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A bottom-up assessment and review of global bio-energy potentials to 2050

Edward M.W. Smeets*, André P.C. Faaij, Iris M. Lewandowski, Wim C. Turkenburg

Department of Science, Technology and Society, Copernicus Institute for Sustainable Development and Innovation, Utrecht University, Heidelberglaan 2, 3584 CS Utrecht, The Netherlands

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Abstract

In this article, a model for estimating bioenergy production potentials in 2050, called the Quickscan model, is presented. In addition, a review of existing studies is carried out, using results from the Quickscan model as a starting point. The Quickscan model uses a bottom-up approach and its development is based on an evaluation of data and studies on relevant factors such as population growth, per capita food consumption and the efficiency of food production. Three types of biomass energy sources are included: dedicated bioenergy crops, agricultural and forestry residues and waste, and forest growth. The bioenergy potential in a region is limited by various factors, such as the demand for food, industrial roundwood, traditional woodfuel, and the need to maintain existing forests for the protection of biodiversity. Special attention is given to the technical potential to reduce the area of land needed for food production by increasing the efficiency of food production. Thus, only the surplus area of agricultural land is included as a source for bioenergy crop production. A reference scenario was composed to analyze the demand for food. Four levels of advancement of agricultural technology in the year 2050 were assumed that vary with respect to the efficiency of food production. Results indicated that the application of very efficient agricultural systems combined with the geographic optimization of land use patterns could reduce the area of land needed to cover the global food demand in 2050 by as much as 72% of the present area. A key factor was the area of land suitable for crop production, but that is presently used for permanent grazing. Another key factor is the efficiency of the production of animal products. The bioenergy potential on surplus agricultural land (i.e. land not needed for the production of food and feed) equaled 215–1272 EJ yr^{-1}, depending on the level of advancement of agricultural technology. The bulk of this potential is found in South America and Caribbean (47–221 EJ yr^{-1}), sub-Saharan Africa (31–317 EJ yr^{-1}) and the C.I.S. and Baltic States (45–199 EJ yr^{-1}). Also Oceania and North America had considerable potentials: 20–174 and 38–102 EJ yr^{-1}, respectively. However, realization of these (technical) potentials requires significant increases in the efficiency of food production, whereby the most robust potential is found in the C.I.S. and Baltic States and East Europe. Existing scenario studies indicated that such increases in productivity may be unrealistically high, although these studies generally excluded the impact of large scale bioenergy crop production. The global potential of bioenergy production from agricultural and forestry residues and wastes was calculated to be 76–96 EJ yr^{-1} in the year 2050. The potential of bioenergy production from surplus forest growth (forest growth not required for the production of industrial roundwood and traditional woodfuel) was calculated to be 74 EJ yr^{-1} in the year 2050.

Keywords: Bioenergy; Potential; Global; Agriculture; Land use; Agricultural production efficiency

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*Corresponding author. Tel.: +31 30 253 76 88; fax: +31 30 253 76 01.
E-mail address: e.m.w.smeets@chem.uu.nl (E.M.W. Smeets).

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Contents

1. Introduction

In this article the potential of the earth to supply biomass for the production of renewable (green or CO_2 neutral) energy is analyzed. In 2001, the use of modern bioenergy was about 6 EJ, the use of traditional bioenergy was about 39 EJ and the global primary energy consumption was 418 EJ [1].[1] The net growth of biomass on the global land surface (the net primary production or NPP), which is defined as the amount of carbon dioxide converted into carbohydrates during photosynthesis (the gross primary

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[1] Traditional bioenergy is the use of biomass in open hearths and stoves for cooking and heating and includes energy from a

(*footnote continued*)
wide range of biomass resources (e.g., agricultural residues, forestry residues and (traditional) woodfuel). Modern bioenergy production is defined as the production of biomass for energy purposes (production of heat, fuels or electricity) and is from now on referred to in this article as bioenergy.

production or GPP) minus the amount lost through autotrophic respiration and decomposition, was estimated to be 2280 EJ yr^{-1} [2].[2] Thus, the use of biomass for energy is presently limited to only ca. 2% of the global NPP. However, an increase in the use of bioenergy is restricted by many factors, such as economic considerations (e.g., significant forest areas are too far from roads and are therefore economically unattractive for biomass production), legal restrictions (e.g., significant forest areas are protected and are therefore unavailable for biomass production), and the use of biomass for other purposes (e.g., food, materials and traditional woodfuel).

The use of biomass for the production of food,[3] materials and traditional bioenergy was estimated at 273 EJ yr^{-1} in 1998, equal to 12% of the global NPP [3–5]. The production of food, industrial roundwood, and traditional woodfuel involved an annual turnover of biomass equivalent to and 213, 28 and 32 EJ yr^{-1}, in 1998, respectively [5]. Roughly three-fourths of the biomass turnover used for the production of food, industrial roundwood and traditional woodfuel is lost during processing, harvesting and transport.[4] These figures suggest that the amount of biomass for modern bioenergy use could be increased by increasing the fraction of the NPP appropriated to human development. Alternatively, the amount of biomass available for modern bioenergy use could be increased by increasing the efficiency of production of food, industrial roundwood and traditional woodfuel. However, when we take a look at the availability of land, it becomes clear that the potential for bioenergy may be more limited, because significant land areas are presently used for other purposes (e.g., urbanization and biodiversity reserve).

From the land area on the surface of the earth of 13 Gha, about 5.0 Gha (38%) is presently used for agriculture, 3.9 Gha (30%) is under forest cover, and 4.1 Gha (32%) includes a range of semi-natural vegetation types such as savannas, tundra's and scrubland, build-up land and barren land [4,6]. Many studies have been carried out that focused on the availability and suitability of land for bioenergy production. Projections showed that the largest bioenergy potential in 2050 comes from dedicated bioenergy crops grown on degraded land (8–110 EJ yr^{-1}) and surplus agricultural land (0–998 EJ yr^{-1}) [7]. The potential of agricultural residues was calculated to be 10–32 EJ yr^{-1} and the potential of forest growth was calculated to be 42–58 EJ yr^{-1}, excluding wastes [7]. One reason for the large range in estimates is the wide variety of approaches, methodologies and datasets used to estimate bioenergy potentials. Existing studies can be classified in various ways based on the approach applied. First, they can be classified as demand driven and supply driven, according to the key driving force that was considered. Demand-driven studies are defined as '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)'. Supply driven studies are 'assessments that focused on the total bioenergy resource base and the competition between different uses of the resources (supply side)' [8]. In a review of 17 studies on bioenergy potentials, 14 are classified as demand or supply driven and consequently ignore demand–supply interactions [8]. Many demand driven studies include some sort of evaluation of the feasibility of the projected use of bioenergy via reference to other studies. The supply-driven assessments roughly justify the ranges of bioenergy use projected in the demand driven assessments. Existing studies can also be classified based on the complexity of the approach applied. The least complex approach involves the use of expert judgment to estimate the future share of cropland, grassland and forests available for bioenergy crop production (e.g., [9]). The most complex approach involves the use of integrated models such as the Global Land Use and Energy Model (GLUE) [10], the Integrated Model to Assess the Global Environment (IMAGE) [11,12] and the Basic-Linked System (BLS) model of the world food system [13]. The use of integrated models allows for a comprehensive analysis of multiple variables using a scenario approach. A second reason for the large range in

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[2] The GPP was estimated at 120 Pg yr^{-1} [2], equal to 4560 EJ yr^{-1}, assuming that roughly half of dry weight biomass is carbon and assuming a higher heating value of 19 GJ odt^{-1}. Roughly half of this amount is lost through autotrophic respiration and decomposition [2].

[3] The term 'food', as used in this article, includes vegetal and animal products; in like manner the term 'food production' includes the production of food crops and the production of feed and the term 'food' includes food and feed.

[4] Of the 213 EJ yr^{-1} biomass turnover in the food production system, 25 EJ yr^{-1} was actually consumed (eaten) by humans in 1998. The biomass turnover in the food production systems includes the use of biomass from permanent pastures through grazing of animals. Of the 28 EJ yr^{-1} biomass turnover for the production of industrial roundwood, 9 EJ yr^{-1} was actually included the final product and of the 32 EJ yr^{-1} biomass turnover for the production of woodfuel, 20 EJ yr^{-1} was actually used as woodfuel.

estimates is the uncertainty of two crucial factors, the availability of land for bioenergy production and the yield (per unit of land; [8]). Most projections indicate that the demand for food, industrial roundwood and traditional woodfuel will increase during the coming decades as a result of population growth and income growth, although the exact growth rates remain uncertain. Also, in most studies the supply of biomass for energy production was restricted to biomass not needed for the production of food, industrial roundwood and traditional woodfuel, and to areas not reserved for the protection of biodiversity. Consequently, the largest uncertainty concerns the future demand for land for these purposes.

In this article, the bioenergy production potential in 2050 is analyzed, taking into account biological and climatological limitations and the future use of biomass for the production of food, materials and traditional woodfuel as well as the need to maintain existing forests for the protection of biodiversity. This analysis was carried out in two ways. First, by developing and applying a bottom-up model, called Quickscan, to calculate bioenergy potentials in 2050. Second, by reviewing existing bioenergy potential assessments using results of the Quickscan model as a starting point. Specific attention is given to various disadvantages of existing studies on bioenergy potentials that were identified. First, in existing studies limited attention was given to the impact of the various factors that determine the bioenergy potential. For a successful introduction of policies to promote bioenergy, insight is required under which conditions the production of bioenergy can be realized. In our study, the impact of various factors is made explicit by means of a transparent bottom-up calculation model and sensitivity analysis. Second, existing studies often ignore or only partially identified weak spots in the knowledge base. The identification of uncertainties and gaps in scientific knowledge is crucial for a correct interpretation of results and to initiate further research. In this study, weak spots in the knowledge base are identified and discussed. Third, in most studies limited attention is given to discrepancies between data and results from bioenergy potential studies and from agricultural and forestry outlook studies (e.g., [14,15]). In our study data from existing databases, model calculations and scenario studies are included. In doing so, we aim to ascertain a high degree of robustness of the results and conclusions. Fourth, the impact of applying sustainability criteria is specifically addressed in this study. Sustainability criteria are e.g., the avoidance of deforestation, the competition for land between bioenergy production and food production and the conservation of biodiversity. Therefore, this study can be categorized as ‘supply driven’.

The model developed in this study allows a ‘quick scan’ of technical bioenergy potentials in the year 2050 and is therefore named the Quickscan model. Three sources of biomass energy sources are evaluated: dedicated bioenergy crops, agricultural and forestry residues and waste, and forest growth. The technical potential of bioenergy crop production is analyzed based on various levels of efficiency of food production. The technical potential of bioenergy from surplus forest growth is based on the yearly increment, i.e. the maximum amount of wood that can be harvested from forests annually without deforestation or reducing the standing stock. The technical potential of residues and wastes is based on the technical potential to collect agricultural and forestry residues and wastes and by considering the amount of residues needed as animal feed. In the model, no matching of demand and supply through prices is made. The model can be applied at a global, regional, national and sub-national level, as long as sufficient data are available. In this article, results are presented at a global and regional level. The model has already been applied at a national level for Brazil and Ukraine [16] and Mozambique [17]. In addition, the model can be expanded with economic analysis, as demonstrated in [16,18].

In Section 2 the approach followed in this study is outlined and also the Quickscan model is presented. In Sections 3–5 the calculation procedures included in the Quickscan model are described. Results of the analysis are presented in Section 6. In Section 7 the bioenergy supply in 2050 in each region is compared with the demand for energy, which may serve as indicator of the bioenergy export potential of a region. Section 8 deals with results of the sensitivity analysis. In Section 9 the results presented in previous sections are compared with results of other studies and critically reviewed. In Section 10 final conclusions are presented.

2. Approach

The key factors that determine land use patterns and consequently the potential to produce biomass for energy production were identified based on a literature review of bioenergy potentials, forestry and agriculture. Fig. 1 provides an overview of the

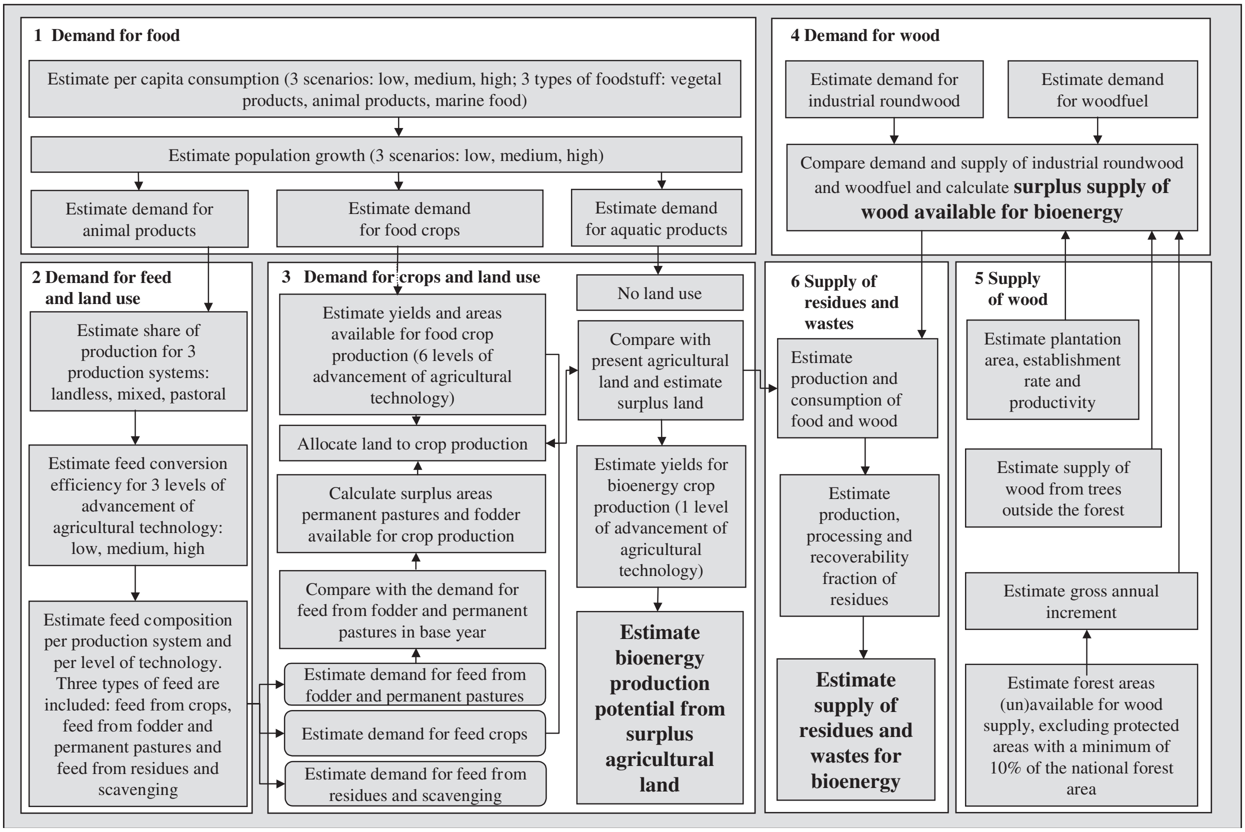

Fig. 1. Overview of the key elements in the methodology to assess the bioenergy potential from dedicated bioenergy crops.

key factors and the most important interactions between them, as included in this study.

For each of these factors historic trends were derived from statistics and literature. Trends to 2050 were analyzed based on forecasting and scenario studies. Therefore, a large part of this exercise involved a review and evaluation of existing databases and outlook studies. In doing so, we identified uncertainties and gaps in the knowledge base. Further, a tool was designed to analyze the bioenergy potential that included the key-variables and correlations depicted in Fig. 1. The tool is an Excel spreadsheet and was called the Quickscan model.

Three sources of bioenergy are included: dedicated crops (see Section 3), surplus natural forest growth (Section 4) and biomass from residues and waste (Section 5), as defined below.[5] The Quickscan model consists of six parts that represent the most important aggregated determinants of bioenergy potentials, see Fig. 1. The results of the Quickscan model were used to make a comparison with existing studies and to explain differences in results.

In our approach the supply of *bioenergy from dedicated crops* is restricted to the production of dedicated (energy) crops from surplus agricultural land, to avoid competition with food production. Agricultural land includes cropland and pastures. Dedicated bioenergy crops include conventional crops (e.g., sugar cane, wheat, maize), woody bioenergy crop (e.g., eucalyptus, willow, poplar) and grasses (e.g., miscanthus). Surplus agricultural land is generated when food consumption decreases and/or when more efficient food production methods offset increases in food demand. However, a decrease of the consumption of food is unlikely, because several studies indicate that the consumption of food will increase during the coming decades [15,20,21]. Therefore, the focus in this study is on the potential to increase the efficiency of food production. Various studies have indicated that the potential to increase

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[5] The bioenergy potential from aquatic plants was excluded from this study, because we considered that insufficient data were available for such an assessment. However, the potential may be substantial compared to conventional energy crops, considering the high yield potential of cultivated micro algae production (up to 150 odt $ha^{-1}\,yr^{-1}$) [19].

the efficiency of especially food production is significant. For example, Wolf et al. [22] calculated that up to 38% of the present agricultural land could be made available for bioenergy production in the year 2050, assuming a moderate population growth, an (on average) affluent diet, and an high input crop production system. Further, the Food and Agricultural Organisation of the United Nations (FAO) reported that in many countries average wheat yields (expressed in $\mathrm{t\,ha^{-1}\,yr^{-1}}$) for the period 1996–2000 were below the agro-ecologically attainable yield levels [15]. For example, in India, Argentina, Brazil, Ethiopia, Tanzania and Turkey, wheat yields were calculated to be 45%, 57%, 54%, 30%, 50% and 44%, respectively, of the attainable yield. Several industrialized regions also had yields that were below the agro-ecologically attainable yield levels, such as Australia and the USA, where the average wheat yields were 48% and 47% of the attainable yield, respectively.

The potential of *bioenergy from dedicated crops* (Section 3) is calculated in parts 1–3 of the model:

(1) *Demand for food* (*Section* 3.1): The demand for food was modeled as a function of population growth and per capita food intake.[6] The demand for food is analyzed separately for vegetal products, animal products and marine food, because of the associated differences in production systems.

(2) *Demand for feed and associated land use* (*Section* 3.2): Assuming a certain demand for food, the demand for feed and the associated amount of land needed for the production of animal products is dependent on the efficiency of production. The efficiency is determined by the production system, the feed composition, the animal species and the level of advancement of agricultural technology.[7] Based on these factors, the demand for land for pastures and feed crop production is calculated. The demand for feed crops is added up to the demand for food crops.

(3) *Demand for crops and associated land use* (*Section* 3.3): Assuming a certain demand for food and feed crops, the amount of land required for the production of crops for feed and food is dependent on the crop yield (expressed in $\mathrm{t\,ha^{-1}\,yr^{-1}}$). Crop yields are determined by the following key factors: (1) the productivity of the land, which is determined by natural conditions (e.g., rainfall, irradiation, temperature, and soil characteristics) and the level of advancement of agricultural technology, and (2) the geographic optimization of land use towards yields that minimizes the cropland.

Note that the potential impact of energy crop production on biodiversity, other than an expansion of the area of agricultural land, is excluded from this study. Potential impacts may occur both directly (as a result of the energy crop production) and indirectly (as a result of the intensification of agriculture).

The assessment of the potential of *bioenergy from surplus natural forest growth* (Section 4) is based on the approach and results presented in Smeets and Faaij [5]. In this approach, three (sustainability) criteria were included that limit the supply of bioenergy from natural forests. First, protected forest areas were excluded from wood production. Second, deforestation[8] for bioenergy production was not allowed, assuming that deforestation endangers sustainable development. Third, competition between the use of forest biomass for energy production and woodfuel[9] or industrial roundwood production should be avoided as it could hamper economic growth and endanger the supply of traditional biomass. Therefore, bioenergy production from forests was limited to *surplus* forest growth, which is defined here as the supply of wood minus the demand for woodfuel and industrial roundwood. The potential from surplus forest growth is calculated in parts 4 and 5 of the Quickscan model:

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[6] The term ‘food intake’, ‘food demand’ and ‘food consumption’ are used alternately in this study. All three terms refer to the intake of food as derived from trend extrapolations and existing studies. They do not reflect the food intake required to avoid undernourishment or hunger, as further discussed in Section 3.1.3.

[7] The term ‘level of advancement of agricultural technology’ refers both to the level of technology (e.g., the use of varieties that are resistant against diseases) and to the level of inputs (e.g., the use of mechanised tools, irrigation, fertilizers and pesticides). The term ‘level of advancement of agricultural technology’ is abbreviated in this study to ‘level of agricultural technology’ or ‘level of technology’.

[8] Deforestation is defined as a reduction of the forest area or a reduction of the standing stock.

[9] The term ‘woodfuel’ refers to the traditional woodfuel only, which includes the use of wood in open hearths and stoves for cooking and heating.

(4) *Demand for wood* (*Section* 4.1). The demand for wood is the sum of the demand for woodfuel and industrial roundwood.

(5) *Supply of wood* (*Section* 4.2). Three sources of wood supply are included, which are trees outside forests (TOF), plantations and natural forest growth.[10] The amount of wood that can be supplied by natural forests (old-growth plus second growth) is determined by the forest area, the rate of forest growth and the fraction of the forest growth that is harvested. In case of a surplus of wood production, the surplus is (in theory) available for bioenergy use.

The third category is *bioenergy from biomass residues and waste* (Section 5), which is represented by part 6 in Fig. 1:

(6) *Bioenergy from residues and waste*[11] (*Section* 5). The potential is calculated by multiplying the consumed, harvested and processed quantities of food and wood (parts 1–5 in Fig. 1) by the conversion efficiency and the recoverability fraction, i.e. the share of the residues that realistically can be recovered for energy production. The demand for residues and wastes to be used for animal feed, as calculated by the model, is subtracted from the potential from agricultural residues.

2.1. Types of potential

The term bioenergy 'potential' as used in this article refers to the energy content of the biomass and excludes the amount of energy required during production, transportation and conversion.[12] Five types of potential (EJ yr^{-1}) are defined (adjusted from [25,12]):

- *Theoretical potential*: the theoretical upper limit of bioenergy production that is limited by fundamental physical and biological barriers. The theoretical potential includes bioenergy production from land, rivers, seas and oceans.
- *Geographical potential*: the fraction of the theoretical potential of bioenergy production that is limited by the area of land.
- *Technical potential*: the fraction of the geographical potential that is not limited by the demand for land for food production, housing and infrastructure, and the conservation of forests, based on a (assumed) level of advancement of agricultural technology.
- *Economic potential*: the fraction of the technical potential that can be produced at economically profitable levels.
- *Implementation potential*: the fraction of the economic potential that can be implemented within a certain timeframe, taking into account institutional and social constraints and policy incentives.

In this study the focus was on the technical potential to identify and analyze the relevant underlying factors of bioenergy production in detail. Economic and implementation potentials are discussed in Sections 9 and 10.

2.2. Selection of results

A large number of variables are included in this study. For each variable, scenarios and/or ranges were included, but results are only presented for a baseline scenario whereby only the key variables were varied. Table 1 gives an overview of the key parameters of the baseline scenario and their values for the base year, 1998 and for 2050. See further Sections 3–5.

Four levels of advancement of agricultural technology[13] for food production are included that represent the (technical) potential to increase the efficiency of food production. These are defined in Table 2. These four levels are from now on referred to as 'agricultural production system' or 'system' 1–4; see Sections 3–5 for detailed information about these systems. These four levels have been selected, as they are the only agricultural production systems sufficiently efficient to meet the global demand for food forecasted for 2050

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[10] The term 'plantation' refers to plantations used for the production of industrial roundwood and woodfuel, excluding plantations used for dedicated energy crops. The production of wood from plantations for modern bioenergy applications is included in the category dedicated bioenergy crops.

[11] Residues and waste include by-products and waste from food crop and wood harvesting, processing, transporting and storing and excludes wood from thinning, as this is included in the category bioenergy from surplus forest growth.

[12] The energy required for the production of woody energy crops is typically equal to 3–10% of the energy included in the biomass [23]. The energy required for the transportation of solid biomass (including drying, storage, preprocessing) could be as high as 15%, depending on circumstances [24].

[13] The term 'system' or 'agricultural production system' as used in this study includes all activities required for the production, harvest, transport, storage and processing of food.

Table 1
Key variables, their assumed values for 1998 and 2050 and the main sources used to obtain the data

Parameter	1998	2050	Unit	Remark	Source
Population	5.9	8.8	billion	Medium growth scenario.	[28]
Per capita consumption	2739	3302	$\text{kcal cap}^{-1}\text{day}^{-1}$	Figures for 2050 are based on trend extrapolations from 2030.	[15]
Economic growth	2.6		$\%\text{ yr}^{-1}$	World Bank economic projections are used as exogenous assumptions in the FAO projections on food consumption, which are used in the Quickscan model. The figure of $2.6\%\text{ y}^{-1}$ is the average GDP growth in the period 1998–2030.	[15]
Climate change	Excluded		—	The impact of climate change on crop yields is limited compared to increase in yields that are technically attainable, at least when looking at regional average numbers. Yet, for specific countries the impacts can be much larger.	—
Feed conversion efficiency	0.02–0.28	0.07–0.32	Kg product kg dm feed^{-1}	Data are based on a high level of advancement of agricultural technology. The first figure is for bovine meat and the second for poultry meat.	[3]
Woody bioenergy crop yields	8.4	18	$\text{t dm ha}^{-1}\text{y}^{-1}$	Global average yield level based on the suitability of the total area land on earth for bioenergy crop production.	[3]
Plantations for industrial roundwood and woodfuel	123	124–284	Mha	Low and high plantation establishment scenario. The 123 Mha refers to the year 1995.	[54]
Forest growth	3.4		m^3ha^{-1}	Average for all forest areas.	[47]
Industrial roundwood demand	1.5	1.9–3.1	Gm^3	Low and high projection in the year 2050.	Various, e.g., [54,74–76]
Woodfuel demand	1.7	1.7–2.6	Gm^3	Low and high projection in the year 2050.	Various, e.g., [3,74,75]
Deforestation	0	0	$\%\text{ yr}^{-1}$	In our analysis deforestation is not allowed, as it endangers biodiversity, also it can be avoided.	—
Global primary energy demand	418	601–1041	EJ yr^{-1}	The 418 EJ yr^{-1} refers to 2001. Low and high scenario.	[1,62]

Table 2
Overview of the four systems included in this study

Factor	System 1	System 2	System 3	System 4
Animal production system used (pastoral, mixed, landless)	Mixed	Mixed	Landless	Landless
Feed conversion efficiency	High	High	High	High
Level of technology for crop production	Very high	Very high	Very high	Super high
Water supply for agriculture (rain-fed = r.f., irrigated = irri)	r.f.	r.f. and irri.	r.f. and irri.	r.f. and irri.

based on the area of agricultural land used in 1998.

3. Bioenergy from dedicated bioenergy crops

In this section the calculation procedure and results are presented for each of the six sections of the Quickscan model depicted in Fig. 1: (1) demand for food (part 1), (2) demand for feed and land use (part 2), (3) demand for crops and land use (part 3; including the availability of land for and productivity of dedicated woody energy crops), (4) demand for wood (part 4), (5) supply of wood (part 5; including the potential supply of bioenergy from surplus forest growth), and (6) supply of residues and waste (part 6).

3.1. Demand for food

The FAOSTAT database of the FAO includes data for many items relevant for our study. The FAOSTAT database is the only database that provides data at a national average and has a global coverage [4]. For most data in the FAOSTAT database historic data are available from 1961 onwards. Some data in the FAOSTAT database may be inaccurate, because missing or inaccurate data have been supplemented by estimates of the FAO. This goes particularly for developing countries. In general, economic and financial data in FAOSTAT have probable the highest quality, being crucial for business and governance. The FAOSTAT database is commonly used in agricultural outlook studies with a global, regional or national scope (e.g., [14,26,27]).

In our model we use national data for the total demand of a specific commodity (*c*) in 1998 from the FAOSTAT Food Balance Sheets (FBS) as a starting point [4]. Data are summed up to regions.[14] Twenty-five animal and vegetal commodities are distinguished, as described below. The demand for a commodity is divided into categories, following the subdivision used in the FBS: food, processed food, other uses, feed, waste, seed and import and export, see Eq. (1).

$$\begin{aligned}\text{Demand} = {} & \text{Pop} \times (\text{Food} + \text{Proc} + \text{Other}) + \text{Feed} \\ & + \text{Waste} + \text{Seed Export} + \text{Import} \qquad (1)\end{aligned}$$

where Demand is the total demand for commodity *c* ($t\,yr^{-1}$), Pop the population (see Section 3.1.1) (number of people), Food the per capita consumption of commodity *c* for food (in unprocessed form; see Section 3.1.2) ($t\,yr^{-1}\,cap^{-1}$), Proc the per capita consumption of processed commodity *c* for food. Proc is assumed to increase at the same rate as Food. The share of Proc of the total global use was about 5% of the total production in 1998. Consequently, errors due to the assumed growth rate of Proc have a small impact on the overall results ($t\,yr^{-1}\,cap^{-1}$), Other the per capita consumption of commodity *c* for non-food purposes. It also included statistical discrepancies. We assume that Other increases at the same rate as Food. The share of Other of the total use was about 2% of the total production in 1998, globally, so errors resulting from the assumed rate of increase of Other have a small impact on the overall results ($t\,yr^{-1}\,cap^{-1}$), Feed the intake of commodity *c* by animals for feed (see Section 3.2) ($t\,yr^{-1}$), Waste the losses of commodity *c* occurring during processing, storage and transportation. The amount of waste is presented as a percentage of the total demand, assuming a low, medium and high level of advancement of technology (see Section 5.3) ($t\,yr^{-1}$), Seed the use of commodity *c* for seed or reproduction. FAOSTAT data on the present percentage of the total demand used as seed show that seed ratios are limited to a few percent of the total demand. Also, no correlation was found between this percentage and the level of advancement of agricultural technology in a region. Therefore, the percentage of the total supply used as seed is assumed constant ($t\,yr^{-1}$) and Export/import the import and export of commodity *c* are assumed to remain constant, unless trade is required to avoid regional food shortages (see further Box 2, Section 3.3.2) ($t\,yr^{-1}$).

3.1.1. Population growth

Population growth has been responsible for 80% of the increase in food consumption between 1970 and 1998 and probably will remain the key driver of increasing food consumption during the coming decades [15]. The United Nations Population Division (UNPD) has become the main authority in this field and UNPD projections are commonly used in outlook studies, see e.g., [15,20]. UNPD data are also used in this study; data are available at a country level and summed up into regional totals [28].

There is general agreement among demographers that population projections, if properly made, are 'fairly accurate for some 5–10 years' [29]. The reason is that the number of children that will be born within this period depends on the number of young adults in a population and this number is known from statistics. This effect is called the population momentum. Long-term population projections have proven to be more uncertain [29], particularly for developing regions. For example, the forecast error[15] in predicting the world population for the year 2000 was +0.5% for projections done in 1996, +3.3% for projections done in 1990,

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[14] 11 regions are included: North America, Oceania, Japan, West Europe, East Europe, C.I.S. and Baltic States, Sub-Saharan Africa, Caribbean and Latin America, Middle East and North Africa, East Asia and South Asia.

[15] Forecast error = 100 × (projected level−acutal level)/actual level, expressed as a percentage. A positive value indicates an overestimation, a negative value an underestimation.

and 7.1% for projections done in 1968 [30]. Errors were found to be higher for small regions (especially regions with a population of under 1 million) compared to large regions. Forecast errors varied between −35% and +9.0% for Africa, and −6.1% to +31% for the former USSR, compared to +0.5% to +7.1% for the world, for projections done between 1957 and 1998. Errors are also higher for developing countries compared to industrialized regions. For example, projection errors varied between −11 and +16 for industrialized regions compared to −35% and +23% for developing regions, for projections done between 1957 and 1998. Projection errors at the regional level used in this study, are 10% or below for a period of 30 years.

To reflect this uncertainty, the UNPD distinguishes six scenarios for the development of population of which the low, medium and high scenario are used in our model. The low and high scenarios are derived from the medium scenario: the fertility rate is set at 0.5 child below and above the medium fertility rate, respectively [28]. Although there is no clear scientific basis for this assumption, the low and high scenarios represent a bandwidth within which population might develop. No distribution of probability is presented for the various scenarios. The medium growth scenario may be considered the most likely scenario and is for that reason frequently used in outlook studies[16] (e.g., [15]). It should be noted that the uncertainty related to population projections seems to have increased during the previous decade: projections have been downward adjusted considerably, in total more than 10% during the last decade, partially because the impact of AIDS is evaluated to be more severe than earlier expected [28].

3.1.2. *Per capita demand for food*

During the last decades the average food intake per capita has steadily increased in most regions: on average from about 2360 kcal $\text{cap}^{-1}\,\text{day}^{-1}$ in the mid 1960s to 2798 kcal $\text{capita}^{-1}\,\text{day}^{-1}$ in 2002 [15]. This progress mainly reflects the increase in consumption in the developing countries, because consumption levels have reached saturation levels in the industrialized regions.

Projecting the consumption of food requires the matching of demand and supply. However, no attempt was undertaken to project food consumption by means of matching demand and supply, because such an exercise is considered too complex considering the purpose of this study; see Section 9 for a further discussion. Instead, projections of the FAO for the years 2015 and 2030 are used [15]. Together with projections from the International Food Policy Research Institute (IFPRI) [20] and the United States Department of Agriculture (USDA); e.g., [21] these are the most detailed projections available. The USDA and the IFRPI projections referred to above go to 2013 and 2020 only, respectively. Therefore, the FAO projections are used in our study.

The per capita food consumption (Food in Eq. (1)) in 2030 is calculated by multiplying the food intake per capita in 1998 (in $\text{t}\,\text{yr}^{-1}\,\text{cap}^{-1}$) derived from the FAOSTAT database [4] by the relative increase in the per capita consumption projected by the FAO [15]. Fourteen food product groups are included: cereals, roots and tubers, sugar crops, pulses, oil crops, vegetables, stimulants, spices and alcoholic beverages, bovine meat, mutton and goat meat, pig meat, poultry meat and eggs and milk. Consequently, changes in food consumption between the different product groups are included. In our study, the projections to 2030 were trend extrapolated to 2050 and the results of the trend extrapolation were down or upscaled using data from other sources [3,20]. For East Asia and South Asia trends were downscaled, because the rapid economic growth projected for the coming decades is assumed to flatten off in the longer term. The trend was upscale for sub-Saharan Africa, because the slow economic growth projected for the near future is assumed to increase in the longer term. In addition, a low and high scenario are included to capture the uncertainty related to extrapolation of projections from 2030 to 2050 and the uncertainty related to long-term projections in general. The low and high scenarios are based on an additional decrease and increase of 50%, respectively, compared to the projected increase between 2030 and 2050 (= 100%). The consumption was however not allowed to increase above 3700 kcal $\text{cap}^{-1}\,\text{day}^{-1}$, of which 1100 kcal $\text{cap}^{-1}\,\text{day}^{-1}$ animal products (including fish and seafood). This level was taken as

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[16] The scenarios described in the Special Report on Emissions Scenarios (SRES) of the Intergovernmental Panel on Climate Change (IPCC) are also a frequently used source of population projections [31]. These scenarios are based on storylines that describe developments in different social, economic, technological, environmental and policy areas. The population projections used in SRES are not intended to be used in modelling separately from the other areas.

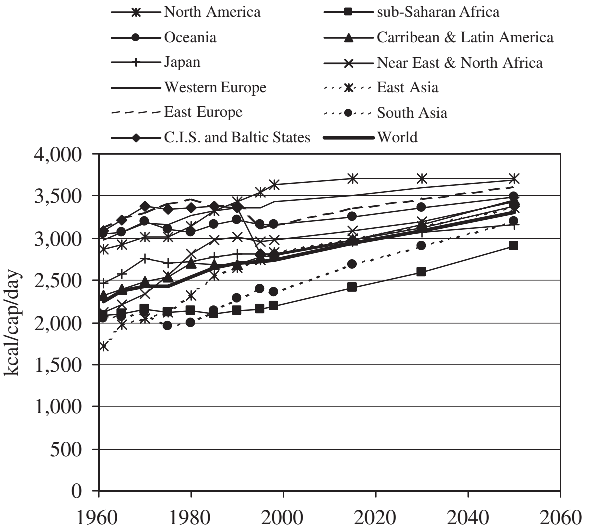

Fig. 2. Historic and projected per capita total food intake in the period 1961–2050 ($\mathrm{kcal\,cap^{-1}\,day^{-1}}$). *Sources*: [3,4,15,20] plus own calculations.

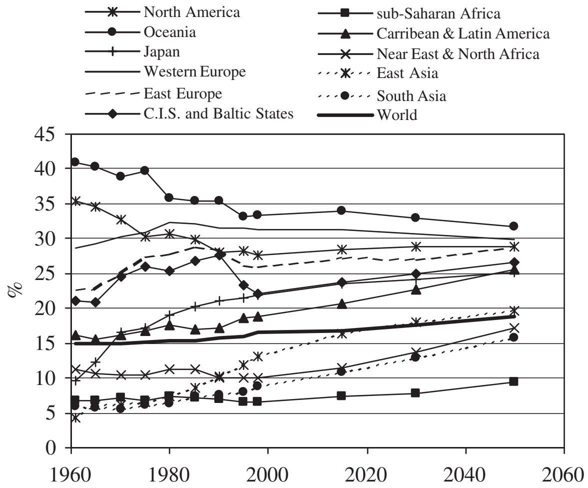

Fig. 3. Consumption of animal products in the period 1961–2050 (% of total daily caloric intake). *Sources*: [3,4,15,20] plus own calculations.

saturation level, because consumption in the industrialized countries is stabilizing at this level, despite increases in income. Fig. 2 shows the daily per capita food intake from 1961 to 2050 in the baseline scenario.

The consumption of food is projected to increase from 2739 $\mathrm{kcal\,cap^{-1}\,day^{-1}}$ in 1998 to 3302 $\mathrm{kcal\,cap^{-1}\,day^{-1}}$ in 2050. The average daily calorie intake in 2050 in the developing countries, transition economies countries, and industrialized countries was calculated at 3236, 3448, and 3629 $\mathrm{kcal\,cap^{-1}\,day^{-1}}$, respectively, of which 549, 941, and 1054 $\mathrm{kcal\,cap^{-1}\,day^{-1}}$ from animal products (including fish and seafood), respectively. The increase in the industrialized regions is limited, because consumption reached saturation levels in these regions. In the transition economies, consumption decreased considerably after the collapse of communism and the following economic restructuring. It may take several decades before consumption levels have reached their former levels. In the developing regions consumption increases rapidly, particularly in Asia. The consumption in sub-Saharan Africa is also projected to increase, although at a slightly lower rate, due to slower income growth compared to Asia. These data indicate that considerable differences in food intake remain present the coming decades, particularly with respect to the intake of animal products.

Vegetal products account for about three-fourth of the increase in the global average food consumption projected for 1998–2050; the remaining one-fourth comes from animal products (including fish and seafood). However, in relative terms the consumption of animal products is projected to increase faster than the consumption of vegetal products: the per capita consumption of vegetal products and animal products is projected to increase by 16% and 38%, respectively. Consequently, the share of animal products as percentage of the daily kcal intake increases, as shown in Fig. 3. The increasing demand for animal products is expected to have a large impact on the world food economy and that has therefore been referred to sometimes as the 'food revolution' or 'livestock revolution' [32].

Figs. 2 and 3 show that consumption levels in many developing regions may remain well below saturation levels in 2050 and consequently undernourishment may not be eradicated in the projections (see Section 3.1.3). Consumption in these regions is responsive to further increases in income or decreases in food prices compared to industrialized regions where saturation levels have nearly been reached. Small changes in GDP or prices may significantly increase consumption in developing regions, which means that projections for these regions are more uncertain.

3.1.3. Undernourishment

The figures on food consumption projected in this study are based on FAO projections and trend extrapolation. Thus, they do not refer to a required level of consumption to avoid undernourishment.[17] The FAO, the IFPRI and the USDA are moderately positive on the global food security situation, meaning that the supply is expected to increase at the same rate as demand and that the average per capita food consumption will remain stable or increase in all regions. Yet, undernourishment will most likely remain to exist during the coming decades: the number of undernourished people is projected to decrease from 815 million in 1990, to 610 million in 2015, and 440 million in 2030 [15]. The Millennium Development Goal (MDG; to halve the number of undernourished between 1990 and 2015) is not likely going to be met, unless additional activities are undertaken other than included in the FAO projections. In the projections of food consumption included in this study, undernourishment may or may not still exist. According to the FAO, the average food consumption per capita in the developing countries will increase from 2681 kcal $cap^{-1} day^{-1}$ in 1997–99 to some 2980 kcal $cap^{-1} day^{-1}$ in 2030. In our model, this trend is extrapolated to 2050, resulting in a consumption of 3236 kcal $cap^{-1} day^{-1}$ in 2050. Although the average intake is well above the undernourishment threshold of 1800–2000 kcal $cap^{-1} day^{-1}$, this is no guarantee for an adequate food consumption at the level of individuals. The FAO estimated that an average food intake of about 2700–2860 kcal $cap^{-1} day^{-1}$ corresponds with an adequate food supply in developing countries, assuming a reasonably egalitarian food distribution, and taking population-specific factors into account [33]. However, since no data are available on food distribution, undernourishment may not have been eradicated in the year 2050 in our scenarios.

We acknowledge that food production and food security must be given priority above energy crop production. However, this does not mean that the production of dedicated bioenergy crops should be banned in case undernourishment exists in a region. In reality, food insecurity is the result of a number of factors, including war, civil unrest and unequal distribution of income, rather than a lack of cropland. Further, the production of energy crops may provide new opportunities for farmers to generate income and diversify agricultural production. Diversification enhances resilience and flexibility with respect to changes in yields and prices, and also reduces the dependence on conventional cash crops of which the production and export is often hampered by saturated markets and trade barriers.

3.2. Demand for feed and land use

The consumption of animal products was identified as a key factor for agricultural land use, because the consumption of animal products increases rapidly and because the production of animal products is far more land intensive per kg product than crop production [15]. More than 70% of the global agricultural land use in 2002 was allocated to the production of animal products, while animal products accounted for some one-sixth of the total calorie intake [4].

Most outlook studies project that the land area used for the production of animal products will increase during the coming decades. For example, the area of pastures is projected to increase from 3.5 to 3.6 Gha between 2002 and 2030 [4,34].[18] In another study, the area of pastures in 2050 was calculated to be 3.5–3.8 Gha, dependent on the scenario [35]. The demand for land for the production of animal products could decrease if the increase in demand for animal products is outpaced by the increase in efficiency of the animal production system. This could generate surplus land that can be used for bioenergy production and this option is further analyzed below.

The efficiency of the production of animal products depends on a large number of factors, such as the species, the physical condition of the animals (e.g., age and weight, and the occurrence of diseases), the type and amount of feed provided (e.g., feed from pastures and concentrated feeds), and the stocking rate. As a result, the demand for feed per kg animal product ranges at present between 3 kg dry weight biomass input per kg poultry meat in a industrialized production system and based on an high level of advancement of technology, to more than 100 kg dry weight

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[17] Undernourishment refers to the status of persons whose food intake does not provide enough calories to meet their basic energy requirements. For an adult a food intake of 1300–1700 kcal $cap^{-1} day^{-1}$ is required for basal metabolic functions, in case of light activity an intake of 1800–2000 is required [15].

[18] Data for 2030 are based on data for 2002 [4] and the annual increase between 1998 and 2030 to avoid inconsistencies in base year data [34].

biomass input per kg bovine meat in a pastoral system and based on a low level of advancement of technology [3].

A consistent and coherent dataset at a national level with a global coverage about the impact of the various factors on the efficiency of the animal production system is not available. Data about the production of animal products are generally available. The FAOSTAT database includes data on, e.g., the number of animals slaughtered and the meat production per animal. Data on the input of feed in the animal production system is generally only available for products that are commercially produced and traded, such as feed crops. Data on the use of pastures are only available expressed in hectares, but not in the actual biomass extruded from pastures through grazing. Data on the use of animal feed from agricultural residues, waste and scavenging are not unavailable. However, various attempts have been made to calculate the biomass turnover in the animal production system, using various equations on daily animal feed and energy requirements (see e.g., [36,37]).

We use data from the IMAGE, which is operated by the Netherlands Environmental Assessment Agency (MNP), to calculate the future demand for feed [3,38].[19] Data for the base year 1998 are not available, so data from the IMAGE model for 1995 were used. Data for the four most important, aggregated factors that determine the efficiency of the production of animal products are included in our calculations, see Eq. (2).

$$\text{Feed} = \text{Demand} \times \text{Prod} \times \text{Fco} \times \text{Fce} \qquad (2)$$

where Feed is the demand for a type of animal feed for an animal product group for a production system for a level of (advancement of) agricultural technology. Four types of animal feed are included, as defined below ($\text{t}\,\text{yr}^{-1}$), Demand the demand for an animal product group (Section 3.1). Five animal product groups are distinguished: bovine meat, mutton and goat meat, pig meat, poultry meat and eggs, and dairy products ($\text{t}\,\text{yr}^{-1}$), Prod the animal production system, being the fraction of Demand produced by a production system (dimensionless), Fco the feed composition, being the fraction of a feed category in the total demand for animal feed. The Fco is determined for each animal product group, for each production system, and for each level of agricultural technology (dimensionless) and Fce the feed conversion efficiency, being the amount of animal product produced per amount of animal feed input. The Fce is defined for each product group, for each production system, and for each level of agricultural technology (dimensionless).

Eq. (2) is applied per region; so all factors in Eq. (2) are defined per region. Further, the amount of feed needed for the production of each type of animal product is calculated for each feed category, for each production system, and for each level of technology and each region. The level of technology refers to a.o., the use of breeding and animal health care programs, and balanced diets that decrease mortality rates, increase the production per animal and as a result increase the Fce. Three levels of agricultural technologies are defined (low, medium, high), as presented in Table 3.

The production system refers to all breeding, feeding and slaughtering activities, related storing and transportation activities and losses due to mortality. In our study, three production systems are defined:

(1) A pastoral system, in which most feed comes from fodder crops and grasses from grazing of permanent pastures.
(2) A landless (or industrial) system, in which animals are kept in stables and all feed comes from feed crops and residues.
(3) A mixed system, which is a combination of a landless and pastoral production system.

The production systems vary with respect to the feed composition and the feed conversion efficiency. Table 4 shows the global average feed composition for various animal product groups in 1998 and the average global feed composition in a pastoral, landless and mixed production system, also for various animal product groups.

Four feed categories are distinguished in our calculations, which are described in detail below: feed from grasses and fodder, feed from crops, feed from residues, and feed from scavenging. Feed from grasses and fodder is produced on cultivated and wild pastures. Wild pastures are by far the most important category in term of land area and feed production, and are from now on referred to as permanent pastures. The Fce is dependent on the

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[19] IMAGE is a dynamic integrated assessment-modelling framework for global change. The main objectives of IMAGE are to contribute to scientific understanding and to support decision-making by quantifying the relative importance of major processes and interactions in the society–biosphere–climate system [3].

Table 3
Level of advancement of agricultural technology for animal production systems

Level of agricultural technology	Description
Low	No or limited use of animal breeding, no disease prevention and treatment, equivalent to subsistence farming (as in rural parts of e.g., Africa and Asia).
Intermediate	Some use of animal breeding, some use of feed supplements (e.g., minerals, enzymes, bacterial inoculates) and some use of dedicated animal housing.
High	Full use of all required inputs and management practices (as in advanced commercial farming presently found in the USA and EU), such as animal breeding, animal disease prevention, diagnosis and treatment, the use of feed supplements (e.g., minerals, enzymes, bacterial inoculates), the use of dedicated animal housing.

Table 4
Feed composition in 1998 and in a low and high level of advancement of agricultural technology for a landless, mixed and pastoral production system (% of total demand for feed per type of animal product)

Production system	Level of technology	Feed category	Bovine meat	Milk	Mutton and goat meat	Pig meat	Poultry meat and eggs
Landless	High	Grasses and fodder	0	0	0	0	0
		Feed crops	80	80	75	75	75
	(= systems 3 and 4)	Residues	20	20	25	25	25
		Scavenging	0	0	0	0	0
Mixed	High	Grasses and fodder	50	50	85	0	0
		Feed crops	30	30	10	75	75
	(= systems 1 and 2)	Residues	20	20	5	25	25
		Scavenging	0	0	0	0	0
Mixed	Low	Grasses and fodder	85	85	90	0	0
		Feed crops	5	5	0	75	75
		Residues	5	5	5	25	25
		Scavenging	5	5	5	0	0
Pastoral	High	Grasses and fodder	95	95	95	n/a	n/a
		Feed crops	5	5	0	n/a	n/a
		Residues	0	0	5	n/a	n/a
		Scavenging	0	0	0	n/a	n/a
Pastoral	Low	Grasses and fodder	95	95	95	n/a	n/a
		Feed crops	0	0	0	n/a	n/a
		Residues	0	0	0	n/a	n/a
		Scavenging	5	5	5	n/a	n/a
World	1998	Grasses and fodder	64	54	79	0	0
		Feed crops	8	12	1	50	53
		Residues	17	25	4	50	47
		Scavenging	11	9	16	0	0

Sources: [15,38] plus own calculations.

production system and the level of technology used in the animal production system. In our study, the lower range of Fce's in different regions in 1995 is used as a proxy for a low level of technology, the higher range of Fce's as a proxy for a high level of technology. The Fce's in a medium level of technology are the average of a low and high level of technology. This approach is used for both the pastoral and the mixed production system. The Fce's in the landless production system are assumed to be the same as the Fce's in the mixed production system, because the potential to increase the Fce's above the level in the mixed production system is likely limited. Table 5 shows the inverse of the global average Fce's for various animal product groups in 1998

Table 5

(a) Inverse of the feed conversion efficiency in 1998 (kg dry weight feed/kg animal product)

Region	Bovine meat	Milk	Mutton and goat meat	Pig meat	Poultry meat and eggs
North America	26	1.0	58	6.2	3.1
Oceania	36	1.2	106	6.2	3.1
Japan	15	1.3	221	6.2	3.1
West Europe	24	1.1	71	6.2	3.1
East Europe	19	1.2	86	7.0	3.9
C.I.S. and Baltic States	21	1.5	69	7.4	3.9
Sub-Saharan Africa	99	3.7	108	6.6	4.1
Caribbean and Latin America	62	2.6	148	6.6	4.2
Middle East and North Africa	28	1.7	62	7.5	4.1
East Asia	62	2.4	66	6.9	3.6
South Asia	72	1.9	64	6.6	4.1
World	45	1.6	79	6.7	3.6

(b) Inverse of the feed conversion efficiencies in a low and high level of advancement of agricultural technology (kg dry weight feed/kg animal product)

Production system	Level of technology	Bovine meat	Milk	Mutton and goat meat	Pig meat	Poultry meat and eggs
Mixed (same as landless)	High (= system 1–4)	15	1.0	46	6.2	3.1
Mixed (same as landless)	Low	60	3.0	125	7.5	4.1
Pastoral system	High	37	1.4	58	—	—
Pastoral system	Low	125	4.5	150	—	—

Sources: [15,38] plus own calculations.

and the inverse of the Fce's in a pastoral, landless and mixed production system for various levels of agricultural technology and for various animal product groups.

As shown in Tables 4 and 5, both the Fco an Fce vary widely between regions, production systems and animal product groups. In 1998, 56% of the global feed consumption came from fodder crops and permanent pastures, 24% from residues, 12% from feed crops, and 8% from scavenging (on dry weight mass basis). These numbers indicate the importance of the use of other sources than crops for feed. The data also show that variation in feed composition and feed conversion efficiencies between regions and between production systems is more limited in pig and poultry production systems compared to bovine meat and dairy production systems. The reason is that pig and poultry production systems are relatively uniform: they can be classified as mixed or landless. Bovine meat and dairy production systems range widely, from landless to grazing systems. The highest feed conversion efficiency is reached in landless production systems, the lowest in pastoral production systems.

Table 6 shows the increase in total feed demand in 2050 for agricultural production systems 1–4 compared to 1998.

Table 6 shows that in agricultural production systems 1–4, the total demand for feed is projected to increase by a factor 1.1 between 1998 and 2050. Note that the Fce is the same for a mixed animal production system (systems 1 and 2) and a landless production system (systems 3 and 4), so there is no difference in the increase in total feed demand between 1998 and 2050. The demand for animal products is projected to increase by a factor 2.2 (on caloric basis). Consequently, the amount of feed required per kcal animal product decreases by a factor 2, due to two reasons. First, the feed conversion efficiency assumed for 2050 in systems 1–4 was based on a high level of advancement of agricultural technology. Second, pig and poultry production systems have lower average feed conversion efficiencies than ruminant production systems and the consumption of pigs and poultry products, was projected to increase compared to ruminants.

Systems 1–4 vary with respect to the animal production system used and consequently with

Table 6
Increase in total feed demand between 1998 and 2050 for various combinations of the production systems and the level of agricultural technology

Level of technology (feed conversion efficiency)	Pastoral (%)	Mixed (%)	Landless (%)
Low	383	201	—
Medium	223	106	—
High	63	12	12

respect to the composition of the feed mix used. In a mixed animal production system (included in systems 1 and 2) some use is made of fodder crops and grasses, while in a landless animal production system (included in system 3 and 4) no use is made of fodder crops and grasses: all feed comes from crops and residues.

Table 6 also shows that in case a pastoral production system and/or a low or medium level of technology would be used in 2050, the demand for feed would increase compared to the demand for feed in 2050 in case of systems 1–4. In case a pastoral animal production system would be used in 2050, the total primary demand for feed would increase by 63–383% compared to 1998, depending on the level of technology. In case a mixed production system would be used in combination with a low and medium level of technology, the demand for feed would increase by 106% up to 201%. In terms of energy, the demand for feed is calculated to be 96 EJ in 1998, which corresponds to 35% of the total turnover of biomass for the production of food, material and woodfuel. The demand for feed in 2050 is calculated to be 156–464 EJ, assuming a higher heating value of 19 GJ odt^{-1} (oven dry ton).

The demand for feed categories is translated into land use as follows:

- *Feed from grasses and fodder*: A suitable method to estimate the area of pastures required to meet the demand for feed from grassess and fodder, would be to limit the supply of feed to the carrying capacity. However, the carrying capacity of pastures in the various regions is difficult to estimate due to a lack of data. Indicators for the pressure on pastures are e.g., the livestock density, the livestock mobility, the net primary productivity (NPP), the rain use efficiency (RUE), the grass species composition and the rate of soil erosion [39]. Data on these issues and our understanding of the complex ecosystems of pastures are insufficient to reach consensus on the carrying capacity of the pastures. In the Quickscan model, the demand for feed from pastures is translated into land use as follows: if the demand for feed from pastures is projected to increase compared to the base year (1998), the increase is added to the demand for feed crops. By doing so, the demand for feed from permanent pastures and fodder crops is kept constant, avoiding increases in grazing intensities to minimize environmental problems (e.g., soil degradation). In case of a decrease, the area of permanent pastures and the areas used for fodder crop production are assumed to decrease correspondingly.
- *Feed from crops*: The demand for feed from crops is added to the demand for food crops and translated into land use as described in Section 3.3.
- *Feed from residues and scavenging*: No land use is allocated to feed from residues. The use of feed from residues and scavenging is subtracted from the amount of residues and waste available for energy production, see Section 5.

Table 7 shows the surplus pasture area in systems 1–4 in 2050. The results illustrate the large impact of changes in the share of the animal production systems on land use patterns. The surplus areas of pastures in Table 6 provide no information on the production potential for bioenergy on these areas, because (part of) the land may be needed for food production.

The decrease of the area of pastures in systems 1 and 2 compared to 1998 is the result of the conversion to a completely mixed production system with a high level of technology. In a mixed production system 50% of the animal feed required for the production of bovine meat and dairy comes from grasses and fodder crops. In 1998, 64% of the feed intake in the bovine production system and 54% of the feed into in the dairy production system came from pastures. In case system 1 and 2 are applied, the demand for feed from pastures and fodder decreases from 56% of the total demand for feed for all animal products in 1998, to 41% in 2050. The remaining 59% of the feed demand is supplied by residues (11%) and feed crops (48%). As a result, the area of permanent pastures and land used for fodder production in systems 1 and 2 was calculated

Table 7
Surplus pasture areas in 2050 in system 1–4 (Mha)

Region	Systems 1 and 2: mixed animal production system (Mha)	Systems 3 and 4: landless animal production system (Mha)
North America	92	322
Oceania	261	449
Japan	0	1
West Europe	31	78
East Europe	2	26
C.I.S. and Baltic States	92	437
Sub-Saharan Africa	311	820
Caribbean and Latin America	395	613
Middle East and North Africa	0	366
East Asia	4	537
South Asia	0	26
World	1188	3675

to decrease to 1.2 Gha between 1998 and 2050. For comparison: the total global area of arable land (excluding fodder crops) and land used for permanent crops was calculated to be 1.3 Gha and the area permanent pastures and arable land used for fodder production was 3.6 Gha [4]. The largest contribution of the surplus areas to be used for food crop or bioenergy crop production in systems 1 and 2 comes from the Caribbean and Latin America (33%), sub-Saharan Africa (26%) and Oceania (22%). The contribution of other regions to the surplus areas was limited to 22%, but from a regional perspective significant percentages of the area of permanent pasture and arable land used for fodder production are surplus. In West Europe, North America, and the C.I.S. and Baltic States 40%, 29%, and 21% of the total area of pastures could be made superfluous, respectively. Further, systems 3 and 4 include a landless animal production system, in which all animals are kept in stables, coops etc., and all feed is supplied by crops and residues. Consequently, all pastures used in 1998 could in theory be made available for the production of food and energy crops. According to the FAOSTAT data, these areas include 3.5 Gha permanent pastures and an area of 0.2 Gha under fodder crop production [4]. The largest contribution comes from sub-Saharan Africa (22%), Caribbean and Latin America (17%), and East Asia (15%).

3.3. Demand for crops and land use

In our study, the area that is agro-ecologically suitable and available for crop production is calculated (Section 3.3.1). Second, the agro-ecologically attainable yield of food and energy crops is calculated (Section 3.3.2). Third, the potential to generate surplus agricultural land for the production of bioenergy is estimated (Section 3.3.3). Fourth, bioenergy potential from surplus agricultural land is calculated (Section 3.3.4).

Base year (1998) data on harvested areas and yields per country are derived from the FAOSTAT database [4]. Projections of the global area under crop production in the coming decades indicate that this area will remain constant or increase. For example, the area under crop production is projected to increase from 1.5 to 1.6 Gha between 2002 and 2030 [4,34].[20] In another study, the area under crop production in 2050 was estimated to be 1.6–1.7 Gha, dependent on the scenario [35]. However, as already highlighted in the introduction, various studies have indicated that the technical potential to increase crop yields above the levels projected for 2050 is substantial.

In this study, the production of food and feed crops is geographically optimized, which means that the production of a crop is allocated to areas with the most favorable natural circumstances for that crop type. In doing so, regions with the highest yield per hectare and the lowest demand for agricultural land for food crop production that can be obtained was found.

Agro-ecologically (technically) attainable crop yields levels can be estimated by means of crop

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[20] Arable land and land use for the production of permanent crops is partially used for the production of feed crops. Data for 2030 are based on the areas in 2002 [4] and the annual increase between 1998 and 2030 as projected by Wirsenius [34] to avoid inconsistencies in base year data.

Table 8
Level of advancement of agricultural technology for food and feed crop production

Level of agricultural technology	Water supply	Description
Low	Rain-fed	No use of fertilizers, pesticides or improved seeds, equivalent to subsistence farming (as in rural parts of e.g., Africa and Asia).
Intermediate	Rain-fed	Some use of fertilizers, pesticides, improved seeds and mechanical tools.
High	Rain-fed	Full use of all required inputs and management practices (as in advanced commercial farming presently found in the USA and EU).
Very high[a]	Rain-fed	Combination of low, medium and high level of technology that has been calculated by the IIASA as follows: 'for each grid cell, first the largest (i.e. out of all the crops considered) extent of very suitable and suitable area under the high technology level was taken. Then the part of the largest very suitable, suitable and moderately suitable area under the intermediate technology, exceeding this first area, was added. Finally the part of the largest very suitable, suitable, moderately suitable and marginally suitable area under the low technology, exceeding this second area, was added. The rationale for this methodology is that it is unlikely to make economic sense to cultivate moderately and marginally suitable areas under the high technology level, or to cultivate marginally suitable areas under the intermediate technology level' [15].
Very high	Rain-fed/irrigated	Same as a very high input system, but including the impact on irrigation on yields and areas suitable for crop production. No data are available on the share of the total land suitable for crop production under rain-fed conditions and the share of the total land suitable for crop production if irrigation is applied; only the total area is given.
Super high	Rain-fed/irrigated	A high and very high (rain-fed/irrigated) level of technology exclude the impact of future technological improvements other than implementation of the best available technologies included in the high and very high rain-fed/irrigated level of technology[b]. We assumed in this level that technological developments (like the development of genetically modified organisms) add 25% above the yield levels in a very high rain-fed/irrigated level of agricultural technology (ceteris paribus).

[a] This level of technology is called a 'mixed input system' in the IIASA classification, but is dubbed 'very high' level of technology, to avoid confusion with the term 'mixed (animal) production system' (Section 3.3) and because it is generally the more efficient than a high level of technology production system.

[b] Some recent developments are improved seed coatings with e.g., (macro)—and micronutrients, better fertilizer formulations, nitrification inhibitors to improve fertilizer uptake, the development of high activity chemicals allowing ultra-low volume spraying, development of resistant varieties, biological control agents, specific additional chemicals such as growth inhibitors, hormones, behaviour-modifying semichemicals and precision farming. One of the few quantitative estimates of theoretical yield levels indicates that the theoretical maximum harvest index is 0.65 for cereals, compared to the present 0.40–0.45, indicating a theoretical cereal yield increase of 40%.

growth modeling using data on, e.g., soil characteristics, climate circumstances, crop characteristics and the level of advancement of agricultural technology. In this study, we use crop growth modeling results generated at the International Institute of Applied Systems Analysis (IIASA) [40]. Country specific data were available for various crops and various levels of agricultural technology. Six levels of technology for crop production are defined, see Table 8.

System 1 is based on rain-fed crop production only; systems 2–4 include irrigation. Irrigation is limited to areas in which climate, soil, and terrain permit irrigation. In our calculations water is excluded as a limiting factor, with the exception of arid and hyper-arid regions, where irrigation is limited to soils that indicate possible availability of surface or groundwater (fluvisols, which are regularly flooded, and gleysols, which indicate regular occurrence of high groundwater tables).[21]

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[21] Berndes [41] analysed the implications of large scale bioenergy production for water use and supply using various up to the year 2100, based on:

- The use of bioenergy as projected by the International Institute of Applied Systems Analysis (IIASA) and the World Energy Council (WEC) (see Section 7 for figures).
- The projected use of water for food crop production and industrial processes.
- The average water use efficiency of woody energy crops.

Results indicate that a large-scale expansion of energy crop production would lead to a large increase of evapotranspiration, potentially as large as the present global evapotranspiration from

From the IIASA dataset, data are aggregated into regional figures. Data on yields and areas for 19 crops and data on areas suitable for crop production in general are included in our calculations.[22,23] Data on areas suitable for crop production were classified by the IIASA based on the crop yield as a percentage of the maximum constraint free yield (MCFY). The MCFY was determined by the temperature and irradiation regimes. In the classification of IIASA, five categories are distinguished: very suitable (VS), which means that crop yields that can be obtained are equivalent to 80–100% of the MCFY, suitable (S) 60–80% of the MCFY, moderately suitable (MS) 40–60%, marginally suitable (mS) 20–40%, not suitable (NS) 0–20%. Yields for NS areas are not given, because these areas are considered to be economically unattractive for commercial food crop production.

The potential impacts of climate change on crop yields and land use patterns are excluded in our study, partly because the impacts are expected to be limited compared to the potential increase in food production efficiency. For example, Parry et al. [42] estimates that, relative to a situation where there is no climate change, cereal yields change by −5.0% to +2.5% in 2050 for most regions [42]. Fischer et al. [43] estimate that climate change will change the production of crops in the world in 2080 by −1.6% to +4.1%, compared to a scenarios without climate change; regional numbers range from −11% to +14%. Although these changes may be significant, they are small compared to the potential increase in crop yields due to technological developments. However, the impacts of climate change are unevenly distributed, and they are projected to be particularly negative for the developing regions [42,43]. According to Parry et al. [44] climatic change could change the number of people at risk of hunger by −11 million up to +280 million, in 2050, compared to a situation without climatic change, depending on the scenario and depending on the assumed CO_2 fertilization effect. For comparision: the number of people at risk of hunger in 2000 was estimated to be slightly above 800 million, and is expected to decrease to 225–725 million in 2050, depending on the scenario and excluding the impact of climate change [44].

3.3.1. Availability of land

A key parameter for the crop production potential is the availability of suitable land: not all areas that are agro-ecologically suitable are available for crop production. Large areas are occupied by e.g., forests, permanent pastures and build-up land. The overlap between various land use categories and areas that are suitable for crop production may be analyzed by means of a Geographic Information Systems (GIS) database that includes maps on agricultural land use and maps depicting the extend of land suitable for energy and food crop production based on crop growth modeling. However, in this study such an analysis was considered too complex because of the scope of our study. Secondly, maps on agricultural land use are generally crop specific and can thus not be matched with the crop-specific data included in the FAOSTAT database. Thirdly, most land use maps have been obtained by remote-sensing techniques and are sometimes inaccurate [45]. More reliable datasets, that make more use of ground-truthing and that are based on finer resolution satellite data, are expected to become available in the coming years.

Two types of land suitable for crop production are discriminated: the ‘crop non-specific area’, which represents the area where at least one crop can grow, and the ‘crop specific area’, which represents the area where one specific crop can grow. We use a relatively simple set of rules to allocate the various land use categories to the crop (un)specific areas. In other words, in our study a fictitious land use ‘map’ was created. The allocation rules are described in Box 1. Data on land use were derived from the FAOSTAT database, unless indicated otherwise.

The crop specific and crop non-specific areas available for crop production are included in the Excel spreadsheet model Quickscan used to allocate crop production, as discussed in Section 3.3.2. Table 9 gives an overview of results of this exercise.

Table 9 indicates that in 1998, 24% of the global area of land that is suitable for crop production was covered by forests and 36% by permanent pastures.

(*footnote continued*)
cropland and the present withdrawal of water for irrigation. In some countries such an expansion may lead to a further water scarcity and/or the emergence of water scarcity.

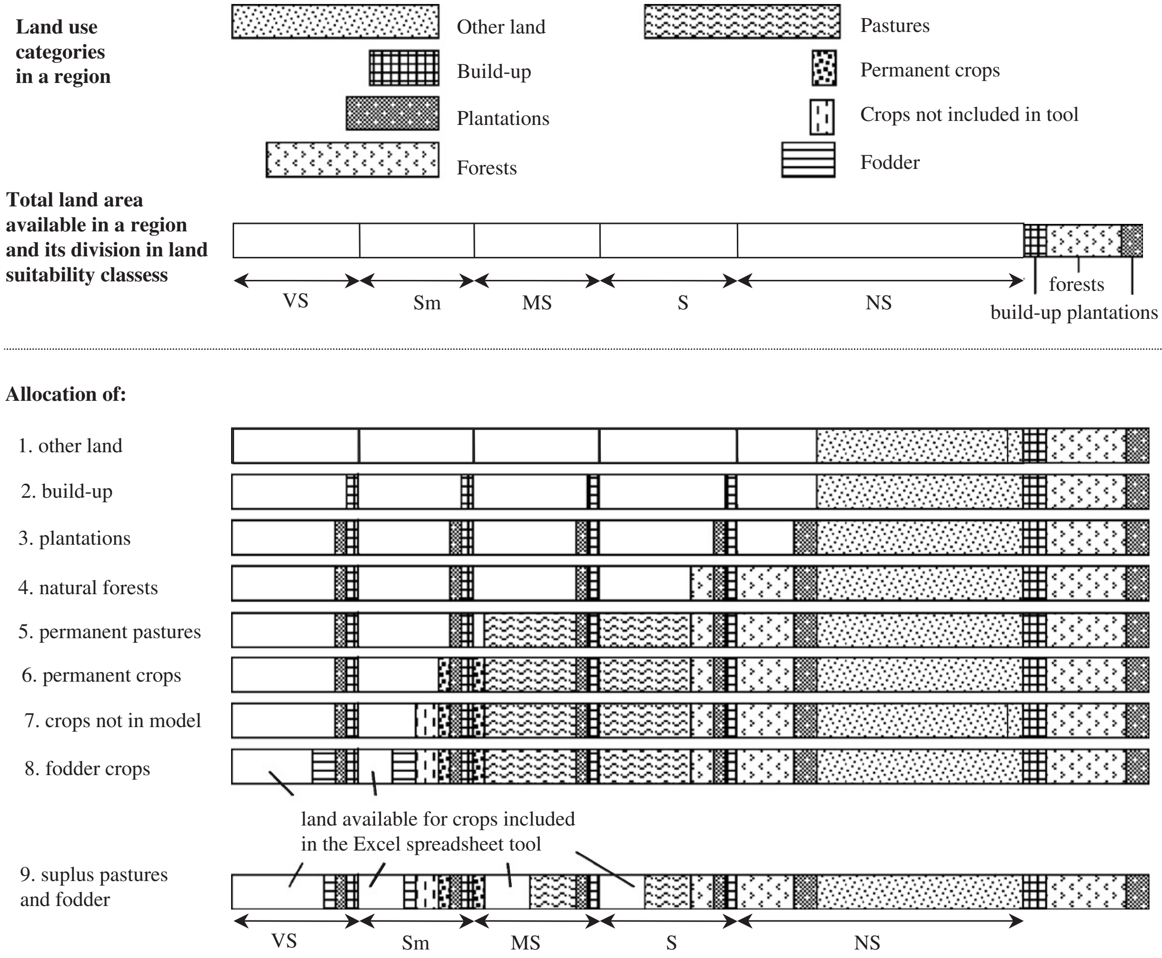
[22] These are: wheat, rice, barley, maize, rye, millet, sorghum, cassava, potatoes, sweet potatoes, sugar cane, sugar beet, pulses, soybeans, groundnuts, sunflower, rapeseed, cottonseed and palmkernels. These crops represent 85% of the global area under crop production. The remaining 15% was assumed to remain constant at the 1998 level.

[23] The area suitable for crop production is the area where at least one crop can grow.

Box 1

Allocation of land use to suitable cropland

Fig. 1 is a visual representation of the allocation procedure of various land use categories to crop non-specific areas. The width of the boxes represents the relative size of various land use categories and land suitability classes in a region for a fictitious situation.Fig. 1. Allocation of various land use categories to various classes of crop non-specific areas (VS = very suitable areas, S = suitable areas, MS = moderately suitable areas, mS = marginally suitable areas, NS = not suitable).



The size of the bars represents the size of the areas of land. Definitions of various land use categories are presented in [78]. Build-up land, forests and plantations are already partially allocated to the crop non-specific area, based on the overlap between build-up land, forests and plantations and the crop non-specific areas available as derived from the present geographic overlap included in the GIS database. The various land use categories are allocated to the various suitability classes of the crop non-specific area, based on the following order and the following principles:

1. *Other land* (includes uncultivated land, grassland not used for pasture, wastelands and barren land) is allocated to NS areas: If the area 'other land' is larger than the area NS, the remaining is allocated to mS areas, and so on. These areas may be partially available for bioenergy crop production, as further discussed in the discussion and conclusions section.
2. *Build-up land*: The build-up area per capita is assumed constant to 2050. The increase of the build-up area as a result of population growth is allocated to the areas mS to VS based on

the percentage of the area of each suitability class of the total area mS, MS, S and VS. The rationale for this is that expansion of infrastructure occurs generally on fertile soils and NS areas are, therefore, excluded as a source of land for this land use category.

3. *Plantation* areas are allocated to all suitability classes based on the percentage of the area of each suitability class of the total area NS to VS to account for the relative scarcity of suitable cropland. Plantations establishment occurs both on areas classified as VS (in case of high yielding industrialized plantations) and on areas classified as NS (in case of non-industrial plantations established for the protection of soil and water or for the regeneration of degraded soils). However, it can be expected that most plantations are not established on the most suitable areas, because suitable cropland is generally more valuable if allocated to agriculture [54].
4. *Natural forest areas* are excluded based on the overlap between forests and crop non-specific area using data from the IIASA GIS database. The forest areas excluded are smaller than the forest areas based on FAOSTAT data. Additional forest areas are subtracted from the areas not suitable for crop production (if not available from mS, and so on), because the classification VS to NS is based on the bio-physiological requirements of crops, not forests. Further, forests are often the remaining areas not suitable for agriculture due to e.g., steepness or unfavorable soil characteristics.
5. *Permanent pastures* are allocated to NS areas, followed by mS areas, and so on. First, because the classification of VS to NS is based on the physiological requirements for crops and not for grasses. Second, other land, which includes barren land, scrubland and other low productive areas are already excluded from the NS area, indicating that the remaining land area is productive and may be used as pasture land. It is assumed that pastures in general require less-productive land than crop production. This is supported by the fact that cropland is generally more expensive than permanent pastures. Third, the land areas for permanent pastures is in many regions larger than the areas VS to mS, indicating that pasture areas are presently (partially) located on NS areas.
6. *Permanent crops* are allocated to NS areas first, followed by mS areas, and so on, because the permanent crops includes a wide range of crops such as coffee, rubber, fruit trees, nut trees, and vines, whose bio-physiological requirements are likely different than for crop production. In practice this means that more than three-fourth of the area permanent crops is allocated to VS, S and MS areas. The land use for permanent crops is taken constant to avoid overestimation of the land available for bioenergy production. This could be an overestimation of the land area required for the production of permanent crops, because results indicate a decrease in land use for crops that are included in the model.
7. *Crops not included* in the model account for 13% of the sum of the total harvested area (with regional variation between 5% and 20%) in 1998. The allocation of VS to NS land to crops not included in the model is based on the same allocation rule as for permanent crops. The land use for permanent crops is taken constant to avoid overestimation of the land available for bioenergy production, although results show a decreasing agricultural land use for crops included in the model.
8. *Fodder crops* are allocated VS to mS areas. The most important fodder crop is silage maize. We assume that the growth demand for silage maize is roughly similar to maize. Consequently, fodder crops require at least mS land. Fodder crops are allocated to mS to VS areas, based on the percentages of the total mS to VS area.
9. *Surplus areas of permanent pasture* and arable land used for *fodder crops* are excluded based on the decrease in demand (if any) for permanent pasture and fodder. Surplus areas of permanent pasture and arable land used for the production of fodder crops are added up to the remaining areas of productive land available for crop production.

The fraction of crop-specific areas allocated to various land use categories is based on the fraction of the crop non-specific area in each suitability class occupied by various land use classes. We are aware that any of these allocation steps includes errors, but considering the goal of this study (a global quick scan) and the long time horizon of 50 years (which makes large changes of land use patterns possible) we consider the chosen allocation rules a suitable methodology.

Particularly in the Caribbean and Latin America, North America, and Oceania a significant portion of the area of suitable land was covered by forests: 42%, 32%, and 30%, respectively. In sub-Saharan Africa, Oceania and the Caribbean and Latin America large areas that are suitable for crop production were used as pastures: 60%, 49%, and 42% of the total area suitable land, respectively, in 1998. In the Middle East and North Africa, South Asia, and partially East Asia, 98%, 93%, and 74%, respectively, of the area suitable for crop production was cropland. These data indicate a potential scarcity of land suitable cropland in these regions. The last column in Table 9 displays the areas that were used as agricultural land, which includes arable land and pastures in 1998, but are classified as NS for conventional commercial crop production. Pastures account for 95% of these areas.

The results point out that considerable land areas that are agro-ecologically suitable for crop production are presently used as pastures, particularly in the developing regions. In theory, the area cropland could roughly double at the expense of pastures, without expanding the total agricultural area.

3.3.2. *Agro-ecologically attainable crop yields*

A second key parameter for the production potential of food, feed and energy crops is the crop yield (in $\mathrm{t\,ha^{-1}\,yr^{-1}}$).

3.3.2.1. Food and feed crops. In our approach, the demand for crops is allocated to combinations of yields and areas. Note that a large area with a low yield could have the same production potential as a small area with a high yield. The area available for the production of food crops is limited by the crop specific area and by the crop non-specific area. The crop non-specific area is used as a proxy for the overlap between the crop specific areas: the sum of crop-specific areas may not exceed the total crop non-specific area. Thus, the crop-specific areas by definition overlap with the crop non-specific area and the crop specific areas overlap partially with other each other.[24] The allocation of crop production involves the simultaneous allocation of the (demand for) 19 crops to yield-area combinations. First, all VS areas are used (as far as the demand for food required), followed by S, MS and mS areas. The result of this procedure is a minimal use of cropland. The remaining and least productive areas are assumed to be available for energy crop production. All calculations are performed per region. Box 2 shows a simplified version of the allocation procedure.

The allocation is carried out per region. In case the self-sufficiency ratio[25] (SSR) of a region is below 100%, the remaining demand for food is allocated to regions that have a remaining production potential following the methodology described above. In reality, this means that trade is applied to meet regional food shortages. After the demand for crops is allocated to yield-area combinations, the remaining area is assumed to be available for energy crop production. Table 10 shows the average increase in crop yields in 2050 compared to 1998 in case of systems 1–4.

The lowest increase in crop yields is projected for system 1 (high level of agricultural technology, rain-fed), namely a factor of 2.9 in 2050 compared to 1998. Regional data vary from 0.9 for West Europe to 5.6 for sub-Saharan Africa. A potential explanation for the decrease in yields is the increase in

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[24] It is assumed that the crop non-specific and crop specific areas can be harvested completely, i.e. the cropping intensity (CI) was set at 1. The CI is the ratio of harvested land to arable land. In 1998 the global CI was 0.8 [4]. In this study the CI is set at 1 in 2050, because the focus in this study is on the technological potential. Note that data on the harvested area (per crop type) and area arable land as included in the FAOSTAT database are not necessarily compatible. Differences are caused by double cropping (harvested areas are included twice in harvested areas statistics), areas sown but not harvested (these areas are included in arable land but not in harvested area), uncultivated land such as footpaths, ditches, headlands, shoulders and shelterbelts (these areas are excluded from harvested areas).

[25] The SSR is the ratio between the total dry weight of the demand for food and feed crops allocated in the model and the total dry weight of the demand for food and feed crops according to the food consumption scenarios.

Table 9
Area of agro-ecologically suitable land under forest cover and used for crop production and pasture in 1998 (in Mha and in % of the total area suitable cropland) and the area not suitable cropland used as agricultural land (Mha)

Region	Area of suitable cropland based on a very high, rain-fed input system (*I*)	Area of suitable cropland under forest cover		Area of suitable cropland used as arable land and land for the production of permanent crops		Area of suitable cropland used as pasture and arable land for the production of fodder crops		Areas not suitable cropland used as agricultural land
	(Mha)	(Mha)	(% of (*I*))	(Mha)	(% of (*I*))	(Mha)	(% of (*I*))	(Mha)
North America	493	157	32	225	46	111	23	157
Oceania	141	15	10	57	40	69	49	354
Japan	12	4	30	5	41	0	3	0
West Europe	146	18	12	87	60	41	28	20
East Europe	72	6	9	47	64	19	27	0
C.I.S. and Baltic States	374	87	23	219	58	69	18	286
Sub-Saharan Africa	1021	148	14	173	17	613	60	205
Caribbean and Latin America	976	408	42	159	16	410	42	191
Middle East and North Africa	72	2	2	71	98	0	0	390
East Asia	312	49	16	230	74	33	11	502
South Asia	201	6	3	186	93	9	4	29
World	3820	900	24	1459	38	1374	36	2134

Sources: [40] and own calculations.

demand for crops requiring an expansion of the area under crop production, which results in an increasing use of moderately, or MS areas and consequently lower yields. The increase in crop yields in case of system 2 (high level of agricultural technology, rain-fed and/or irrigated) is calculated at a factor 3.6. The yield increase in system 2 is higher than in case of system 1 as a result of irrigation. The impact of irrigation is particularly important in the C.I.S. and Baltic States, Oceania, and the Middle East and North Africa. Further, the increase in yields in system 3 (very high level of agricultural technology, rain-fed and/or irrigated) is comparable to system 2. Regional increases range from a factor 1.3 for West Europe to 6.2 for sub-Saharan Africa. The increase in crop yields in case of systems 2 and 3 is similar, despite the higher level of agricultural technology applied in system 3. The impact of a higher level of technology is counteracted by a higher demand for feed crops in system 3 compared to system 2. The higher demand for feed crops in system 3 requires a higher use of less productive areas for crop production, compared to system 2. The highest average increase in crop yields is

Box 2

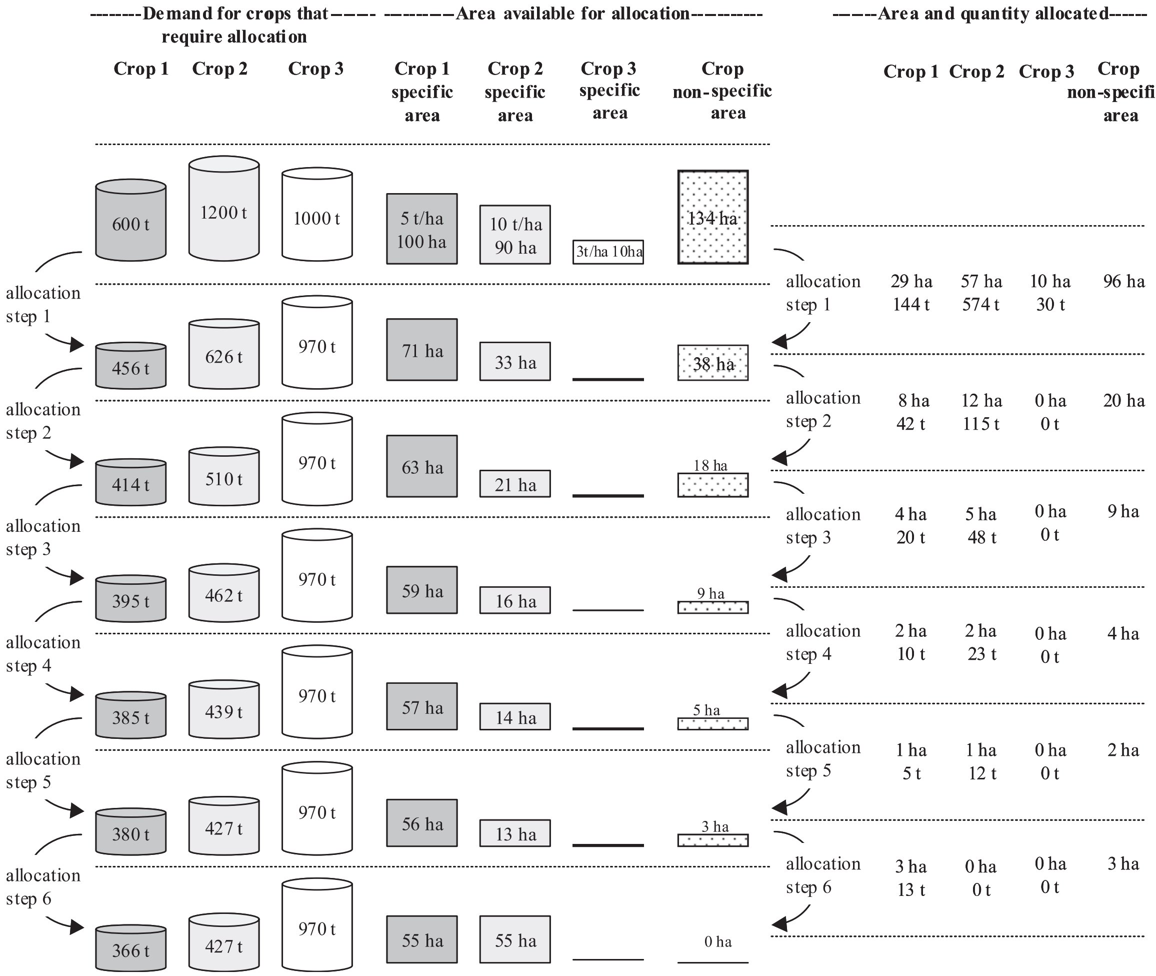
Allocation of crop production to suitable cropland

Each allocation involves three steps:

- The preliminary allocation of the total non-specific area to various crops on the basis of the share of dry weight of the demand for a crop of the total dry weight demand for all crops.
- The final allocation of the non-specific and specific crop area by comparing the crop-specific area available for each crop and the crop non-specific area temporarily allocated to each crop: in case the crop specific area is larger than the non-specific area then the non-specific area is the bottleneck for crop production; in case the crop-specific area is smaller than the non-specific area, the crop-specific area is the bottleneck for crop production, i.e., the smaller one of the two areas determines the size of the area that is allocated.
- The calculation of the remaining demand for each crop that is not yet allocated and the remaining crop (un)specific areas. The previous step results in the partial allocation of crop production to area-yield combinations. The crop production that is allocated in the previous step is the crop specific area multiplied by the yield. The remaining crop production that needs to be allocated in a previous allocation step is reduced by the production that is allocated. Similarly, the remaining crop non-specific area is the total non-specific area that is available for crop production, minus the sum of the areas that are allocated to the various crops. The remaining crop specific area of each crop is the total crop specific area minus the area that is allocated to each crop.

For practical reasons, the number of iterations is limited to five for each land suitability class. A sixth allocation step is included in which the remaining demand for food and the remaining crop (un)specific areas are allocated per crop, starting with the crops that have globally the largest harvested area: wheat and rice, followed by other cereals, roots and tubers, sugar crops and oil crops.

Fig. 1 shows an example of the allocation procedure. The first row of figures shows the demand for crops that need to be allocated to yield–area combinations, the crop non-specific area and the crop-specific area available for allocation and the yield of the crop-specific area. The demand for crops is represented by the column-shaped figures and the height represents the quantity that needs to be allocated. The crop (un)specific area is represented by the rectangles, in which the height represents the area available for allocation. The second and following rows show the remaining demand for crops that need to be allocated and the remaining (un)specific area available after each allocation step. The numbers indicate the quantity of the demand for crops that is allocated and the crop (un)specific area that is allocated in each allocation step.Fig. 1. Principles of the land use allocation. See text for explanation.



Step 1. Allocation step 1 involves three steps as described in the main text:

1. The crop non-specific area preliminary allocated to crop 1, 2 and 3 is: $600 \times 134/(600+1200+1000) = 29$ ha, $1200 \times 134/(600+1200+1000) = 57$ ha and $1000 \times 134/(600+1200+1000) = 48$ ha, respectively.
2. The crop non-specific area that is preliminary allocated is compared with the crop specific area, to determine which area is limiting for crop production. For crop 1 the crop non-specific area is 29 ha, the crop specific area is 100 ha; 29 ha is allocated, which is equal to 144 t. For crop 2 the crop non-specific area is 57 ha, the crop specific area is 90 ha; 57 ha is allocated which is equal to 574 t. For crop 3 the crop non-specific area is 48 ha, the crop specific area is 10 ha; 10 ha is allocated, which is equal to 30 t.
3. The remaining demand that needs to be allocated and the remaining crop (un)specific areas available for allocation are calculated. For crop 1 the remaining demand is $600-144 = 456$ t, the crop non-specific area is $100-29 = 71$ ha. For crop 2 the remaining demand is $1200-547 = 626$ t, the crop unspeficic area is $90-57 = 33$ ha. For crop 3 the remaining demand is $1000-30 = 970$ t, which cannot be fulfilled.

Step 2–5. Allocation steps 2–5 are the same as step 1 and, therefore, not further described in detail. In each allocation step a part of the remaining demand is allocated.

Step 6. Allocation step 6, the remaining demand is allocated to the remaining crop (un)specific areas, starting with crop 1, followed by crop 2 and crop 3. The remaining demand for crop 1 is 380 t. The crop specific area available for crop 1 is 56 ha, the total crop non-specific area available for crop production is 3 ha, and thus 3 ha are allocated to the production of crop 1, equal to 15 t.

calculated for system 4 (super high level of advancement of agricultural technology, rain-fed and/or irrigated). In this system, the global average yield increases by a factor 4.6. Regional figures range from 1.9 in West Europe to 7.7 in sub-Saharan Africa.

3.3.2.2. Bioenergy crops. Various crop and tree species are suitable for energy production, e.g., sugar crops, cereals, oil crops, miscanthus, hemp, eucalyptus, willow and poplar. In this study woody energy crops are included, such as eucalyptus, poplar and willow, because of the relatively high yield potential, wide geographic distribution, and the relatively extensive production system (and thus relatively lower environmental stress) compared to annual crops. Further, woody biomass is a versatile source of energy, because it can be converted in various solid and liquid fuels.

Many studies on bioenergy potentials ignore the regional impact of soil and climate on yields and assume an average yield instead (e.g., [8]). Data on the yield of energy crops are derived from the IMAGE model [3], which are based on a crop growth model and data on soil, climate and data on the characteristics of woody energy crops. The calculated yields are multiplied by a management factor that accounts for non-optimal agricultural practices as well as for the future impact on yields of breeding, a higher harvest index, an increasing use of irrigation and fertilizers, general (bio)technological improvements and the (limited) effect of CO_2 fertilization. In our study a management factor of 1.5 is assumed for the year 2050, following scenario A1 of the IPCC Special Report on Emission Scenarios (SRES).[26] This yield level and management factor was taken as a proxy for the super high level of technology. For comparison: yields in 1995 are estimated to be 53% lower than in the A1 scenario in 2050 and yields in 2050 in the B1 and the B2/A2 scenario are 14% and 26% lower than in the A1 scenario in 2050, respectively.

Data on the availability of surplus land for energy cropping were classified into VS to NS, as described in Section 3.3. IMAGE data discern some 50-yield classes that were reclassified into NS to VS. The yield in the highest yield class in the IMAGE model is taken as a proxy for the MCFY. The area in each yield category is calculated by summing up the land areas given in the IMAGE model per yield class. Fig. 4 shows the yield–area curve for woody energy crops. The area under the curve represents the technical bioenergy crop production potential at the total global land surface, which is calculated to be 4435 EJ yr^{-1}.[27] This figure is in line with the circa 4200 EJ yr^{-1} given by Hall et al. [9].

The global geographical potential (or NPP) of energy crops of 4435 EJ yr^{-1} is much larger than the NPP of 2280 EJ yr^{-1} of natural vegetation that is mentioned in the introduction. A NPP of

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[26] The four Intergovernmental Panel on Climate Change (IPCC) SRES scenarios are: A1, A2, B1 and B2 and are defined as follows [46]. A1: A future world of very rapid economic growth, low population growth and rapid introduction of new and more efficient technology. Major underlying themes are economic and cultural convergence and capacity building, with a substantial reduction in regional differences in per capita income. In this world, people pursue personal wealth rather than environmental quality. A2: A very heterogeneous world. The underlying theme is that of strengthening regional cultural identities, with an emphasis on family values and local traditions, high population growth, and less concern for rapid economic development. B1: A convergent world with rapid change in economic structures, 'dematerialization' and introduction of clean technologies. The emphasis is on global solutions to environmental and social sustainability, including concerted efforts for rapid technology development, dematerialization of the economy, and improving equity. B2: A world in which the emphasis is on local solutions to economic, social, and environmental sustainability. It is again a heterogeneous world with less rapid, and more diverse technological change but a strong emphasis on community initiative and social innovation to find local, rather than global solutions.

(footnote continued)

[27] Based on a higher heating value of 19 GJ t^{-1} dry weight and including areas classified as NS. Contrary to food crop production, the production of energy crops can be considered feasible on NS areas, because the production of woody energy crops is less demanding and can therefore be economically attractive.

Table 10
Potential increase in crop yields from 1998 to 2050 in systems 1–4

Region	System 1	System 2	System 3	System 4
North America	1.6	2.3	2.3	3.2
Oceania	2.4	3.7	3.7	4.6
Japan	2.7	2.8	2.4	3.0
West Europe	0.9	1.5	1.3	1.9
East Europe	2.1	3.3	3.3	4.1
C.I.S. and Baltic States	3.2	5.4	5.3	6.7
Sub-Saharan Africa	5.6	6.2	6.2	7.7
Caribbean and Latin America	2.8	3.6	3.5	4.5
Middle East and North Africa	1.4	2.3	2.3	2.9
East Asia	2.3	2.7	2.5	3.2
South Asia	3.7	4.5	4.5	5.6
World	2.9	3.6	3.6	4.6

Figures indicate the factor of yield increases between 1998 and 2050, i.e. in system 1, yields in 1998 are set at 1 and in 2050 yields are 2.9 (the average figure for all crops included in the spreadsheet).

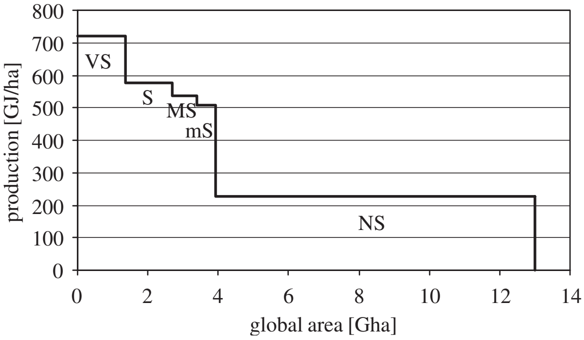

Fig. 4. Simulated productivity of woody bioenergy crops on the total global land area based on a super high level of advancement of agricultural technology (VS = very suitable areas, S = suitable areas, MS = moderately suitable areas, mS = marginally suitable areas, NS = not suitable areas). The figure has been derived from IMAGE data [3].

2280 EJ yr^{-1} corresponds with an average yield of 8.9 $odt^{-1} ha^{-1}$; a NPP of 4435 EJ yr^{-1} equals an average yield of 18 odt ha^{-1}, assuming a higher heating value of 19 GJ odt^{-1}. The difference in yield is caused by the fact that in stable natural ecosystems, plants have passed their rapid growth phase. Food and energy crops are usually harvested during or soon after the rapid growth phase and have thus higher average yields.

3.3.3. Surplus agricultural land

Table 11 shows the surplus area surplus agricultural land that is available for energy crop production in 2050.[28] The results (indirectly) include surplus pastures. Table 11 also displays the SSR of each region. All results presented in this article are based on a world SSR of 100% or close to 100%, thus demand for food in 2050 is met. Regional food shortages are compensated by imports from other regions. The impact of this on land use patterns was considered in the results in Table 11.

Table 11 shows that the area of land used for food production could be decreased by 14%, 22%, 64% and 70% in 2050 compared to 1998, in systems 1–4, respectively.[29] The area of surplus agricultural land ranges from 0.7 Gha in systems 1–3.6 Gha in system 4. The Caribbean and Latin America and sub-Saharan Africa are the regions with the largest area of surplus agricultural land. The area of surplus agricultural land in the Caribbean and Latin America is calculated to be 0.15 Gha in system 1 and 0.56 Gha in system 4, which is equal to 20–72% of the agricultural land in 1998. For sub-Saharan Africa the results are 0.10 Gha in system 1 and 0.72 Gha in system 4, equal to 10–72% of the agricultural land in 1998. The Middle East and North Africa, South Asia, and partially East Asia are relatively scarce of agricultural land. The SSR in these

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[28] Areas classified as ‘other land’ may be partially available for bioenergy crop production; the potential is, however, limited compared to the potential of dedicated bioenergy crops from surplus agricultural land and uncertain and therefore excluded from the main results. The bioenergy potential from ‘other land’ is discussed in Section 10.

[29] In case the total area of agricultural land used in 1998 would be used for food production, than the carrying capacity was calculated to be 13 billion people, based on the average level of food intake projected for 2050.

regions is calculated to be 20–60%, 40–54%, and 36–45%, respectively, depending on the assumed system.[30] The surplus areas reported in Table 11 are:

- Areas classified as NS for conventional commercial crop production [40]. These areas are considered suitable for energy crop production as it is less intensive compared to conventional crop production. Note that in reality, NS areas are occasionally used for food crop production, mainly for subsistence farming and particularly in land scarce regions such as South Asia [15], or they are used as pasture as shown in Table 9.
- Areas suitable for crop production for which there is no demand, due to a mismatch between demand and supply. For example, the production potential for wheat in South Asia is insufficient to meet the demand in 2050, but at the same time South Asia has a surplus production potential for sorghum.

These results are in line with other studies that indicate shortages of land suitable for crop production in the Middle East and North Africa, South Asia and East Asia (e.g., [15]). The SSR achieved in system 1 (high level of technology, rain-fed agriculture) in the Middle East and North Africa and South Asia is calculated to be 20% and 40%, while in system 2 (high level of technology, rain-fed and/or irrigated agriculture), the SSR increases to 57% and 54%, respectively.

The C.I.S. and Baltic States could have a surplus agricultural land of 0.1 Gha up to 0.5 Gha in 2050, equal to about one-fifth to three-fourth of the total agricultural land use. The potential surplus agricultural land in the Eastern European countries ranges between 4 and 40 Mha, equal to one-twentieth up to half of the total agricultural land use in 1998.

The industrialized regions are nearly or fully self-sufficient in 2050 in all four systems except Japan. Japan is clearly the most land-stressed region with a SSR of 30–56%. Oceania is the least land stressed-region: in case of a medium feed conversion efficiency and medium level of agricultural technology, Oceania

Table 11
Total area of agricultural land in 1998 (Mha), and the potential surplus agricultural land (in Mha and in % of the total agricultural area in 1998) and the self-sufficiency ratio (SSR) in 2050 (%) for systems 1–4

Region	Total agric area 1998	System 1			System 2			System 3			System 4		
	Mha	Mha	Area (%)	SSR (%)	Mha	Area (%)	SSR (%)	Mha	Area (%)	SSR (%)	Mha	Area (%)	SSR (%)
North America	493	54	11	97	105	21	100	307	62	100	348	71	100
Oceania	480	216	45	100	236	49	100	405	84	100	428	89	100
Japan	5	0	0	30	0	0	30	0	0	46	0	0	54
West Europe	147	12	8	86	22	15	100	38	26	97	61	41	100
East Europe	66	4	6	99	16	24	100	35	53	100	40	60	100
C.I.S. and Baltic States	574	113	20	97	153	27	98	470	82	99	491	86	99
Sub-Saharan Africa	991	104	10	98	240	24	98	619	62	99	717	72	99
Caribbean and Latin America	760	152	20	98	310	41	99	500	66	98	555	73	99
Middle East and North Africa	461	23	5	20	11	2	57	372	81	50	372	81	60
East Asia	765	15	2	36	23	3	38	509	67	37	510	67	45
South Asia	224	36	16	40	38	17	54	57	25	47	63	28	54
World	4966	729	15	99	1154	23	100	3312	67	100	3585	72	100

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[30] Food shortages in these regions are covered by imports from regions with a surplus food crop production potential, such as sub-Saharan Africa and the Caribbean and Latin America. This approach reduces the surplus area of land available for energy crop production in food exporting regions. For example, food exports from sub-Saharan Africa reduced the surplus area from 396 to 310 Mha, and in the Caribbean and Latin America the surplus area was reduced from 346 to 240 Mha, in system 2.

would still have a surplus agricultural area of 30 Mha for bioenergy production (data not shown). In case of systems 1–4, 45–89% of the total agricultural land use in 1998 could in 2050 be dedicated to bioenergy production. North America also has a considerable potential of 54–348 Mha, equal to 11–71% of the area of agricultural land in 1998. The surplus areas in Oceania and North America are the result of areas that are suitable for crop production but presently used as pasture (Table 9), and the impact of irrigation (compare systems 1 and 2; Table 10).

3.3.4. Bioenergy production from surplus agricultural land

The results presented in the previous section indicate that up to 3.6 Gha of agricultural land could (in theory) come available, globally, in 2050 for bioenergy production. The bioenergy potential from these areas depends on the suitability of these areas for energy crop production, which is shown in Fig. 5.

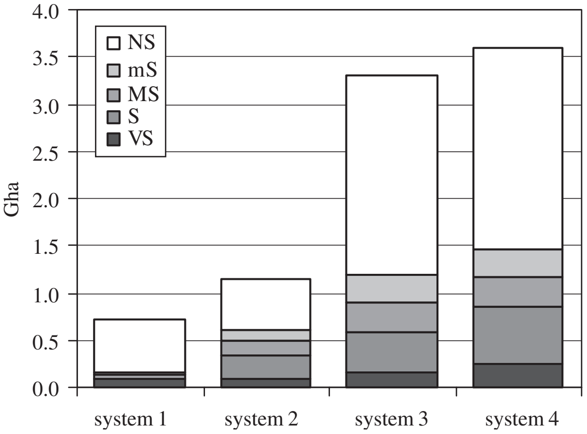

Fig. 5. Suitability of the global surplus agricultural land in 2050 (in Gha). VS = very suitable for crop production, S = suitable, MS = moderately suitable, mS = marginally suitable, NS = not suitable.

Fig. 5 shows that the bulk of the surplus agricultural land consists of areas classified as NS for conventional commercial crop production. These areas are considered suitable for bioenergy crop production as outlined in the previous sections. However, global average yields on NS areas are much lower than yields obtained on areas classified as VS: 12 vs. 38 odt ha^{-1} yr^{-1} in the year 2050. Table 12 shows the average yield per hectare of bioenergy crops on surplus agricultural land in systems 1–4.

Yields differ between systems 1–4 as a result of differences in the suitability of the surplus agricultural land for bioenergy crop production. Global average yields range between 16 and 21 odt ha^{-1} yr^{-1}. Average yields in systems 3 and 4 are lower than in systems 1 and 2, because in systems 3 and 4 all animal feed comes from crops and residues, which results in large areas of surplus pastures that are generally less suitable for energy crop production than areas of arable land. Table 13 shows the energy crop production potential from surplus agricultural land in 2050 in various regions, taking into account the productivity of these areas.

The largest potential for energy crop production potential comes from sub-Saharan Africa and the Caribbean and Latin America, up to 317 EJ yr^{-1} and up to 221 EJ yr^{-1} in system 4, respectively. These results are in line with the relatively large areas that are agro-ecologically suitable for crop

Table 12
Woody bioenergy crop yields in various regions in 2050 on surplus agricultural land (odt ha^{-1} yr^{-1})

Region	System 1 (odt ha^{-1} yr^{-1})	System 2 (odt ha^{-1} yr^{-1})	System 3 (odt ha^{-1} yr^{-1})	System 4 (odt ha^{-1} yr^{-1})
North America	19	27	25	27
Oceania	9	11	11	13
Japan	—	—	—	—
West Europe	20	26	23	18
East Europe	35	35	33	36
C.I.S. and Baltic States	21	25	21	25
Sub-Saharan Africa	16	22	22	24
Caribbean and Latin America	16	20	20	23
Middle East and North Africa	5	5	4	5
East Asia	38	39	15	19
South Asia	22	24	20	22
World	16	21	17	20

Table 13
Bioenergy production potential in 2050 based on the production of dedicated woody bioenergy crops on surplus agricultural land (EJ yr^{-1})

Region	System 1 (EJ yr^{-1})	System 2 (EJ yr^{-1})	System 3 (EJ yr^{-1})	System 4 (EJ yr^{-1})
North America	20	53	144	174
Oceania	38	51	87	102
Japan	0	0	0	0
West Europe	5	11	16	30
East Europe	3	11	22	26
C.I.S. and Baltic States	45	73	184	199
Sub-Saharan Africa	31	102	260	317
Caribbean and Latin America	47	120	190	221
Middle East and North Africa	2	1	30	31
East Asia	11	17	146	147
South Asia	15	17	21	25
World	215	455	1101	1272

production in these regions, but which are presently not used as such (Section 3.3.1). East Asia also has a considerable potential for energy crop production of up to 147 EJ yr^{-1}. Other developing regions are more land scarce and therefore have limited potentials. The countries with transition economies also have a considerable potential. For the C.I.S. and Baltic States region a potential is found of 199 EJ yr^{-1} in system 4. Of the industrialized countries, Oceania and North America have considerable potentials of 102 and 174 EJ yr^{-1} in case of system 4, respectively. West Europe has a limited potential of up to 30 EJ yr^{-1}. Land stressed regions such as Japan, South Asia and the Middle East and North Africa all have zero or a very limited potential.

4. Bioenergy from forest growth

The technical potential of bioenergy from forest growth is calculated as the supply of wood (Section 4.2) minus the demand for wood (Section 4.1). Final results are presented in Section 4.3. For further details of the methodology and for detailed regional results for various other types of potentials, see Smeets and Faaij [5].

4.1. Demand for wood

The demand for wood is defined as the sum of the demand for industrial roundwood (Section 4.1.1) and (traditional) woodfuel (Section 4.1.2), excluding (modern) bioenergy.

4.1.1. Demand for industrial roundwood

Data in the FAOSTAT database [4] indicate that the demand for industrial roundwood in 1998 was 1.5 Gm^3 (17 EJ). The quality of the data is generally high. Based on the range of projections of the demand for industrial roundwood in 2050 found in the literature, three projections are included in our calculations that represent possible developments of the global demand for industrial roundwood to 2050:

- The low projection: 1.9 Gm^3 (22 EJ).
- The medium projection: 2.5 Gm^3 (29 EJ).
- The high projection: 3.1 Gm^3 (36 EJ).

The three global projections for 2050 have been translated into regional projections using data from the Global Fibre Supply Model (GFSM) of the FAO [47] as further described in Smeets and Faaij [5].

4.1.2. Demand for woodfuel

Projections of woodfuel use are hampered by conflicting trends and the lack of reliable data (e.g., [48]). The global demand for woodfuel in 1998 can be estimated at 1.7 Gm^3 (20 EJ; [4]). Using the same approach as for industrial roundwood, three projections are included in our calculations for the demand for woodfuel in 2050:

- The low projection: 1.7 Gm^3 (20 EJ).
- The medium projection: 2.2 Gm^3 (25 EJ).
- The high projection: 2.6 Gm^3 (30 EJ).

The three global projections have been translated into regional projections following the same approach as used for industrial roundwood.

4.2. Supply of wood

The demand for wood is compared with the supply of wood to calculate the surplus forest growth available for energy production. As shown in Fig. 1, three sources of wood are distinguished: TOF (Section 4.2.1), forest plantations (Section 4.2.2) and natural forests (Section 4.2.3).

4.2.1. Wood from TOF

TOF are defined as trees excluded from the definition of forests,[31] e.g., trees located in urban areas, orchards, home gardens, alongside roads, and so on. A global assessment of the number of TOF and their products does not exist [6]. In this study estimates of the contribution of TOF to the supply of woodfuel and industrial roundwood are made based on national and regional assessments (e.g., [49–52]). It is estimated that in the 1990s TOF contributed for some one-third of the total global wood supply, or 1.1 Gm^3 (13 EJ). No information could be found in literature about the potential or future wood supply from TOF. In our calculations the supply of wood from TOF was kept constant to 2050 to avoid an overestimation of the bioenergy potential.

4.2.2. Wood from forest plantations

In this section, the supply of wood from forest plantations refers to the supply of industrial roundwood and woodfuel, excluding the supply of wood for the production of bioenergy, which is specifically dealt with in Section 3. Data on the area and productivity of plantations is often incomplete or unreliable [6,53,54]. In this study, three projections of the supply of wood from plantations are included and these projections vary with respect to the plantation establishment rate and yield level. Data are derived from the Global Outlook for Future Wood Supply from Plantations [54], which is the only study that we found that includes projections for both industrial and non-industrial plantations[32] to 2050 at a country level with a global coverage. The supply of wood from plantations in 1995 is estimated at 0.4 Gm^3 (5 EJ) from 124 Mha. For 2050 the following scenarios are included:

- The low scenario: 0.8 Gm^3 (9 EJ) from 124 Mha (the plantation area in 1995). The increase of wood supply is the result of an increasing yield level due to the large share of young, immature forest plantations in the present plantation age-class structure, which will become productive in the coming decades.
- The medium scenario: 1.1 Gm^3 (13 EJ) from 191 Mha.
- The high scenario: 2.0 Gm^3 (23 EJ) from 292 Mha.

If we assume that all wood from non-industrial plantations is used as woodfuel, then industrial plantations supplied 24% of the total industrial roundwood production and 6% of the woodfuel production in 1995 [4,47]. In the year 2050, plantations could supply between 12% and 78% of the industrial roundwood production and 7–42% of the woodfuel production.

4.2.3. Wood from natural forests

The wood production that is not supplied by TOF or by plantations comes from natural forests. In 1998, 1.2 Gm^3 or 76% of the industrial roundwood production and 0.6 Gm^3 or 34% of the woodfuel production was produced from natural forests. In the year 2050 the share of natural forests in the supply of industrial roundwood is calculated to range between 21% and 80%, and for woodfuel between 8% and 52%, depending on the demand and plantation establishment scenario.

There is a paucity of accurate and up-to-date data on the harvest intensity of forests under sustainable forest management (SFM) regimes [55,56]. We use data on the Gross Annual Increment (GAI) per hectare as a proxy for the technical production potential of wood from forests, in combination with data on the forest area.[33] The forest area is kept

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[31] The definition of forests is ‘land with tree crow cover (or equivalent stocking level) of more than 10% and area of more than 0.5 ha. The trees should be able to reach a minimum height of 5 m at maturity in situ’; natural forests exclude plant ions [47].

[32] Industrial plantations are established to produce industrial roundwood. Non-industrial plantations are primarily established for woodfuel production or soil and water protection, although some may be planted for recreation or similar non-productive purposes [54].

(*footnote continued*)

[33] The GAI is the annual forest growth, excluding mortality. Mortality is dependent on site characteristics (e.g., climate, slope, soil structure), age stand and management system. In general, in undisturbed full-grown forests mortality offsets annual growth and the net annual increment (NAI) is zero, while in managed

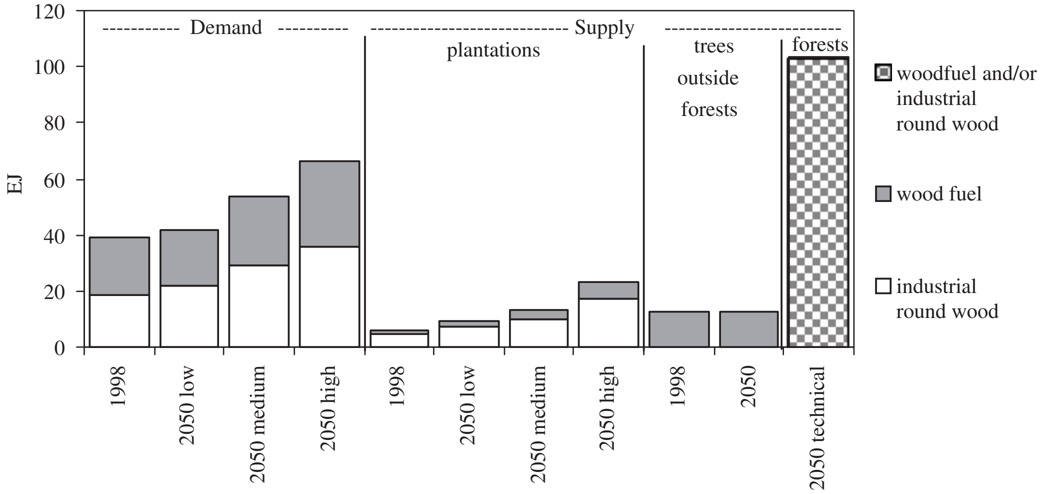

Fig. 6. Demand and supply of wood in 1998 and 2050 from plantations, trees outside forests and forests (EJ yr^{-1}). The potential from forests in 2050 is the same as for 1998. The terms low, medium and high refer to the consumption and plantation establishment scenarios.

constant up to 2050, because deforestation is considered unsustainable and should be avoided. Protected areas and physically inaccessible areas that cannot be harvested using conventional logging technologies are also excluded. By harvesting the annual increment only, the volume-standing stock is kept constant and thus an unacceptable pressure on biodiversity is avoided. Also, these yields can in principle be sustained continuously, with the exception of limiting factors such as nutrient depletion. Yet, we acknowledge that the increase in the average yield of biomass from forestry to a level that is equal to the GAI, including the removal of dead wood, will most likely increase the pressure on biodiversity. Data on natural forest area and GAI are taken from the FAOSTAT [4] and the GFSM of the FAO [47] as further described in Smeets and Faaij [5].

The technical potential of wood supply from forests (excluding harvest residues) is calculated to be 8.9 Gm^3 (103 EJ) from 2.6 Gha forest. The global average GAI is 3.4 m^3 ha^{-1} yr^{-1} (39 GJ ha^{-1} yr^{-1} [47]. This yield level is in line with the global average yield level of biomass from forestry of 30–38 GJ ha^{-1} yr^{-1}, estimated by Fischer and Schrattenholzer [13], but is substantially higher than the present global average harvest intensity, which is estimated at 0.5 m^3 ha^{-1} yr^{-1} (6 GJ ha^{-1} yr^{-1}).

4.3. Forest growth available for bioenergy production

Fig. 6 shows a comparison of the global demand and supply of wood in 2050.

Fig. 6 shows that the technical potential of wood from natural forest growth is sufficient to meet the future demand for industrial roundwood and woodfuel, without further deforestation or a decrease of the standing stock. The supply of wood from natural forests in 2050 is estimated to be 8.9 Gm^3 yr^{-1} (103 EJ yr^{-1}) and the demand for wood (industrial roundwood and traditional woodfuel) at 3.6 Gm^3 (42 EJ) to 5.7 Gm^3 (66 EJ). The energy potential from surplus forest growth in 2050 ranges between 5.1 Gm^3 (59 EJ) in case of a low plantation establishment scenario and a high demand, and 8.9 Gm^3 (103 EJ) in case of a high plantation establishment scenario and a low demand. The potential in case of a medium plantation establishment scenario and medium demand is calculated to be 74 EJ yr^{-1}.

The largest contribution to the energy potential from surplus forest growth comes from the C.I.S and Baltic States, the Caribbean and Latin America, and partially North America and Western Europe (data not shown; regional results are presented in a separate article [5]). Sub-Saharan Africa has a limited surplus forest growth, due to a combination of high woodfuel consumption and low annual forest growth per hectare. In Japan, South Asia and the Middle East and North Africa the supply of wood may be insufficient to meet the projected demand in 2050.

(*footnote continued*)
forests the mortality rate can be as low as 2–6% of the GAI [57]. Data on GAI are measured in m^3 ha^{-1} yr^{-1} for wood of a minimum diameter at breast height of zero cm.

5. Bioenergy from residues and waste

Three types of residues and waste are included in this study, harvest residues (Section 5.1), process residues (Section 5.2), and biomass waste (Section 5.3), as defined below. The availability of residues for energy production is dependent on a large number of variables, e.g., the crop or tree species and the type of technology used to harvest or process the crops or wood logs. It also depends on the alternative use of residues as animal bedding, traditional fuel, soil improver and erosion protector. Considering the large number of variables involved and the lack of detailed data, no detailed assessment of the energy potential of residues is carried out. Instead, the potential is calculated by multiplying the quantities of food or wood by a residue to product ratio and a recoverability fraction, as shown in Eqs. (3)–(5). The alternative use of residues is excluded, with the exception of the use of crop process and harvest residues as animal feed, which was subtracted from the available crop residues. Results are presented in Section 5.4.

5.1. Harvest residues

Crop harvest residues are e.g., straw, stalk, and leaves. Wood harvest residues are, e.g., twigs, branches, and stumps. Harvest residues are also called primary residues. The bioenergy potential of harvest residues is calculated using Eq. (3).

$$\mathrm{HR} = P\,h\,\mathrm{hr} \tag{3}$$

where HR is the energy potential from crop or wood harvest residues ($\mathrm{t\,yr^{-1}}$), P the production of crops or wood (industrial roundwood and woodfuel) ($\mathrm{t\,yr^{-1}}$), h the harvest residue generation fraction, defined as the ratio between the amount of residues generated and the amount harvested (dimensionless) and hr the harvest residue recoverability fraction, defined as the fraction of the harvest residues that realistically can be recovered (dimensionless).

For crops h equals (1/HI)−1, where HI is the harvest index. The HI is defined as the ratio between the part of the crop harvested, and the total above ground biomass of the crop at the time of harvesting. The HI is dependent on the level of agricultural technology. For example, the HI of winter wheat is 0.25, 0.35, and 0.45 in a low, medium, and high level of advancement of agricultural technology, respectively. In our study, data on the HI for the 19 different crops are included for three levels of technology (low, medium, high) [40]. For wood, the harvest residue ratio is set at 0.6 for both industrial roundwood and woodfuel. Data found in the literature for industrial roundwood ranges between 0.60 and 0.82 (see [5] for references and further details).

Not all residues can be recovered realistically because of their scattered production, limited size, high moisture content, and so on. Therefore, in our calculations a harvest residue recoverability fraction is included. Most studies on the energy potentials of residues assume a recoverability fraction of 0.25 [8]. The same value is used in this study, both for crops and wood.

5.2. Process residues

Process residues (or secondary residues) are residues generated during the processing of wood and crops into final products. Crop process residues are, e.g., oilcakes, hulls, and shells. Wood process residues are e.g., sawdust and wood chips. The potential energy supply from these residues is:

$$\mathrm{PR} = C\,p\,\mathrm{pr} \tag{4}$$

where PR is the bioenergy potential from process residues ($\mathrm{t\,yr^{-1}}$), C the consumption of crops or industrial roundwood ($\mathrm{t\,yr^{-1}}$), p the process residue generation fraction, defined as the share of the consumed crops or industrial roundwood that is converted into residue during processing (dimensionless) and pr the process residue recoverability fraction, which is the share of the process residues that realistically can be made available for energy production (dimensionless).

In our calculations global average process ratios are used. The reason is that no correlation could be found between the process residue generation fraction and the advancement of agricultural technology in various regions, based on differences between present and agro-ecologically attainable crop yields. Data are taken from FAO statistics [58]. The process residue generation fraction of wood is set at 0.5 for all regions. The recoverability fraction of crop process residues is set at 1.0. The recoverability fraction of wood process residues is set at 0.75% (see [5] for details).

5.3. Waste

Biomass waste is also referred to as tertiary residues. Tertiary crop residues include, e.g., foodstuff unsuitable for human consumption as a result of decay (human excretions and other post retail losses are excluded). Wood waste is discarded wood products, such as waste paper and demolition wood. The potential energy supply from waste is calculated as follows:

$$\mathrm{WA} = C\,w\,\mathrm{wr} \qquad (5)$$

where WA is the bioenergy potential from waste ($\mathrm{t\,yr^{-1}}$), C the consumption of crops (feed, seed and food) or industrial roundwood ($\mathrm{t\,yr^{-1}}$), w the waste generation fraction, defined as the fraction of the total amount of product consumed that becomes available as waste (dimensionless) and wr the waste residue recoverability fraction is the fraction of the waste that realistically can be recovered for energy production. For crop waste the recoverability fraction is set at 1.0. For wood process residues a recoverability fraction of 0.75 is used, equal to the recoverability fraction of wood process residues and of municipal solid waste (e.g., [59]) (dimensionless).

Data on the quantities waste and on produced and consumed products per region are derived from FAO statistics [4]. The highest and lowest regional waste generation fractions are used as a proxy for the waste ratios in a low and high level of technology production system, respectively. For wood, waste generated during the end-consumer phase is included. The wood waste generation fraction equals the part of the industrial roundwood not converted into residues during the processing of industrial roundwood (= 1−the wood process residue generation fraction). For both crops and wood waste it is assumed that all waste is available in the year 2050, thereby ignoring that waste is generated at the end of the lifespan of a product.

5.4. Residues and wastes available for bioenergy production

Table 14 shows the supply of agricultural residues, forestry residues, discarded wood products and the demand for residues for animal feed in various regions in various systems in 2050.

Table 14 shows that the amount of residues and wastes that can be recovered in 2050 is estimated at 95–115 $\mathrm{EJ\,yr^{-1}}$. The bulk (53–61%) of this potential comes from crop harvest residues. The remaining supply comes from crop process residues (14–17%) and from wood residues and wood wastes (25–30%). The use of crop residues for animal feed limits the amount of residues available for energy production by 19 $\mathrm{EJ\,yr^{-1}}$ in 2050. The remaining supply of residues and wastes available for energy production is, therefore, calculated at 76–96 $\mathrm{EJ\,yr^{-1}}$, depending on the agricultural production system. Note that the amount of crop harvest residues and crop process residues in system 4 is the same as in system 3, because the food consumption, the feed conversion efficiency, the feed mix and the residue generation fraction are assumed the same in system 4 as in system 3.

The agricultural production system determines the amount of food crops and feed crops produced, and consequently also the amount of harvest residues generated. System 3 is based on a landless animal production system in which all feed comes from crops and residues. Systems 1 and 2 are based on a mixed production system, in which a significant part of the feed comes from grazing. The production of harvest residues from food and feed crop production is consequently the highest in system 3. Small differences in residue production between systems 1 and 2 are caused by differences in the allocation of crop production. The production system also determines the level of advancement of agricultural technology and herewith the crop harvest residue generation fraction. Systems 1–3 are based on a high level of advancement of agricultural technology. In such systems, varieties are used with a higher HI and thus a lower crop harvest residue generation fraction, compared to traditional varieties. For example, the harvest residue generation fraction of winter wheat is 3.0, 1.9 and 0.8, in a low, medium and high level of advancement of agricultural technology. As a result, the production of harvest residues increases on average by 40% and 117% in a medium and low level of agricultural technology, compared to a high level of agricultural technology. For a super high level of agricultural technology (system 4) no data were available about the crop harvest generation fraction; the crop harvest generation fraction in system 4 was assumed to be the same as in system 3.

The use of residues and wastes for other purposes than energy production will limit the potential from residues and wastes. For example, Junginger and co-workers estimated that in the end of the 1990s in Thailand 50–100% of the woody residues are used as fuel or fibre feedstock in the pulp and paper industry, whereas 0–100% of the crop residues are used as fuel, fertilizer or feed, dependent on the crop type [60]. Another issue is the recovery of paper. At this moment, globally roughly half of the paper

Table 14
Potential supply of agricultural residues and wastes in 2050 for systems 1–4 (EJ yr^{-1})

Region	Crop harvest residues			Crop process residues	Wood harvest residues, medium demand and plantation scenario	Wood process residues, medium demand and plantation scenario	Wood wastes, medium demand and plantation scenario	Sum of all residues and wastes, excl. demand for feed from residues			Use of residues for feed	Sum of all residues and wastes, incl. demand for feed from residues		
	1	2	3, 4	1–4	—	—	—	1	2	3, 4	1–4	1	2	3, 4
North America	5	8	10	1	2	4	4	16	19	21	2	14	17	19
Oceania	2	4	5	0	0	0	0	2	4	5	0	2	4	5
Japan	0	0	0	0	0	1	1	2	2	2	0	2	2	2
West Europe	2	2	3	1	1	2	2	8	8	9	2	6	6	7
East Europe	1	1	1	0	0	0	0	1	1	1	0	1	1	1
C.I.S. and Baltic States	3	3	4	0	1	1	1	6	6	7	1	5	5	6
Sub-Saharan Africa	15	12	20	2	0	0	0	17	14	22	2	15	12	20
Caribbean and Latin America	11	10	12	2	1	1	1	16	15	17	3	13	12	14
Middle East and North Africa	1	2	2	1	0	0	0	2	3	3	2	0	1	1
East Asia	4	4	5	5	2	2	2	15	15	16	5	10	10	11
South Asia	5	6	7	4	1	0	0	10	11	12	2	8	9	10
World	49	52	69	16	8	11	11	95	98	115	19	76	79	96

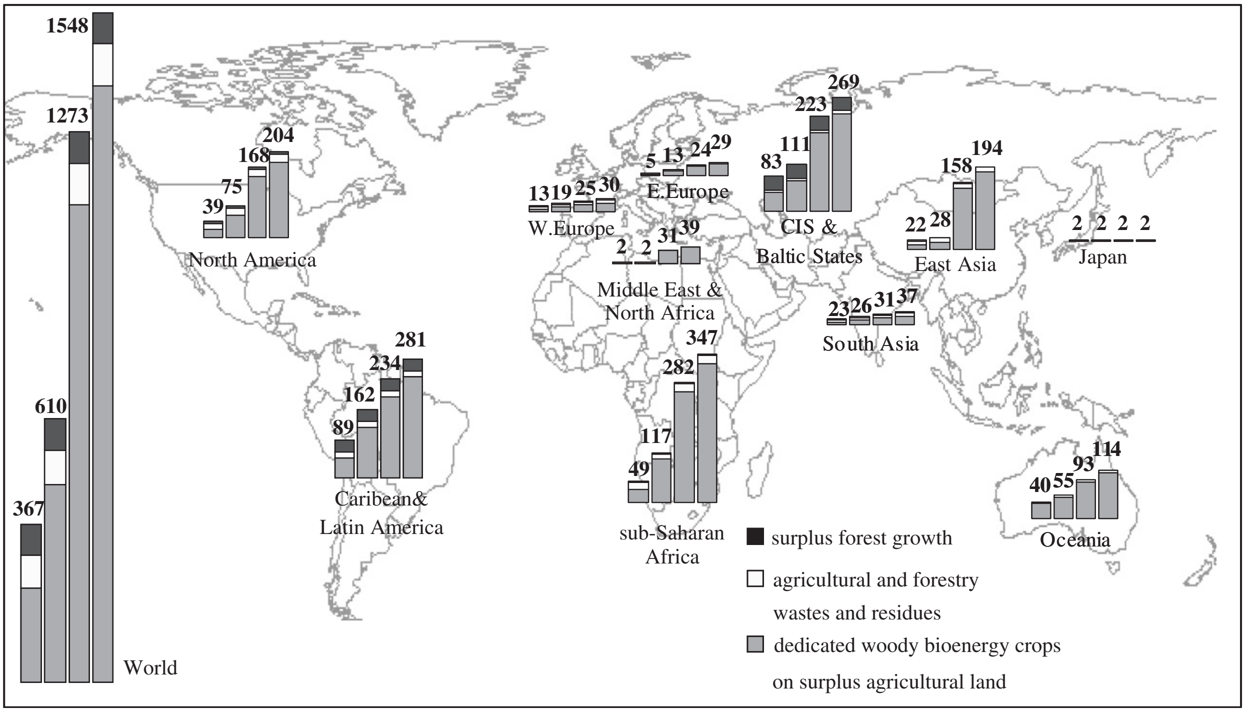

Fig. 7. Total technical bioenergy production potential in 2050 based on systems 1–4 (EJ yr^{-1}; the left bar is system 1, the right bar is system 4).

consumption is being recovered, but projections indicate that this share could increase substantially, up to some three fourth of the paper consumption [61].

6. Total potential bioenergy supply in 2050

Fig. 7 shows the potential bioenergy supply per region in 2050 for various systems.

The results show that the technical potential to increase the efficiency of food production is sufficiently large to compensate for the increase in food consumption projected between 1998 and 2050. The total global bioenergy potential in 2050 is calculated to be 367, 610, 1273, and 1548 EJ yr^{-1} for systems 1–4, respectively. The bulk of this potential comes from specialized energy crops grown on surplus agricultural land that is no longer required for food production. The variation in surplus agricultural land between the various systems is mainly dependent on the efficiency with which animal products are produced. Residues and wastes account for 76–96 EJ yr^{-1} of the technical potentials, although the alternative use of residues and wastes as for instance traditional fuel, animal bedding or as a source of fiber for the paper industry may reduce the availability of energy production. The range in potential from residues and waste between the various production systems is the result of differences in the demand for feed crops and differences in the technology applied during production, harvesting and transportation. The technical potential from wood obtained from natural forests is estimated to range from 59 to 103 EJ yr^{-1}, depending on the plantation establishment scenario and wood demand scenario. The energy potential of surplus forest growth and woody residues and wastes is further discussed in a separate article [5].

7. Export potential of bioenergy in 2050

The export of bioenergy should not hamper the use of bioenergy in the exporting region. Therefore, bioenergy exports should be limited to the bioenergy production potential minus the regional use. This approach most likely underestimates the export potential, because there are various other energy sources and technologies that could be applied for sustainable development and that could

Table 15
Ratio between the projected bioenergy production potential and the energy demand in 2050

Energy demand scenario	System 1			System 2			System 3			System 4		
	High	Medium	Low	High	Medium	Low	High	Medium	Low	High	Medium	Low
North America	0.2	0.3	0.5	0.4	0.5	1.0	1.0	1.2	2.3	1.2	1.4	2.8
Oceania	5.0	6.7	9.9	6.9	9.2	13.7	12	15	23	14	19	28
Japan	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
West Europe	0.1	0.2	0.2	0.2	0.2	0.3	0.3	0.3	0.4	0.3	0.4	0.5
East Europe	0.2	0.3	0.4	0.6	0.7	1.0	1.0	1.2	1.9	1.3	1.5	2.3
C.I.S. and Baltic States	0.8	1.1	2.0	1.1	1.5	2.7	2.3	3.0	5.5	2.7	3.6	6.6
Sub-Saharan Africa	0.7	0.9	1.0	1.6	2.1	2.3	3.9	5.1	5.6	4.8	6.3	6.9
Caribbean and Latin America	1.2	1.4	1.8	2.2	2.5	3.3	3.2	3.7	4.8	3.9	4.4	5.8
Middle East and North Africa	0.0	0.0	0.0	0.0	0.0	0.0	0.3	0.4	0.5	0.4	0.5	0.6
East Asia	0.1	0.1	0.1	0.1	0.1	0.2	0.6	0.8	1.0	0.8	1.0	1.3
South Asia	0.2	0.3	0.3	0.2	0.3	0.3	0.3	0.4	0.4	0.3	0.5	0.5
World	0.4	0.4	0.6	0.6	0.7	1.0	1.2	1.5	2.1	1.5	1.9	2.6

reduce the demand for bioenergy, such as solar, wind and hydro energy as well as the use of fossil fuels in combination with CO_2 capture and storage.

In this article, the ratio between the bioenergy potential (excluding energy required for production, conversion and transporation) and the future primary energy demand is used as an indicator for the bioenergy export potential in each region. Three scenarios for the total primary energy consumption are taken into account, based on the relative increase of primary energy consumption projected by the World Energy Council [62]. Country-specific base year data are derived from the International Energy Agency (IEA) database [63] and aggregated into regions. The total global primary energy consumption in 2001 was 418 EJ [1]. The total global primary energy use in 2050 in the high, medium and low energy consumption is estimated to be 1041, 837 and 601 EJ, respectively. Table 15 shows the total gross bioenergy potential as obtained for the year 2050 relative to the primary energy consumption.

The fraction of the global energy use projected for the year 2050 that could in theory be met by bioenergy is 0.4 in case of system 1 (assuming a high energy demand) to 2.6 in case of system 4 (assuming a low energy demand). Oceania is the region with the highest potential supply of bioenergy compared to the regional energy demand in 2050, with ratios ranging from 5 to 28. The only other industrialized region with a ratio larger than one is North America, with figures up to 2.8. Other regions for which a ratio larger than one is projected are sub-Saharan Africa, the Caribbean and Latin America and the C.I.S. and Baltic States, with ratios up to 6.9, 5.8 and 6.6, respectively, depending on the primary energy consumption scenario and the agricultural production system assumed. The ratios in East Asia range between 0.1 and 1.3. Japan, Middle East and North Africa and South Asia all have low ratios, due to the relative scarcity of land in these regions, and consequently limited potential of energy crops, which is in general the most important source of bioenergy.

8. Sensitivity analysis

The sensitivity of the results for variations of the input parameters is shown by means of scenario and sensitivity analysis. The goal is to evaluate the sensitivity of the results for uncertainties in the data and methodology and to indicate the relative impact of the different parameters. In Section 8.1, the focus is on the sensitivity for methodological assumptions. In Section 8.2, the focus is on the sensitivity for parameter values. Parameters that were found to have a limited ($<5\%$) impact on the bioenergy potentials, such as seed ratios, are excluded from the results. Results for Japan and the Middle East and North Africa will not be shown, because of the high sensitivity of the potential in these regions for the scarcity of land. Final conclusions about the sensitivity analysis are also given in Section 8.2.

Table 16
The impact of various parameters, scenario and methodological issues on the total global production potential of bioenergy crops in 2050 (in EJ and in % change compared to system 2, which is used as a baseline)

	System 2 (baseline)	Limitation of suitable cropland to areas suitable for wheat, rice, maize		Medium plantation establishment scenario (scenario 2)		Low plantation establishment scenario (scenario 1)		Low food demand scenario and low population scenario		High food demand scenario and high population scenario	
	EJ	EJ	%	EJ	%	EJ	%	EJ	%	EJ	%
North America	53	52	−3	66	+24	73	+38	55	+4	49	−8
Oceania	51	48	−6	57	+12	59	+16	55	+8	41	−19
Western Europe	11	10	−7	14	+29	16	+51	10	−5	11	+4
East Europe	11	10	−3	12	+9	12	+15	13	+21	9	−17
C.I.S. and Baltic States	73	70	−4	73	0	80	+10	87	+19	57	−22
Sub-Saharan Africa	102	77	−25	118	+15	122	+19	123	+20	78	−24
Carribean and Latin America	120	106	−12	133	+11	139	+16	132	+10	103	−14
East Asia	17	12	−31	18	+8	18	+10	17	+1	16	−5
South Asia	17	13	−23	20	+20	22	+27	18	+6	16	−6
World	455	399	−12	511	+12	541	+19	511	+12	380	−17

8.1. Methodological sensitivity analysis

The area available for crop production was limited by the crop specific area and the crop non-specific area (see Section 3.3.2). The sum of the crop specific areas allocated to crop production may not exceed the crop non-specific area. This procedure overestimates the area that is agro-ecologically suitable for crop production in case the crop-specific areas overlap maximally in reality, instead of partially. An example: a crop non-specific area of 100 ha represents a crop specific area of 100 ha (crop 1), 10 ha (crop 2) and 10 ha (crop 3). If in reality the crop 2 specific area and the crop 3 specific area overlap completely, and these 10 ha are used for the production of crop 2, then the crop specific area available and suitable for crop 3 is zero. In the Quickscan model, if 10 ha is used for the production of crop 2, then the crop specific area of crop 3 remains 10 ha. The risk of overestimation decreases if the total area of suitable and available land for crop production decreases. If the crop non-specific area is restricted to areas where at least one of the three most important cereals (wheat, maize and rice) can grow, instead of all crops, then the crop non-specific area decreases. Results are shown in Table 16, in which system 2 is used as a benchmark. Globally, the energy potential from energy crops may decrease by 12%. In the other systems the potential may decrease with a maximum of 14% (system 3; results not shown).

A set of allocation rules was used in the Quickscan model to allocate the area of agro-ecologically suitable cropland to various land use categories (e.g., forest, other land, permanent pasture, build-up land; see Section 3.3.1). This allocation procedure inevitably introduces errors that could result in an over- or underestimation of the area suitable and available for food crop production. Here, the sensitivity of the results for these errors is analyzed by exchanging suitable (crop non-specific) areas with (crop non-specific) areas classified as NS: 10% of the area that was allocated to the land use category ‘other land’ is allocated to crop production and an equal area previously allocated to crop production is now allocated to ‘other land’. The 10% is an artificially chosen value. As a result, the bioenergy potential from energy crops decreases by 6%, 11%, 4% and 3%, in case of system 1–4, respectively. In all cases, no food shortages were projected. The area of suitable cropland available for crop production could also have been underestimated, but this is less likely, because the most suitable areas are allocated to crop production. The impact of the error in the allocation of agro-ecologically suitable cropland to various land use categories is dependent on the land use profile in each region. The impact is small if the ratio suitable cropland to present cropland is high, and vice versa. Table 9 shows the area that is agro-ecologically suitable for crop production in comparison with the cropland in 1998. The regions with the highest percentage are the Middle East and North Africa (98%), East Asia (74%) and South Asia (93%); the regions with the lowest percentages are sub-Saharan Africa (17%) and the Caribbean and Latin America (16%). The risk of an overestimation of the land available for crop production is the highest in the regions with the highest percentage. However, one could also argue that in land scarce regions the relative scarcity of land suitable for crop production leads to a land use pattern that is more optimized with respect to yields compared to more land abundant regions. Note that economic optimization generally leads to a situation in which the most productive areas are used as cropland, instead of pasture or are left unutilized as in the case of other land. For example, in the USA, cropland is roughly three times as valuable as pasture [64].

In our approach the production of dedicated energy crops is not allowed to endanger the supply of food. In reality, energy crop production may compete with food crop production. Therefore we will now investigate the energy potential of dedicated energy crops in case the most productive areas are used for energy crop production and the least-productive areas are allocated to food and feed crop production. A prerequisite remains that the global demand for food is met. In such an approach, the technical potential of energy crops changes by +22%, −13%, −14% and −13% in system 1–4, respectively. Yet, the impact in terms of land use patterns is larger: between 30% and 51% of the most productive land previously allocated to food crop production is now allocated to energy crop production and vice versa. The impact on the bioenergy potential is smaller, because large areas low-productive land are exchanged with small areas highly productive land.

In the approach used in this study the production of projected consumption of food was allocated within each region. If the production potential was found to be insufficient to meet the demand, then the remaining demand was allocated to other regions. This methodology does not result in the most-efficient geographic optimization of land use patterns, i.e. the highest global average yield and the lowest land use. For example, according to our model, wheat in Oceania can be produced with an average yield of about 6 $\mathrm{t\,ha^{-1}\,yr^{-1}}$, while in certain areas in Western Europe, East Europe and C.I.S. and Baltic States wheat can be produced with a yield of about 8 $\mathrm{t\,ha^{-1}\,yr^{-1}}$ to 12 $\mathrm{t\,ha^{-1}\,yr^{-1}}$. A further geographic optimization of land use patterns and reduction of the area of land required for food crop production can be realized when food production would be allocated to the most productive regions globally. As a result, the energy potential from dedicated energy crops would increase by 38%, 9%, 10% and 8% in system 1–4, respectively.

8.2. Parameter sensitivity analysis

In the baseline scenario a high forestry plantation establishment scenario was included to avoid an overestimation of the surplus areas of cropland available for bioenergy production. A low or medium scenario would lead to a lower demand for land for plantations and a higher availability of land for bioenergy production of 160 and 68 Mha, respectively. Table 16 shows the bioenergy potential based on a low and medium plantation establishment scenario. Compared to the 0.7–3.5 Gha that in theory can be made available in 2050 for energy crop production, the global demand for land for plantations for material and traditional woodfuel use is limited: 0.1–0.3 Gha. Nevertheless, the impact on the potential of energy crops is larger: the potential in case of a medium and low scenario is 12–19% higher, respectively. The regional impact is larger: the energy potential in Western Europe is 51% higher and in North America 38% higher in case of a low scenario compared to a high scenario for plantations. We conclude that plantations that are established for the production of industrial roundwood and woodfuel could be a significant limiting factor for the production of energy crops in these regions.

Three scenarios for population growth and three scenarios for the per capita food consumption growth were included. The results described so far were based on a medium population growth and medium per capita food consumption. As part of the sensitivity analysis we will now investigate the impact of two other future developments. One is

Table 17
Impact of different scenarios for per capita consumption and population growth to 2050 on the total demand for food

Region	Medium food demand scenario and medium population scenario			Low food demand scenario and low population scenario			High food demand scenario and high population scenario		
	POP 1998 = 1	PCC 1998 = 1	TOT 1998 = 1	POP 1998 = 1	PCC 1998 = 1	TOT 1998 = 1	POP 1998 = 1	PCC 1998 = 1	TOT 1998 = 1
North America	1.47	1.04	1.53	1.28	1.04	1.34	1.68	1.04	1.75
Oceania	1.35	1.11	1.49	1.21	1.08	1.32	1.50	1.13	1.69
Japan	0.87	1.13	0.99	0.80	1.12	0.89	0.95	1.15	1.09
West Europe	0.98	1.07	1.05	0.88	1.06	0.93	1.10	1.08	1.19
East Europe	0.84	1.14	0.95	0.75	1.12	0.83	0.93	1.16	1.08
C.I.S. and Baltic States	0.83	1.20	1.00	0.72	1.16	0.83	0.96	1.25	1.20
Sub-Saharan Africa	2.55	1.32	3.36	2.15	1.25	2.68	2.99	1.39	4.15
Caribbean and Latin America	1.53	1.22	1.87	1.24	1.17	1.46	1.84	1.27	2.35
Middle East and North Africa	2.05	1.15	2.35	1.70	1.11	1.88	2.44	1.19	2.90
East Asia	1.22	1.16	1.42	0.99	1.12	1.12	1.49	1.20	1.79
South Asia	1.70	1.35	2.29	1.39	1.28	1.78	2.06	1.39	2.87
World	1.50	1.19	1.79	1.25	1.15	1.43	1.79	1.23	2.20

POP = population; PCC = per capita consumption; TOT = total demand for food. *Sources*: [3,15,20,77], own calculations.

based on a high population growth and high per capita food consumption and the other on a low population growth and low per capita food consumption. Table 17 shows the population size, the per capita food consumption and the total food consumption in 2050 relative to 1998 for each of the three scenarios.

The global in food intake was projected to increase between 1998 and 2050 by +79% in the medium population growth and per capita consumption scenario, compared to +43% in the low and +120% in the high scenario, respectively (food intake is expressed on a kcal basis). In the high food consumption scenario the bioenergy potential decreases by 16%. It increases by 12% in case of the low food consumption scenario. The impact of a low and high population and food consumption scenario is particularly large in the developing regions, indicating that the projections from these regions are less certain compared to other regions.

The results of the methodological and parameter sensitivity analysis indicate that the energy potential from dedicated energy crops varies up to plus or minus one-fifth as a result of uncertainties in the input data and the methodology. Yet, the combined impact of various uncertainties is larger. Even so, we conclude that the results are sufficiently robust to identify which regions are promising bioenergy exporters and to show the impact of various key factors on the technical potential for bioenergy production.

9. Discussion

In this section, various bioenergy potential assessments found in the literature are reviewed, using results of the Quickscan model as a starting point. The review is limited to the bioenergy potential of dedicated crops, since this is the source with the highest potential and largest uncertainty. In Section 9.1, the focus is on the approach applied in various studies, in Section 9.2, the focus is on data quality and in Section 9.3 results from various studies are compared.

9.1. Approach

A prerequisite for the production of biomass for energy use is that the demand for food, industrial roundwood and traditional woodfuel must be given priority, because competition between these factors is considered unsustainable and should, therefore, be avoided in this study. Further deforestation or disturbance of protected areas as a result of the production of bioenergy is also considered unsustainable and, therefore, avoided. Consequently, the supply of biomass in this study is restricted to:

- Surplus agricultural land not needed for food production and on which energy crops are produced. Therefore, the production efficiency of food, in terms of output per unit of land, is a key variable in this study. The production efficiency of the agricultural sector assumed in this study can be increased in two ways. First, by increasing the level of advancement of agricultural technology. Second, by changing the geographic optimization of land use patterns, i.e. the allocation of crop production to areas with the most favorable natural circumstances for that crop type (highest yields). As a result the agricultural land used for food production is minimized, leaving the least-productive areas available for the production of dedicated bioenergy crops.
- Surplus natural forest growth, which is defined as the supply of wood from forests minus demand for (traditional) woodfuel and industrial roundwood. In this study, wood from protected forest areas or from was excluded as a source of wood supply.
- Surplus residues and waste not required for food production or material production.

Consequently, first an assessment of the future consumption of food and wood was made, followed by an assessment of the land areas required for the production of the consumed food, industrial roundwood, and traditional woodfuel in 2050. Estimates of bioenergy potentials found in the literature do not always take these limitations into account. Supply driven studies focus on the resource base and competition between biomass uses, and thus usually take into account the impact of, e.g., the demand for food, industrial roundwood and woodfuel. Demand-driven studies focus on the demand for bioenergy as a result of the economic competitiveness of bioenergy or exogenous targets on greenhouse gas emission reductions. Demand driven studies thus generally exclude the impact of sustainability criteria listed above, although many include a feasibility check in which the projected plantation area or bioenergy production is compared to the availability of resources, often via reference to other studies and thus indirectly include the impact of sustainability criteria [8]. However, there is no guarantee that the economic conditions assumed in demand driven assessments ensure that the sustainability criteria as included in supply driven assessments are met. Ideally, the production of bioenergy and impact on land use is modeled using a general equilibrium model that mimics the competition for resources (e.g., water, land, labor) for the production of food, industrial roundwood, woodfuel and bioenergy, and mimics the impact of agricultural and energy policies. Such an exercise would allow for an assessment of the conditions under which bioenergy production is feasible and the impact of various sustainability criteria on costs and potential of bioenergy crop production. However, such calculations are problematic, as discussed below.

First, the modeling of food prices, thus (economic) supply and demand interactions is hampered by various methodological problems and problems related to the availability of reliable data. For example, the calculation of price-demand elasticities is difficult, because historic data are distorted by e.g., price fluctuations due to (agricultural) policies and yield fluctuations due to technological improvements and variation in weather. As a result, projections found in the literature differ as a result of differences in the elasticities assumed and due to differences in the (exogenous) long-term GDP growth figures used in the calculations, see e.g., [20,65]. Nevertheless, various studies have shown that comprehensive economic food demand and supply modeling is possible [15,20]. The modeling of food consumption is used as an example here, but a similar discussion also goes for wood consumption. The modeling of the demand and supply of bioenergy may be even more complicated, because in most regions the present use of bioenergy is limited and consequently little historic data series are available and also because various bioenergy conversion technologies are still under development. Second, the capacity of the natural resource base to support an increasing production of food is uncertain. Ideally, resource scarcity and resource degradation are incorporated in the economic analysis. However, resource scarcity and degradation are often accounted for in prices. Consequently, environmental or spatial problems are not discussed separately. Well-known problems are the overuse and scarcity of fresh water, soil degradation (e.g., salinisation, soil nutrient depletion and soil erosion), and various forms of pollution. Despite their importance, data on these issues are often insufficient and uncertain and a detailed understanding of many of the underlying biological and physiological processes is not available. Consequently, assessments of the capacity of the natural resource base of food production to increase the output are rather subjective [30,66]. As a result, projections of food consumption range from very pessimistic (e.g., [67,68][34]) to very optimistic (e.g., [70,71]). Some of the more pessimistic studies suggest the capacity of the natural resource base to increase food production may be insufficient to meet the increase in population, but these pessimistic projections are so far not (yet) confirmed by reality and therefore excluded. Similar discussions go for projections of the consumption of wood. Projections of the consumption of bioenergy seem relatively optimistic about the capacity of the natural resource base to increase food production and simultaneously increase bioenergy production, at least compared to the pessimistic studies on food consumption. Note that this is not necessarily a contradiction, because many studies on bioenergy potentials suggest that bioenergy crops could be produced on degraded agricultural areas, set aside areas and other areas no longer suitable or required for food production (e.g., [72,73]), see further Section 9.3).

For the development of the Quickscan model, the issues discussed above were considered too complex and time consuming to take into account. Instead, mainstream projections of food, industrial roundwood and woodfuel consumption were included that (partially) included the matching of demand and supply and included limitations of the natural resource base to supply for supply food. Advantages of this approach are:

- The scenarios are based on state-of-the-art outlook studies that are commonly accepted.
- The methodology is (relatively) simple, which makes it transparent and allows for an analysis of the impact of various factors.

A disadvantage is that the combination of scenarios from various sources ignores feed back mechanisms between the various factors. In reality, developments in land use and yields are affected by the entire socio-economic system, which comprises a wide variety of factors, such as the prices of land and labor, the availability of infrastructure, the natural circumstances, the interest rates and the level of education level of workers. Future research should, therefore, focus on the dynamics of the socio-economic system that determine the efficiency of food consumption and land use patterns, including the impact of bioenergy crop production. The approach developed in this article can be used as a framework for such research. An example is the EU 'Clear Views on Clean Fuels' project (VIEWLS; [18]) that involved the application of our approach in combination with scenario analysis and cost calculations. Scenarios were included to estimate the bioenergy potential of the Central and Eastern European Countries (CEEC) in 2030, based on the availability of surplus agricultural land. The scenarios follow broadly the storylines of the IPCC SRES scenarios, as described in Section 3.3.2 [31]. The storylines were translated into quantitative parameters, e.g., on food consumption, food trade and the level of advancement of technology used for food production. Food consumption scenarios were based on the FAO projections to 2030 [15] and adapted for some scenarios. The level of trade of food was varied by changing the geographical scale of allocation of land use and crop production. The allocation resolution itself was done at a sub-national level (NUTS-3 level).[35] Four agricultural production systems were defined (current, ecological, high input, and high input advanced), of which the level of advancement of agricultural technology is comparable to the range included in this article. Further, the methodology was expanded with a module that deals with the production costs of six energy crops and a module that calculates the transportation costs related to the export of bioenergy to West Europe. The results allow a comparison of the costs and potentials of bioenergy from various crops, for various regions, for various transport chains and for various scenarios. The results also allow the identification of the

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[34] In the middle of the 1990s global cereal stocks decreased rapidly, the cereal prices increased rapidly and the stagnating yield increases were seen by some analysts as indicators of upcoming global food shortages [69]. These trends were however the result of a combination of poor harvests in the USA in 1993 and 1995, policy changes and other factors. By the end of the 1990s cereal production hit record levels and prices reached the lowest level since decades [20].

[35] NUTS stands for Nomenclature of Territorial Units for Statistics. At the NUTS-0 level the EU is divided into countries. At the NUTS-1, -2 and -3 level the EU is devided into increasingly smaller units. At the NUTS-3 level the countries are sub-divided into regions that are nationally defined, e.g., departements (France), provincias (Spain), Landkreise (Germany) or Kantone (Switzerland).

parameters and conditions for the large-scale production and trade of bioenergy at attractive cost levels. Results of the VIEWLS project show that the methodology applied in this study can serve as a framework for more comprehensive and detailed assessments. However, the availability and reliability of data remains a key-limiting factor.

9.2. Data quality

A general problem when modeling the consumption of food and wood, and land use patterns, is that many data sets used in the calculations, are incomplete and/or uncertain. Data on the following parameters included in the Quickscan model are judged by us as particularly uncertain, although the exact level of uncertainty is unknown:

- *Land use*: The reliability of data on land use (changes) varies significantly. Main problems when estimating bioenergy potentials are related to the lack of explicit geographical information in the (tabular, national) data in the FAOSTAT database. As a result, the overlap between various land use categories included in the FAOSTAT database and the areas that are agro-ecologically suitable for crop production is uncertain. In this study, a fictitious land use 'map' was composed, depicting the total extent of suitable cropland (the crop non-specific area) by various land use categories, e.g., cropland and forests. The composition of this fictitious land use map was partially based on spatially explicit data in combination with the tabular data and simple allocation rules. This approach inevitably introduces errors. However, we consider the chosen allocation rules a suitable methodology, considering the goal of this study (a quick scan of bioenergy production potentials) and the long time horizon of 50 years (which makes large land use changes possible). In practice, of course, land use changes may differ from those included in the land use allocation rules applied in our model. Research based on GIS databases may solve this issue during the coming decades, when more reliable datasets come available that make more use of ground-truthing and that are based on finer resolution remote sensing data, compared to the present datasets.
- *The animal production system*: The production efficiency of the animal production system is a key variable when estimating bioenergy potentials. Some three-fourths of the global agricultural land use is permanent pasture [4] and the consumption of animal products is projected to increase rapidly in the coming decades [15]. Despite this importance, data about the input of feed in the animal production system and the impact of various parameters (such as breeding, animal disease prevention, diagnosis and treatment, and the use of feed supplements) on the production efficiency are scarce and relatively uncertain. This goes particularly for the bovine meat and milk production sector, which comprise a wide range of production systems, and not so much for the relatively uniform pig- and poultry-production system. Data on the input of biomass from pastures or the carrying capacity (potential production of animal products) of these areas are often not available or uncertain due to a lack of understanding of pasture ecosystems and a lack of consensus on the definition of sustainable pasture management and a healthy pasture ecosystem.
- *The supply of wood from plantations*: Data on forest plantations are often incomplete or unreliable [6,53,54].
- *The supply of wood from TOF*: A comprehensive global assessment of the number of TOF and their products does not exist [6]. Existing data on the supply of wood from TOF are based on estimates and come with considerable uncertainty.
- *The supply of wood from natural forest growth*: There is a lack of data on the (potential) supply of wood from natural forests. Also the impact of SFM schemes is uncertain, due to a lack of understanding of forest ecosystem processes and lack of consensus on the definition of SFM.
- *The various parameters used to estimate the energy potential of residues and waste*: Particularly, data on the fraction of the total amount of residues that can be recovered realistically and the demand for residues and waste for non-energy purposes (traditional woodfuel, animal bedding, soil improver and so on) are rare and uncertain.

Uncertainties in other parameters, particularly those that change over time, such as population growth, the per capita consumption of food, the level of advancement of agricultural production system, the geographic optimization of crop production, the plantation establishment rates, the land use allocation rules and the demand for wood (industrial roundwood and woodfuel) were included in the Quickscan model by means of scenario analysis and sensitivity analysis. This also allows for an analysis of the impact of these parameters on other parameters as well as the overall results.

9.3. Results

The bioenergy production potential in the year 2050 was calculated for three types of biomass: dedicated woody bioenergy crops (215–1377 EJ yr^{-1}), agricultural and forestry residues and wastes (76–96 EJ yr^{-1}), and biomass from surplus forest growth (59–103 EJ yr^{-1}). In the remaining of this section, the results of the Quickscan are compared with results from the literature. Two studies were available in which a similar approach was used as in the Quickscan model to calculate the global bioenergy potential in the year 2050, which are Hoogwijk et al. [7] and Wolf et al. [22], and which are from now on referred to as Hoogwijk and Wolf. In both studies, the global bioenergy potential from surplus agricultural land in the year 2050 was calculated using three population growth scenarios, three diets, and two agricultural-production systems (a low and high external input crop-production system). In a high-input system, inputs, such as chemical fertilizers and biocides, are applied to attain high yield levels. In a low-input system environmental risks are minimized, no chemical fertilizers and biocides are applied, using the 'best technical and ecological means'. For these factors Hoogwijk and Wolf used the same datasets and scenarios. The main difference between the method applied in this study and the studies by Hoogwijk and Wolf is the calculation of the area of agricultural land needed for the production of animal products. In our study, results for 2050 are presented for two types of animal production systems (a mixed production system and a landless production system), which were both based on a high level of advancement of agricultural technology. In Wolf and Hoogwijk, the feed conversion efficiency in 2050 is based on the 'best technical means' applied in the Netherlands, based on data published in 1985. In addition, the productivity (expressed in odt $\mathrm{ha}^{-1}\,\mathrm{yr}^{-1}$) of permanent pastures used for grazing is kept constant in the Quickscan model, to avoid overgrazing, while in Wolf and Hoogwijk, the productivity of pastures was allowed to increase. Results of Hoogwijk and Wolf indicate that in the year 2050 up to 84% or 4.2 Gha of the present agricultural land use could be made available for energy crop production in case an high input system is applied [22]. The scenarios for food demand that are the most similar to the scenarios included in the Quickscan model are based on the following assumptions: a medium population growth scenario, medium to affluent diet and a high input system for crop production.[36] Based on these assumptions, between 38% and 64% of the present agricultural land can in theory be made available for energy crop production, which is equal to 1.9–3.2 Gha, respectively [22]. These figures are comparable to the areas of surplus agricultural land projected by the Quickscan model in 2050 based on systems 2–4, namely 1.2, 3.3 and 3.6 Gha, respectively. Results for system 1 in the Quickscan model were excluded from this comparison, because system 1 is based on rain-fed crop production, while in Wolf and Hoogwijk irrigation is included.

Further, results presented in Wolf show that if a low-input system for crop production is applied, then there is no surplus agricultural land in 2050. These results are in line with results from the Quickscan model that indicate that in case a low or intermediate level of advancement of technology is applied the demand for food in 2050 cannot be met and the area surplus agricultural land is close to zero.[37] Results presented in Wolf also show that if a vegetarian or moderate diet in combination and a

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[36] In Wolf, three population scenarios for 2050 were included, which were derived from the UNPD database that was published in 1997: a low scenario (7.7 billion), a medium scenario (9.4 billion), and a high scenario (11.2 billion). Further, three diets were included: a vegetarian diet (2388 kcal $\mathrm{cap}^{-1}\,\mathrm{day}^{-1}$ of which 166 kcal $\mathrm{cap}^{-1}\,\mathrm{day}^{-1}$ from animal products), a moderate diet (2388 kcal $\mathrm{cap}^{-1}\,\mathrm{day}^{-1}$ of which 554 kcal $\mathrm{cap}^{-1}\,\mathrm{day}^{-1}$ from animal products), and an affluent diet (2746 kcal $\mathrm{cap}^{-1}\,\mathrm{day}^{-1}$ of which 1160 kcal $\mathrm{cap}^{-1}\,\mathrm{day}^{-1}$ from animal products). For comparison, in the Quickscan model three population scenarios for 2050 are inlcuded, which are derived from UNPD projections published in 2003: a low scenario (7.3 billion), a medium scenario (8.8 billion), and an high scenario (10.5 billion). Three consumption scenarios were included: a low scenario (3069 kcal $\mathrm{cap}^{-1}\,\mathrm{day}^{-1}$ of which 582 kcal $\mathrm{cap}^{-1}\,\mathrm{day}^{-1}$ from animal products), a medium scenario (3236 kcal $\mathrm{cap}^{-1}\,\mathrm{day}^{-1}$ of which 622 kcal $\mathrm{cap}^{-1}\,\mathrm{day}^{-1}$ from animal products), and a high scenario (3327 kcal $\mathrm{cap}^{-1}\,\mathrm{day}^{-1}$ of which 670 kcal $\mathrm{cap}^{-1}\,\mathrm{day}^{-1}$ from animal products).

[37] This comparison is however not entirely correct, because of differences in definitions: in Wolf, the feed conversion efficiency in both the low and high input production system represents the efficiency of production of animal products in the Netherlands in early 1980's; in the Quickscan model, the feed conversion efficiency in a low level of technology represents the efficiency

low-input system for crop production are assumed, then a surplus area of agricultural land of up to 3.1 Gha can be realized. Such a scenario is excluded in this study, because a vegetarian and moderate diet are unlikely, based on the increase in per capita food intake projected by the FAO, IFPRI, USDA for the coming decades [15,20,21].

Although the maximum area of surplus land calculated in Hoogwijk and Wolf and this study are comparable, the estimated bioenergy potentials from these areas are not. Wolf calculated the bioenergy potential from 4.2 Gha land at 577 EJ yr^{-1} in case of a high-input crop-production system. Hoogwijk calculated the bioenergy potential from 3.7 Gha land at 988 EJ yr^{-1}. In this study, the bioenergy potential from 3.6 Gha land is estimated at 1377 EJ yr^{-1}. These differences are caused by differences in the assumed yield. In Wolf and Hoogwijk, an average yield of 7.3 and 14 odt ha^{-1} yr^{-1} was assumed. In the Quickscan model the average yield is 20 odt ha^{-1} yr^{-1} in case of system 4. The difference in yield levels is the result of differences in definitions and assumptions. The yield of 7.3 odt ha^{-1} yr^{-1} assumed by Wolf represents the global average yield for rain-fed grassland in case of a high-input crop-production system based on existing 'best technological means'. The yield of 14 odt ha^{-1} yr^{-1} assumed by Hoogwijk represents the global average yield for rain-fed woody bioenergy crops and takes into account the suitability of the surplus areas of land for woody bioenergy crop production, assuming the level of advancement of agricultural technology in 1995. The yields in the Quickscan model have been derived from the same source and were based on the calculation of an attainable yield level, using a crop growth model and soil climate data presented by the IMAGE team [3]. The calculated attainable yields were multiplied by a management factor that accounts for non-optimal agricultural practices as well as the future impact on yields of technological improvements. In Hoogwijk, a management factor of 0.7 was assumed, while in the Quickscan model a management factor of 1.5 was taken, following the SRES A1 scenario in the year 2050 (yields in 1995 were 53% lower, yields in the year 2050 in the B1 and the B2/A2 scenario were 14% and 26% lower compared to the A1 scenario). The management factor of 1.5 used in the Quickscan model includes the impact of breeding, a higher HI, an increasing use of irrigation and fertilizers, general (bio)technological improvements and the (limited) effect of CO_2 fertilization between 1995 and 2050. The difference between the average yields in Hoogwijk and this study is, however, smaller compared to what one would expect based on the management factor. This is probably the result of differences in land allocation: in the Quickscan model the least productive areas are by definition available for bioenergy crop production; in the study of Hoogwijk this was not the case. No simple explanation could be found for the difference in yields calculated for a high-input crop-production system (7.3 odt ha^{-1} yr^{-1}) as defined in Wolf and the yield in 1995 assumed in Hoogwijk (14 odt ha^{-1} yr^{-1}). Potential explanations are, e.g., differences in the land allocation procedure and differences in the crop species used (yield data in Wolf represent herbaceous crop yields, yield data included in Hoogwijk model are for woody crops). In the literature generally constant global average crop yields are assumed that are lower than the yield levels included in Hoogwijk and this study for the year 2050. The reason is that most studies exclude productivity improvements over time. An exception is a study by the United States Environmental Protection Agency (USEPA), in which three scenarios for yields levels are included (no year specified): low: 25 and 49 odt ha^{-1} yr^{-1}, medium: 37 and 74 odt ha^{-1} yr^{-1}, and high: 49 and 99 odt ha^{-1} yr^{-1} in temperate and tropical regions, respectively (USEPA, 1990 in [8]).

Some of the yield levels reported above may seem high, but they are feasible taking into account the efficiency of photosynthesis. The present global production of biomass (NPP) per hectare land, averaged across all vegetation types, is estimated to be 8.9 odt ha^{-1} yr^{-1}.[38] This corresponds to an energy storage of 0.3% of the average 180 W m^{-2} solar energy falling on the earth surface [19]. The maximum efficiency of photosynthesis is, however, much higher: 3.3% for C_3 plants and 6.7% of C_4 plants. However, it seems unlikely that the practical efficiency for recoverable terrestrial plant matter will exceed 2% of the solar energy [19]. These data suggest that the average yields could increase

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(*footnote continued*)
of a non-industrialized, traditional production system as found in developing regions.

[38] The present NPP of the global area of land is 2280 EJ yr^{-1} [2], the global area of land is 13 Gha [4]. In addition a higher heating value of 19 GJ odt^{-1} is assumed.

roughly by a factor 7 to an average of 62 odt ha^{-1} yr^{-1}, thereby ignoring water and nutrient constraints for crop growth. For comparison: the present average yield of energy crops on earth is calculated to be 8.4 odt ha^{-1} yr^{-1}, and projected to increase to 18 odt ha^{-1} yr^{-1} in 2050 following the A1 SRES scenario.[39]

The studies discussed above indicate that the (technical) potential to increase the efficiency of food production and thus to generate surplus areas of agricultural land for bioenergy crop production is large. The area surplus agricultural land ranges from at 0.7 Gha in case of system 1 to 3.6 Gha in case of system 2. However, most outlook studies on agricultural land use indicate that the area of agricultural land is likely to decrease or remain stable in industrialized regions, and increase in developing regions, resulting in a global increase of the area of agricultural land (e.g., [13,15,23,34,35]). For example, FAO projections of the change in area of agricultural land to 2030 indicate that the area of agricultural land may increase from 5.0 Gha in 1998 to 5.3 Gha in 2030 [34]. Yet, scenario analysis reveals that land use changes could be larger, dependent on the assumptions. For instance, Wirsenius et al. [34] calculated that the area agricultural land could decrease by 0.2–0.9 Gha between 1998 and 2030 as a result of increases in livestock productivity, the partial substitution of beef, sheep and goat meat by pig and poultry meat, a shift in the structure of diets towards more vegetable and less animal food and less food wastes. Scenario analyses using integrated models such as IMAGE, show that the change in cropland between 1990 and 2050 could range between −0.02 and +0.17 Gha based on the four SRES marker scenarios. The change in the area of grassland between 1990 and 2050 is projected to range between −0.65 and +0.16 Gha based on the four marker scenarios [46].

The differences in the projected area of agricultural land are caused by numerous factors, including crop yields. Results of the Quickscan model indicate that the application of production systems 1–4 results in an annual increase in cereal yields between 1998 and 2050 of 2.0%, 2.5%, 2.5% and 3.0%. Compared to the global average increase in cereal yields between 1961 and 1998 of 2.2% yr^{-1}, these numbers seem plausible [4]. However, most outlook studies on agriculture indicate that it is unlikely that this yield increase will be maintained during the coming decades [15]. Yield growth has been slowing down for some decades now, and this process is projected to continue during the coming decades. The average increase in cereal yields in the developing countries between 1961 and 1998 has been 2.5% yr^{-1}, compared to 1.7% yr^{-1} between 1989 and 1999 [15]. The FAO projects that cereal yields in the developing will increase on average by 0.6% yr^{-1} between 1998 and 2030 [15]. Calculations representing the four SRES scenarios families that are included in IMAGE, indicate that the global average annual yield of temperate cereals, tropical cereals, maize and rice may increase between 1998 and 2050 by 0.3–1.6%, depending on the crop species and scenario [3]. The reason for the slowdown in yield growth is the diminishing effect of the Green Revolution,[40] the slowdown in food demand in several regions, and the resulting decrease in food prices over the previous decades [20,71]. Decreasing prices of food have resulted in declining investments in fundamental agricultural research, rural infrastructure, and a shift in research and development from research focused on increasing the productivity towards research focused on reducing the environmental impacts of agriculture.

Despite the lower increase in food crop yields assumed in the SRES scenarios included in the IMAGE runs, the (theoretical) bioenergy potential of dedicated bioenergy crops produced in 2050 is still considerable: 657, 311, 322 and 699 EJ yr^{-1} in the A1, A2, B1 and B2 scenario, respectively [12]. The apparent contradiction between these results and results from the Quickscan model is due to differences in the assumed population and income growth as well as differences in the definitions, assumptions and scope. First, in the IMAGE model the area agricultural land and the productivity of pastures were allowed to increase. In the Quickscan model both were kept constant. The increases in IMAGE allowed for lower crop yields compared to the Quickscan model, without that the food supply is endangered. Second, results of the IMAGE model

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[39] The bioenergy production potential on the global area of land in 2050 is assumed to be is 4435 EJ y^{-1}. The global area of land is 13 Gha [4]. In addition a higher heating value of 19 GJ odt^{-1} is assumed.

[40] The Green Revolution involved the development of genetically engineered cereal varieties with higher grain to total plant biomass ratios. These new varieties were also more responsive to controlled irrigation and to petrochemical fertilizers, which allowed the more efficient conversion of industrial inputs into crops.

also included bioenergy crop production from low productive land and rest land in 2050, which was calculated to be 248, 182, 53 and 43 EJ yr^{-1}, respectively [12]. In the Quickscan model, 'other land', which includes various low productive (semi)-natural vegetation types such as barren land, scrubland and savannas, was excluded from production for reasons of maintaining biodiversity. The global bioenergy potential of woody energy crops produced on the 3.6 Gha classified as other land (excluding build-up areas), was calculated to be 247 EJ yr^{-1}. Further, comparison is not straightforward and, therefore, difficult, because of differences in the approach, methodology and scenarios used to estimate bioenergy potentials.

Another category of land frequently mentioned in the literature as potentially available for bioenergy production is degraded land. This category was not specifically included in this study. Estimates found in the literature indicate that at this moment between 0.58 and 0.76 Gha land are degraded, of which 0–0.43 Gha could be available for bioenergy crop production [12]. Assuming a maximum area of 0.58 Mha, the bioenergy potential from degraded was calculated to be 110 EJ yr^{-1}, assuming the yield of energy crops in 1995 as calculated as described above.

10. Conclusions

Part of the research presented in this article involved a review of existing databases and outlook studies, in order to develop a bottom-up model, called the Quickscan model, to estimate the technical potential of bioenergy crop production in the year 2050. Specific attention was paid to the impact of gaps and weak spots in knowledge, the impact of the (most important) underlying factors that determine the bioenergy potential and the impact of sustainability criteria such as the avoidance of deforestation for the sake of bioenergy production, and the competition for land between bioenergy crop production and food production, and the protection of biodiversity. Three sources of biomass for energy production were discriminated: dedicated crops, surplus natural forest growth and biomass from residues and waste. The global potential of bioenergy production from agricultural and forestry residues and wastes was calculated to range between 76 and 96 EJ yr^{-1} in the year 2050. The technical potential of surplus forest growth was calculated to be 59–103 EJ yr^{-1}, dependent on the assumed wood demand and plantation establishment scenario. The potential of bioenergy production from surplus natural forest growth (forest growth not required for the production of industrial roundwood and traditional woodfuel) was calculated to be 74 EJ in the year 2050. It should be noted that the potential of natural forest growth is based on a constant forest area, which makes the estimate conservative. The largest potential comes from energy crops: 215–1272 EJ in 2050, so the focus of this study was mainly on this category. In addition, bioenergy crop production from low productive and degraded land is another important source of bioenergy, with a maximum potential of one and a half times the present global energy consumption.

A prerequisite for the realization of energy crop production is that more advanced agricultural production systems are implemented (including an increasing use of inputs such as fertilizers and agrochemicals) and that crop production is optimized geographically with respect to yields, so that the increase in efficiency of food production more than offsets the increase in food consumption projected for the coming decades. As a result, between 15% and 72% of the agricultural area used in 1998 could be made available for energy crop production, in case of system 1 and system 4, respectively.

These results are broadly in line with several other estimates published in the scientific literature [7,22]. A key issue is the uncertainty with which animal products are produced because the consumption of animal products increases rapidly and because the production of animal products is far more land intensive per kg product than crop production [15]. Despite this importance, data on the feed throughput in the animal-production system and the capacity to increase the feed subtracted from pastures is often uncertain or lacking. Results of the Quickscan model indicate that particularly an increase in the efficiency of the production of animal products and a shift in feed mix (from feed from pastures to feed from crops) could (in theory) reduce the area of agricultural land drastically. Another source of land for energy crop production are areas classified as 'other land', which include various low-productive natural and semi-natural vegetation types such as barren land, scrubland and savannas. The global bioenergy potential of woody energy crops from areas classified as 'other land' was calculated to be 247 EJ yr^{-1} for the year 2050. However, these areas may be excluded from energy crop production for reasons of maintaining biodiversity. Another key issue is the assumed energy crop yield. In this study, the average yield was calculated at 16–21 odt $ha^{-1} yr^{-1}$, depending on the suitability of the surplus agricultural land and taking into account the future impact of a.o., breeding and improved management. Yields for energy crops assumed in other studies range broadly from 7 to 49 odt $ha^{-1} yr^{-1}$. Note that the impact of resource constraints and resource degradation were only partially taken into account when estimating the potential increase in food-production efficiency and yield of energy crops. Potential important issues are soil erosion, overuse of fresh water resources, and pollution from agrochemicals. Data on these issues are, however, uncertain. Also there are many trade offs possible (e.g., increasing the use of irrigation for crop production and thereby increasing the risk of environmental degradation as a result of irrigation, but thereby also reducing the need for additional cropland and reducing the risk of further deforestation). As a result, assessments of the impact of these issues on food production have come to very different conclusions, ranging from very pessimistic to very optimistic. In this study we used the more mainstream projections for food, industrial roundwood and woodfuel consumption. These projections indicate that, under current trends, the efficiency of food production may increase substantially during the coming decades, but that the rate of increase may be insufficient to decrease the area of agricultural land in most regions. The area of agricultural land is projected to decrease or remain stable in industrialized regions, and increase in developing regions, resulting in a global increase of the area of agricultural land. Thus, major transitions in the production of food are required to increase the efficiency of food production as assumed in this study. The required level of increase beyond which surplus agricultural areas are realized and the probability of the transition is dependent on the region. Several developing regions (sub-Saharan Africa, the Caribbean and Latin America, and East Asia), have large bioenergy production potentials (31–317, 47–221 and 11–147 EJ yr^{-1}, respectively in system 1–4). In sub-Saharan Africa and the Caribbean and Latin America the potential is the result of a combination of the availability of large areas of land suitable for food and feed crop production presently not used as such and the potential to increase the efficiency of food and feed crop production as well as the efficiency of the animal-production system. Efficiency gains can in theory outpace the strong increase in the projected population and food consumption. However, various outlook studies indicate that the projected efficiency gains are not likely to be realized, resulting in a continued increase of the area agricultural land required for food production. The land balance of East Asia is less favorable, but the combination of large areas unsuitable for conventional commercial crop production and a modest growth in population and food consumption results in a considerable potential. Despite the projected increase in population and the high level of food consumption in North America and Oceania, both regions have a substantial potential (20–174, 38–102 EJ yr^{-1}, respectively in systems 1–4). These potential are the result of the combined effect of: (1) the geographic optimization of food production, (2) the future use of pasture as cropland, and (3) the potential impact of irrigation and more intensive production systems. The ratio of bioenergy potential to energy demand in 2050 is particularly favorable for Oceania, with an exceptionally high figure of 5–28. These results are broadly in line with projections found in the literature that indicate a stable or decreasing agricultural land use. These data suggest that the realization of the bioenergy production potentials calculated in this study requires less drastic changes compared to the developing regions. The same goes for the countries of the transition economy regions (East Europe (bioenergy potential of 3–26 EJ yr^{-1}) and the C.I.S. and Baltic States (bioenergy potential of 45–199 EJ yr^{-1}). As a result of economic restructuring the food consumption and production has decreased since 1992. In addition, the population is projected to decrease. As a result, the agricultural land area is relatively large compared to the projected demand for food, which makes the potential of bioenergy production in these regions more robust than in other regions. The ratio of bioenergy potential to energy demand is in general well above one and can be classified as favorable for bioenergy exports. This makes that the potential of these regions for bioenergy production robust when compared to other regions. The introduction of large-scale energy crop production may facilitate the transition to more efficient food production systems. Bioenergy may provide new incentives for investments in agricultural research and development and by providing farmers with a new source of income that allows these farmers to invest in modernization of the agricultural production systems. The latter goes particularly for developing regions. The production of bioenergy in these regions can be a driver to reduce poverty and to reduce environmental degradation resulting from poverty.

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