha. Using the upper level of productivity of energy crops on these land types and a HHV of 19 GJ, this results in a primary potential for energy on surplus agricultural area of 0–988 EJy^{-1} and for degraded land of 8–110 EJy^{-1}.

4. The potential supply of biomass residues

4.1. Agricultural residues (Category III)

The availability of agricultural residues depends on the food and fodder production (see Section 3). The residues are either field based or process based (primary or secondary, see Fig. 1). The availability of field-based residues depends on the residue to product ratio and on the production system. Most studies included in the overview (Section 1) assume that about 25% of the total available agricultural residues can be recovered [5,17,18,20]. Hall (1993) [12] presents the potential of agricultural residues based on this assumption, respectively 14 EJy^{-1} and 25 EJy^{-1}. The potential contribution of crop residues is assessed by Lazarus at 5 EJy^{-1} [14]. Fischer and Schrattenholzer [10] have assessed the crop residue potential for five crop groups: wheat, rice, other grains, protein feed, and other food crops similar to Hall. The contribution of crop residues is 27 EJy^{-1} in their high potential assessment and 18 EJy^{-1} in their low potential assessment. Hence, the range of primary agricultural residues included in this study varies between 5 and 27 EJy^{-1}.

Secondary or process-based residues are residues obtained during food processing, like bagasse and rice husk. This has to be derived from the production of crops that produce valuable secondary residues and from the residue fraction available after processing these crops. Of the secondary residues, only bagasse has been included by some studies in the overview. It is assumed that all bagasse can be recovered and used for energy applications [18,20,12,5]. Based on these assumptions, total potential of secondary residues is assessed at 5 EJy^{-1}.

Hence, the range of total agricultural residues included in this study varies between 10 and 32 EJy^{-1}.

4.2. Forest residues (Category IV)

Hall [12] assumed that 25% of logging residues plus 33% of mill and manufacturing residues could be recoverable for energy use (total 13 EJy^{-1}). Yamamoto and the RIGES scenario gave higher figures i.e. 50% harvesting residues and 42% sawmill residues in the developing regions (only Yamamoto) and 75% in developed regions [20,5,33]; this results in a forest residue contribution of 10–11 EJy^{-1}, for the year 2025. However, this figure is assumed for the lower limit in this study for the year 2050. Lazarus assumes that the forest residues availability could increased from 0 to 16 EJy^{-1} over a 40 year period [14].

Hence, the range of forest residues included in this study varies between 10 and 16 EJy^{-1} depending on the recoverability of the residues and the productivity of the forests.

4.3. Animal residues (Category V)

One can consider animal residues as dung and slaughter residues. Here we only include dung. The available amount of dung depends on the number of animals and the requirement of manure as fertilizer. Wirsenius has assessed the total current (1992–1995) amount of manure produced annually at 46 EJy^{-1}r [22]. Several studies have assumed that 12.5% [12] to 25% [17,18,20,5] of the total available manure can be recovered for energy production. With the figure of Wirsenius the net available amount would be 6–12 EJy^{-1}. However, it should be reckoned that this is a static figure for 1992–1995. Within scenario simulations with IMAGE 2.1. (SRES A1b and B1) it is assumed that the number of animals may increase annually with 1% from 1990 to 2050. Thus if we assume that the manure production per animal is constant over time, the amount of animal residues may increase also with 1%/year. This results in a range of 9 to 19 EJy^{-1}. Other studies that have included the growth of animals and so manure production resulted in assessments of 25 EJy^{-1} [5] and 13 EJy^{-1} [18] annually available for energy production.

Hence, the availability of energy from animal manure included in this study ranges from 9 to 25 EJy^{-1}, depending on the animal growth and the recoverability of the residues.

4.4. Organic waste (Category VI)

The availability of organic waste (see Table 1: tertiary residue) for energy use depends strongly on variables like economic development, consumption pattern and the fraction of biomass material in total waste production. Several studies on the biomass energy potential have considered the theoretical availability of organic waste for energy purposes. The RIGES [5] and the LESS-BI scenario [18] have assumed that 75% of the produced organic urban refuse is available for energy use. Furthermore, it is assumed that the organic waste production is about 0.3 tonne cap^{-1} y^{-1}, resulting at 3 EJy^{-1}. Dessus [8] has assumed in his assessment of the biomass energy potential in 2030 that the urban waste production could be between 0.1 and 0.3 tonne per capita (less developed regions and developed regions), resulting in 1 EJy^{-1}. Hence the range of organic waste could vary from 1 to 3 EJy^{-1}.

5. Bio-material production (Category VII)

The biomass use for materials ('biomaterials') is analyzed in more detail, since it can be an important competing application of biomass for energy. Production of bio-materials can make sense from an energy and CO_2 point of view because biomass can have a double benefit: its use can save fossil fuels by replacing other materials (e.g. oil feedstock in the petrochemical industry) and waste bio-materials can be used for energy and material recovery. In case bio-materials can be recycled several times before energy recovery (e.g. in the case of construction wood and for pulp and paper), the material and energy savings may even increase further. Often, the quality of the waste materials poses constraints for recycling, resulting in down-cycling. In such a case, biomass is used in a cascade of applications, energy recovery being the final step in the cascade.

The use of biomass for materials in industrialized countries varies widely. Wood is currently used for building and construction materials. Rubber and natural fibers such as cotton constitute examples of important materials crops. The use of biomass for materials can be expanded to new applications. For example, biomass can be used further as a carbon neutral alternative for coal and coke in the iron and steel industry. Biomass can also be used as a renewable carbon feedstock in the production of synthetic organic materials such as basic chemicals, plastics, paint and solvents [34].

The future demand for bio-materials depends on the present demand for materials, the expected annual growth of this demand, the market share of bio-materials and the biomass use per unit of bio-material product. In order to make a projection for the potential future biomass demand for material applications we assume the following: The present global wood production (sawnwood and wood-based panels) is 600 million m^3 according to the FAO statistics [35]. The projected growth for wood is assumed

Table 8
Demand projections for biomaterials [34]

Type of material	Current prod. (Mt y^{-1})	Yearly growth (%)	Potential product demand (2050) (Mt y^{-1})	Market share bio-materials (%)	Biomass use per ton product[a]	Global potential biomass demand (Mt y^{-1})	Yield[b] (odt ha^{-1} y^{-1})	Land use (Mha)[c]
Pulp[d]	175	3	307	100	1.7	511	10	51
Petrochemicals	200	2	398	5–100	2.5	50–996	10	5–100
Wood	350	3	1756	100	2	3512	10	351
Sawn wood			*975*			*1950*		
Woodboard			*781*			*1561*		
Crude iron[e]	550	1	1274	5–100	0.7	89–892	10	9–89
Cotton	20	4	142	100	1	142	2	71
Rubber	7	3	31	100	1	31	2	15
Total	1300		3338			4335–6084		503–678

[a]Indication of required biomass per product (ton biomass per ton product). When producing construction wood for example, 50% can be lost during sawing.
[b]Various land types (ranging from cropland to grassland) and crop types (e.g. woody crops, cotton and rubber) are assumed for yield figures.
[c]Based on assumed yield and the required biomass for biomaterial production.
[d]It is assumed that the share of recycled products increases from 40% in 2000 to 60% in 2050.
[e]It is assumed that the share of recycled products is 30% over the whole time period.

to be 3% as is taken from historical trends presented by the FAO [36]. The expected growth for pulp is related to the growth in GWP of 3%, based on SRES scenarios of the Intergovernmental Panel on Climate Change (IPCC) [3]. The demand for cotton and rubber is based on historical trends in FAO statistics (resp. 4% and 3% growth) [25].

The data for the potential use of biomass as feedstock in the petrochemical industry are based on Gielen and Yagita [37]. For the year 2020 this potential is assessed at 550 Mt. To assess the demand for 2050, this number is assumed to increase annually with 2%. The total demand for materials is converted to areas using average oven dry ton yields for the production of biomass. The assumptions and results are shown in Table 8. The global potential biomass demand for materials in the year 2050 is calculated at about 4335–6084 Mt y^{-1}, 83–116 EJy^{-1}.

In case cascading is applied, the primary biomass demand for materials decreases. Maximum cascading can be obtained when all wood residues from building and construction are used for petrochemicals, pulp or charcoal for iron production. In this case (maximum cascading), the demand for biomaterials can be reduced to 820–2570 Mt (325–230 Mha). Part of this biomass returns as process residue, e.g. black liquor in the pulp and paper industry and processing waste in petrochemical industry and construction materials. We assume an upper limit for residue availability of 0.5 tonne residue/tonne pulp (HHV of 18 GJ $tonne^{-1}$), and 0.25 tonne residues $tonne^{-1}$ bio-material, for the other materials (HHV of 19 GJ $tonne^{-1}$) and a lower limit of no residues available. This is similar as studies presented in Section 4.2. This results in an extra amount of organic waste of bio-materials that becomes available of 32 EJy^{-1}. The bulk of the land required for bio-materials production is woodland. As a consequence the impact of a bio-materials strategy on surplus agricultural land use will to a large extent depend on the future intensity of forest use.

6. Integration and discussion

6.1. Integration

The final range is composed by two extreme possible combinations (Table 9). The first combination, the overall lowest limit of the biomass potential, is composed of the lowest figure in categories I, II and the upper limit of category III, V and VI, minus the

Table 9
Contribution of each category to the global site potential

Category	Remarks	Potential bioenergy supply in EJy^{-1}
I: Biomass production on surplus agricultural land	Available area 0–2.6 Gha, yield energy crops 10–20 Mg $h^{-1}y^{-1}$	0–988
II: Biomass production on degraded lands	Available area 430–580 Mha, yield 1–10 Mg ha^{-1} y^{-1}	8–110
III: Agricultural residues	Estimate from various studies	10–32
IV: Forest residues	The (sustainable) energy potential of the world's forest is unclear. Part is natural forest (reserve). Range is based on estimate from various studies	10–16 (+32 from bio-materials waste)
V: Animal manure (dung)	Estimates from various studies	9–25
VI: Tertiary residue (organic waste)	Estimates from various studies	1–3
VII: Bio-materials	This depends highly on demand for biomaterials. Area 416–678 Mha. This demand should come from category I and II	Minus (0) 83–116
Total		33–1130

upper limit of the bio-materials. It is assumed that bio-materials compete for the energy crops, as well as the residues. Therefore, the potential processing residues from bio-materials (32 EJy^{-1}) are add to category VI. The highest range is based on the most optimistic estimates (opposite figures). Furthermore, it is assumed that no bio-materials are used. This results in a range for the potential of primary biomass of 33–1130 EJy^{-1}. The highest figure implies a potential of energy on surplus land and degraded areas at 988 and 110 EJy^{-1}. The lowest figure is caused by low numbers for energy crop potential and high figures for bio-materials.

6.2. Discussion

This study has aimed to explore the ranges of the geographical potential of biomass energy on the longer term. Six supply options are identified and one competing option; biomass for material applications. By taking these potential supply options into account, we have included the main possible biomass resources. The categories are described independently other, i.e., interactions between categories are not taken into account in an integrated matter. Two extreme scenarios have been used. Using this approach, the transparency of the results is high and therefore insight in influential factors is increased.

The high estimate for energy crop is a result from the high estimate of surplus agricultural area assessed in this study. This range can be explained by several factors:

1. It is assumed that all surplus agricultural (and degraded land) can be used for energy farming whereas other estimates only used part of the surplus area.
2. The assumed future food consumption is low compared to other studies. The FAO for example, assumes 13.0 MJ $day^{-1}person^{-1}$ in 2030 [26] and IMAGE simulations with baseline A and B, as developed by the RIVM [31], assume an energy intake from agricultural products in 2050 of, respectively, 15 and 14 MJ $day^{-1}person^{-1}$.

Based on Luyten [23] we use a figure of 11.7 MJ $day^{-1}person^{-1}$. Assuming a further increase of energy intake will not change our results, as with the present upper limit, already no surplus agricultural land has been assessed. However, it can be a signal that even the assumed moderate diet might be rather low compared to other studies.

3. The assumed agricultural yields of the HEI system (highest figure) are high compared to present yields and historical yield growths. The yields from the HEI system can only occur if the present yield increases 2%/year. Between 1990 and 1999 the global average yield increased by only 1%/year.

We are aware of the uncertainties accompanying the input data and assumptions. Some assumptions have been discussed above. The result of the biomass production on surplus agricultural land depends highly on the assumed yield of energy crops and to the assumed security factor. However, the results of the biomass production on surplus agricultural area are not sensitive to the assumed share of irrigated area.

7. Conclusions

The study presented analysis of the ranges of the global potential of biomass for energy on the long term. It is stressed that this study is explorative. The focus is not on the exact figure of the biomass energy potential, rather on the underlying factors influencing this potential. The analysis shows that the future geographical potential of biomass energy ranges from 35 to 1135 EJy^{-1}. The result is mainly determined by the potential of energy farming that is the result of land availability and biomass productivity. The biomass productivity—assumed to range from 10 to 20 tonne ha^{-1} y^{-1}—is mainly determined by local factors, like the soil quality, climate, water availability and management factors. However, the upper limit requires higher energy inputs. At this point energy balances of the biomass production should be studied. The land availability is determined by the land requirements for food demand. This is a function of the future diet, population growth, but most important, the food production system (e.g. HEI vs. LEI system and meat and dairy production methods). In order to achieve high biomass energy potentials, considerable transitions are required in the agricultural system, especially in the way meat and dairy products are being produced. Application of high production levels implies that the knowledge available in the western countries is diffused world-wide (e.g. in developing countries in particularly, the present efficiency of cattle breeding and food production is relatively low). This requires transfer of capital and adaptation of production technologies to local conditions. However, "although the time horizon of fifty years encompasses two generations, the feasibility to achieve 'best technical means' world-wide may be doubted" [23].

As indicated by the range, a shortage of agricultural land may also occur e.g. when the world population and the food intake increase sharply (the latter accompanied by a high share of meat and dairy products) and the agricultural technology development stagnates. Due to interactions between food/forest products supply systems and energy, a high demand for food/forestry products results in less available land for energy farming (Category I and II). However, more residues are becoming available (Category III and IV). Nevertheless, the net impact is a significant reduction of the bio-energy potential.

Hence, from this study, one can conclude that the range of biomass potential is large, ranging from 33 to 1135 EJy^{-1}. To what extent biomass can contribute to the primary energy consumption, depends on crucial factors: (1) Population growth, economic development, global diet, and so food demand. (2) The efficiency of the production of food (e.g. HEI versus LEI food production system). (3) Yield of energy crops on surplus agricultural area and degraded land. (4) Future developments of competing products, like bio-materials, and competing land use types, e.g. other applications of surplus agricultural area and degraded land.

These figures imply that in order to release this amount of biomass, considerable transitions are required. Particularly in the way meat and diary products are being produced in developing regions. Large-scale implementation of biomass could only be possible under affluent diet consumption if the global average productivity per hectare increases. Hence, sustainable development policies could on the one hand meet economic development policies in improving the efficiency of the food production system. On the other hand they could diverge if extensive food production systems and biomass for energy are both pushed on a large scale.

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